Quantifying river water contributions to riparian trees along a losing river: Lessons from stable isotopes and iteration method

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Abstract. River water plays a critical role in riparian plant water use and riparian ecosystem restoration along losing rivers (rivers losing flow into underlying groundwater) under warming climate~~s warming~~. How to quantify the contributions of river water to riparian plants under different ~~water table~~groundwater level~~s~~s and the related responses of plant water use efficiency is a great challenge. In this study, ~~experiments~~ observations of ~~stable~~water isotopes (δ^2H~~,~~ and δ^{18}O ~~and ^{222}Rn~~), ^{222}Rn, ~~in different waters~~ and leaf δ^{13}C were conducted for ~~riparian~~ deep-rooted riparian weeping willow (*Salix babylonica* ~~(~~L.) ~~dur~~ing 2019 ~~dry year (~~ ~~dry year~~ 2019) and 2021~~wet year~~ (wet year~~2021~~) along the Chaobai River in Beijing, China. We ~~The MixSIAR model in combination with an~~proposed an ~~–~~iteration method in combination with the MixSIAR model ~~were proposed~~ to quantify the proportional river water contribution ~~(RWC)~~ to transpiration ~~flux~~ of riparian *S. babylonica* and its correlations with the ~~depth of to the water table~~water table depth ~~(WTD)~~ and leaf δ^{13}C. Results showed that riparian *S. babylonica* took up deep water (in the 80−170 cm soil layer and groundwater) by 56.5 ± 10.8%. River water that recharged riparian deep water was an indirect water source and contributed by ~~by~~ 20.3% of water to riparian trees near~~by~~ the losing river. Significantly increasing river water ~~acquisitions~~uptake (by 7.0%) ~~but~~and decreasing leaf δ^{13}C (by −2.0‰) of riparian trees were observed as the ~~WTD~~water table depth changed from 2.7 m in dry 2019 to 1.7 m in wet 2021 ($p < 0.05$).~~–~~ The higher water availability probably promoted stomatal opening and thus increasing transpiration water loss, which led to the decreasing leaf δ^{13}C in wet year compared to dry year. ~~A short residence time (no more than 0.28 days) of groundwater indicated that there was rapid and frequent river recharge~~

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30 ~~to riparian groundwater in 2021.~~ It was found that the ~~RWC~~ river water contribution to riparian *S. babylonica* was negatively correlated with the ~~WTD~~ water table depth ~~but positively related to the~~and leaf $\delta^{13}C$ in linear functions (p ~~=~~ ≤ 0.~~000~~001). The rising ~~water table~~ groundwater level would ~~stimulate~~ trigger riparian trees to increase the water extraction from ~~maximize~~ groundwater/river ~~transpiration water consumptions~~ and show a~~~~ consumptive river-water-use pattern, which could not be recommended in order to protect both rivers and riparian

35 vegetation.~~profligate water use strategy with increasing water extraction from the losing river.~~ This study provides critical insights into understanding the mechanism~~s~~ of water cycle in ~~Groundwater~~groundwater-~~Soil~~soil-~~Plant~~plant-~~Atmosphere~~atmosphere ~~Continuum~~continuum, managing water resources and riparian afforestation along losing rivers.

1 Introduction

40 Ongoing climate warming ~~as well as~~and groundwater overexploitation ~~has~~have altered ~~precipitation regimes,~~ river ~~flow~~ runoff and bank storage globally, further leading to widespread risk~~ss~~s of rivers losing flow into underlying groundwater ("losing" river) and even running dry (Winter et al., 1998; Schindler and Donahue, 2006; Allen et al., 2015; Jasechko et al., 2021). ~~Ecological w~~Water replenishment ~~of~~to losing rivers and riparian revegetation have been pushed forward worldwide to restore the river ecosystem (Smith et al., 2018; Long et al., 2020). The

45 ~~W~~water ~~replenishing~~ replenishment to losing rivers contributed ~~by~~by ~~~~40% to bank storage and groundwater storage recovery (Long et al., 2020). However, large-scale riparian revegetation increased ~~the~~ ~~~~plant transpiration substantially, which in turn led to great loss of riparian bank storage and even river ~~flow~~runoff (Moore and Owens, 2012; Dzikiti et al., 2013; Missik et al., 2019; Mkunyana et al., 2019). Therefore, ~~deeply understand~~determining ~~w~~hat water source~~s~~~~here~~ and how much river water is taken up by riparian trees~~took up~~ and the~~ir~~ responses of tree

50 water use characteristics to ~~the variations in the~~ groundwater level~~water table~~ variations ~~could~~ can help ~~to~~ implement management strategies for maintaining ~~balance the~~ river ~~flow~~runoff and tree water ~~requirement~~need of revegetated riparian ~~species~~zones.

The potential water sources of riparian trees along a losing river are generally considered ~~as~~ a mix of soil water at different depths, groundwater, and river water (Alstad et al., 1999; White and Smith, 2020). However, there

55 ~~wa~~is a ~~drastic~~ debate on whether ~~the~~ river water is a potential water source ~~for~~of riparian trees ~~or not~~ and how it beca~~~~omes available to plants. ~~The river water contribution (RWC) to riparian trees has been widely estimated~~

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~~using the data comparison, graphical inference, two- or multi-source linear mixing models and Bayesian mixing models (MixSIR, SIAR, SISUS, MixSIAR) accompanied with stable water isotopes (δ^2H and $\delta^{18}O$) (Dawson and Ehleringer, 1991; Ehleringer and Dawson, 1992; White and Smith, 2020).~~ Most of previous studies considered ~~the~~ river water as a ~~separate~~ direct water source to ~~quantify~~ evaluate the river water contribution (RWC) to transpiration ~~flux~~uptake of riparian trees (Alstad et al., 1999; Zhou et al., 2017; White and Smith, 2020). ~~A number of previous~~These studies showed that ~~the separate~~ the river water directly ~~source~~ contributed up to 80% to riparian plant transpiration ~~directly~~ based on the stable isotopic signatures of different water~~s~~ sources and ~~the~~ plant stem water (Dawson and Ehleringer, 1991; Busch et al., 1992; Alstad et al., 1999; Zhou et al., 2017; White and Smith, 2020). Nevertheless, ~~For example, riparian *Liquidambar styraciflua* growing along a perennial stream took up river water by 30–35% in the southern Appalachian foothills, USA (White and Smith, 2020). Alstad et al. (1999) found that riparian *Salix* relied on rivers for approximately 80% of its water, which made it vulnerable to changes in river water and hydrological conditions on the northeast side of Rocky Mountain National Park, Colo.~~

~~However, there was a debate on whether the river water is a potential water source for riparian trees or not and how it became available to plants.~~ ~~S~~some studies argued that ~~the~~ river water was not a ~~direct~~ potential water source and rarely contributed to riparian trees (Dawson and Ehleringer, 1991; Bowling et al., 2017; ~~Dawson and Ehleringer, 1991;~~ Wang et al., 2019a). Dawson and Ehleringer (1991) firstly discovered that the mature streamside trees growing in or next to a perennial river did not use river water but depended on ~~the~~ water ~~sources~~ from deeper strata. ~~This~~Similar finding has also been found~~proven~~ in riparian phreatophytic trees (*Populus fremontii* and *Salix gooddingii*) and riparian deep-rooted tree species (Busch et al., 1992; Bowling et al., 2017; Wang et al., 2019a). Even under shallow groundwater with high salinity, no river water was directly ~~absorbed~~ taken up by riparian *Eucalyptus coolabah* alongside an ephemeral arid zone river in Australia (Costelloe et al., 2008). Growing evidence showed that riparian trees rarely took up river water directly at a certain distance away from the riverbank because their lateral roots could not reach the river (Mensforth et al., 1994; Thorburn and Walker, 1994); Nevertheless, riparian trees could indirectly utilize ~~the~~ river water that recharges ~~riparian~~ deep zone (e.g., deep soil water and groundwater) when their roots tap into the groundwater level (Mensforth et al., 1994; ~~Thorburn and Walker, 1994;~~ Wang et al., 2019a). If we take ~~the~~ river water as a direct water source, the RWC to transpiration ~~flux~~ of riparian trees may be overestimated. H~~Other studies claimed that river water merging into deep riparian soils and groundwater could be indirectly utilized by riparian trees under shallow water table conditions~~

85 (Mensforth et al., 1994; Wang et al., 2019b). It remained unclear that how much river water exactly contributed to riparian trees nearby a losing river. This might lead to inaccurate estimations when river water could not be directly accessed by lateral roots of riparian trees growing at a certain distance away from the riverbank (Mensforth et al., 1994; Thorburn and Walker, 1994). How to separate and quantify the ~~indirect~~ contributions of the indirect river water source to riparian trees near~~by~~ losing rivers is a great challenge.

90 The graphical inference and direct comparison of stable isotopic values between plant stem water and different water sources (Dawson and Ehleringer, 1991; Busch et al., 1992; Costelloe et al., 2008; Zhao et al., 2016), statistical two- or multi-source linear mixing models (Alstad et al., 1999; Zhou et al., 2017), and the MixSIAR Bayesian mixing model (Wang et al., 2019a; Wang et al., 2020; White and Smith, 2020; Li et al., 2021) integrated with ~~the~~ stable ~~water~~ isotopes (δ^2H and δ^{18}O) have been widely used to identify the potential water sources taken

95 up by riparian trees. The MixSIAR model has more advantages in quantifying water source contributions and accounting for uncertainties in the isotopic values (Stock and Semmens, 2013; Ma et al., 2016). The RWC to riparian trees can be estimated ~~indirectly~~ by quantifying both the direct water source contributions to riparian trees and the RWC to riparian deep water. A multi-iteration method (Marek et al., 1990; Zaid, 2010) is key to calculate the proportional contributions of total (old and current) river water to riparian deep water, which improves the

100 estimation accuracy of the RWC to riparian trees. The radioactive isotope (^{222}Rn) has been widely used for tracing groundwater origins and corresponding pathways in the riparian zone (Close et al., 2014; Zhao et al., 2018). It is helpful to estimate the residence time of recharged groundwater from river water and its effects on the RWC to riparian trees. A combination of these methods can give a more reliable quantification of the RWC to riparian trees.

105 The RWC to riparian trees could substantially affect the leaf-level water use efficiency (WUE) and ~~healthy~~ growth of riparian trees. ~~The t~~Tree WUE is a key characteristic of plant water use, which can be defined as the ratio of photosynthetic rate to transpiration rate. Since leaf δ^{13}C values are positively related to tree WUE, ~~the~~ leaf δ^{13}C has been widely used as an indicator of tree WUE for C$_3$ photosynthesis plants (Farquhar et al., 1989). For example, Thorburn and Walker (1994) found that the riparian *Eucalyptus camaldulensis* beside the ephemeral

110 stream had higher tree WUE with more frequent access to river water based on the leaf δ^{13}C measurements. Moreover, the fluctuation of the ~~depth to the water table~~water table depth (WTD) in the riparian zone resulting from changing river water levels plays a critical role in the RWC to riparian trees and tree WUE (Horton and

Clark, 2001; Liu et al., 2017; Xia et al., 2018). However, little attention has been paid to quantifying the relationships between the RWC to riparian trees and ~~the~~ tree WUE ~~as well as~~or WTD near a losing river.

115 ~~The river water contribution (RWC) to riparian trees has been widely estimated using the data comparison, graphical inference, two- or multi-source linear mixing models and Bayesian mixing models (MixSIR, SIAR, SISUS, MixSIAR) accompanied with stable water isotopes (δ^2H and $\delta^{18}O$) (Dawson and Ehleringer, 1991; Ehleringer and Dawson, 1992; White and Smith, 2020).Several previous studies reported that the WUE of riparian trees varied with the flucuation of water table depth (WTD) in the riparian zone due to changing river flow (Horton~~
120 ~~and Clark, 2001; Liu et al., 2017; Xia et al., 2018).~~

~~The RWC could substantially affect the leaf-level water use efficiency (WUE) and healthy growth of riparian trees. The WUE is a key characteristic of plant water use, which can be defined as the ratio of photosynthetic rate to transpiration rate. Since leaf $\delta^{13}C$ values are positively related to WUE, the leaf $\delta^{13}C$ has been widely used as an indicator of WUE (Farquhar et al., 1989). Thorburn and Walker (1994) found that the riparian Eucalyptus~~
125 ~~camaldulensis beside the ephemeral stream had higher WUE with more frequent access to river water based on the leaf $\delta^{13}C$ measurements. Nevertheless, Sun et al. (2008) observed that the river water availability had little effect on WUE because there was no significant difference in WUE between riparian Pinus massoniana and non-riparian Pinus quercus. Several previous studies reported that the WUE of riparian trees varied with the flucuation of water table depth (WTD) in the riparian zone due to changing river flow (Horton and Clark, 2001; Liu et al.,~~
130 ~~2017; Xia et al., 2018). For example, Horton and Clark (2001) showed that the WUE of riparian Salix gooddingii and Populus fremontii increased with increasing WTD, and riparian Tamarix chinensis had significantly higher WUE under fluctuated deep WTD in dry year than those under constant shallow WTD in wet year. In comparison, the WUE of riparian species decreased significantly along a gradient of increasing WTD (from 0.5 m to 12 m) in the middle reaches of Heihe River Basin, China (Liu et al., 2017). However, little attention has been paid to~~
135 ~~quantifying the relationships between the RWCs to riparian trees and WUE as well as WTD.~~

The overall aim of this study was to clarify the effects of river water on water use of riparian trees along a gradient of WTD. Focusing on a losing river in Beijing, China, the specific objectives of this study were to: (1) ~~to~~ propose an iteration method together with the MixSIAR model and water stable isotopes (δ^2H and $\delta^{18}O$) to quantify the RWC~~s~~; (2) ~~to~~ determine the proportional contributions of river water to riparian trees at different
140 distances away from the riverbank; (3) ~~to~~ identify the relationships between the RWC~~s~~ to riparian trees and WUE

(indicated by leaf $\delta^{13}C$ values) as well as WTD. These results will provide critical insights into plantation management, bank storage conservation and ecosystem and healthy ecosystem enhancement for losing rivers.

2 Materials and methods

2.1 Study area

145   The study area was in the reaches of the Chaobai River, located in Shunyi district, Beijing, China (40°07′30″N, 116°40′37″E) (Fig. 1). The temperate continental sub-humid monsoon climate prevails in this area, with an annual mean temperature and evaporation of 11.5 °C and 1175 mm, respectively. The average total precipitation from April to November between 1961 and 2021 is 532.8 mm, with 84.5% of which falling in rainy season (from June to September) (Fig. 2a). Due to continuous drought and groundwater overexploitation, the Chaobai River dried

150   up during from 1999 to 2007 and the riparian ecosystem seriously degraded seriously. The "ecological water" (including reclaimed water, reservoir water, and diverted water by the South-to-North Water Transfer Project) has been supplied via a systematic water release by dams to restore this dry river since 2007., A total of 51.1 million and 380 million cubic meters of ecological water sources were released to the Chaobai River in 2019 and 2021, respectively. Mand more than 33 km² of the riparian zone has been reeovegetatred with different tree species

155   byuntil 2020. The *Salix S.* babylonica (L.) was one of the most widely planted species alongside the Chaobai River. Three plots at distances of 5 m (D05), 20 m (D20), and 45 m (D45) away from the riverbank were selected for field measurements and sample collection (Fig. 1).

2.2 Field measurements and data collection

The field measurements were conducted during from April to November in 2019 and 2021, with no field

160   observation in 2020 due to the COVID-19. The daily precipitation data from 1961 to 2021 and the daily mean temperature (T), relative air humidity (RH), solar radiation and reference evapotranspiration (ET_0) data during the observation period in the Shunyi district was were collected from the China Meteorological Data Service Centre (http://data.cma.cn/en). Daily mean vapour pressure deficit (VPD) was calculated using the RH and T data (Schoppach et al., 2019).

165   The groundwater levels in each plot were recorded monthly in 2019 and 2021 via the a pressure stage gauge (HOH-S-Y, King Water Co Ltd., Beijing, China) installed in the groundwater monitoring well. The river water

level was recorded using a water level gauge at the same time with the observation of groundwater levels.

~~The average total precipitation during April to November between 1961 and 2021 is 532.8 mm (Fig. 2a). The observation period in 2021 was wet with total precipitation of 802.5 mm, which was 1.8 times of that in dry year of 2019 (445.6 mm) (Fig. 2b and c). The river water level fluctuated at 27.9–28.9 m in 2019 and 27.3–29.7 m in 2021 (Fig. 3). The mean WTD in three plots in 2019 (2.7 ± 0.3 m) was significantly larger than that in 2021 (1.7 ± 0.5 m) ($p < 0.05$). The WTD decreased with increasing distances from the riverbank in both 2019 and 2021.~~

2.3 Sample collection and isotopic analyses

Twelve sampling campaigns on May 5, June 14, July 26, August 15, September 26, November 5 in 2019 and April 24, May 25, June 26, July 15, September 1, November 5 in 2021 were conducted to collect groundwater, ~~precipitation,~~ river water, soil, stem, and leaf samples. Groundwater in each plot was sampled by a sucking pump from the monitoring well, and a plexiglass hydrophore water sample collector with capacity of 1L was used to collect the nearby river water. Precipitation was sampled after each precipitation event via a device consisting of a funnel, a polyethylene bottle, and a ping-pong ball. A total of 135 precipitation samples were collected throughout the whole years of 2019 and 2021.~~in the observation period via a device consisting of a funnel, a polyethylene bottle and a ping-pong ball.~~ All precipitation, groundwater, and river water samples were stored in a refrigerati~~ng~~on box with several ice bags to ~~avoid~~minimize evaporation ~~effects~~ in the field, then they were delivered to the laboratory and kept at 4 °C in the refrigerator until water isotope (δ^2H and δ^{18}O) analysis. The groundwater and river water were also collected with ~~the~~ 100-ml brown glass vials ~~bottles~~ to measure ~~the~~ ^{222}Rn concentration in the ~~study area~~field.

~~Three~~ One riparian *S. babylonica* tree~~s was chosen~~ ~~(with mean diameter of 28.6 ± 4.4 cm at breast height)~~ ~~growing~~ in ~~three~~ each plot~~s were chosen on each sampling campaign~~ for δ^2H and δ^{18}O measurements in xylem~~stem~~ water as well as δ^{13}C analysis in plant leaves. The mean diameter at breast height of three sampled trees was 28.6 ± 4.4 cm. Five mature and~~Several~~ suberized stem samples were taken ~~firstly cut~~ from the same riparian *S. babylonica* tree in each plot using an averruncator with the length of 5 m. We~~,~~ removed the bark and phloem of the sampled stems, and then put the remaining xylem samples into a 12-ml brown glass vial sealed with ~~the~~ parafilm. Meanwhile, the mature leaves without petioles were sampled from the collected stems using pruning shears.~~stored at –10 °C until water isotope analysis.~~ The remaining xylem and mature leaf samples were stored in a refrigerati~~ng~~on box with several ice bags in the field. Then the xylem samples were transported to the laboratory

and kept in a refrigerator at −10 °C before water extraction and isotope analysis. The mature leaves were ~~sampled from the collected stems,~~ oven-dried at 65 °C for 72 h on the day of sampling, then ~~grinned~~ grinded and passed through a 0.15 mm sieve to analyze leaf $\delta^{13}C$ (Wang et al., 2019b; Cao et al., 2020~~; Wang et al., 2019b~~).

Soils at depths of 0−5, 5−10, 10−20, 20−30, 40−60, 60−80, 90−110, 150−170, 190−210, 250−270, and 280−300 cm in one soil profile near~~by~~ the selected *S. babylonica* trees were sampled by a power auger (CHPD78, Christie Engineering Company, Sydney, Australia). One ~~part~~ portion of each soil sample was put into a 12-ml brown glass vial and stored at −10 °C ~~for~~ before water stable isotope analysis, and the other ~~part~~ portion was packed into an aluminum box for gravimetric soil water content (SWC) measurement via the oven-dry~~ing~~ method (Wang et al., 2019b; Li et al., 2021~~; Wang et al., 2019b~~).

The automatic cryogenic vacuum distillation system (LI-2100, LICA, Beijing, China) was used to extract water ~~in~~ from xyl~~st~~em and soil samples, which generally ran for at least 2.5 h. We weigh~~t~~ed all the xylem and soil samples before and after extraction. Subsequently, the efficiency of water extraction was calculated in order to ensure the water extraction efficiency above 99% ~~and no~~to avoid isotopic fractionation during ~~the~~ water extraction process~~and kept the efficiency of water extraction more than 99% to ensure no isotopic fractionation~~. The δ^2H and $\delta^{18}O$ in soil water, river water, groundwater, and precipitation were analyzed through an isotopic ratio infrared spectroscopy system (IRIS) (DLT-100, Los Gatos Research, Mountain View, USA) (Li et al., 2021). The Isotope Ratio Mass Spectrometry system (IRMS) (MAT253, Thermo Fisher Scientific, Bremen, Germany) which could prevent from organic pollution of plants was used to measure δ^2H and $\delta^{18}O$ in ~~stem~~ xylem water as well as leaf $\delta^{13}C$ value. There was the same measurement accuracy ~~of ±1‰ for δ^2H and ± 0.1‰ for $\delta^{18}O$ between~~ for both the IRIS and IRMS systems ($\pm1‰$ for δ^2H and $\pm 0.1‰$ for $\delta^{18}O$). The Vienna Standard Mean Ocean Water (VSMOW) was used to calibrate and normalize the δ^2H and $\delta^{18}O$ measurements in different waters, while the Vienna Pee Dee Belemnite (V-PDB) was used for calibrating leaf $\delta^{13}C$ values.

The ^{222}Rn concentration in the groundwater and river water samples (C_{Water}, Bq/l) was determined based on the air ^{222}Rn concentration values (C_{Air}, Bq/m^3) measured by a ^{222}Rn monitor (Alpha GUARD PQ2000 PRO, Bertin Instruments, Germany) ~~(C_{Air}, Bq/m^3)~~. 100 ml of the water sample was slowly poured into the air-tight glass bottles and then purged with air in a closed gas ~~cycle~~ cycling system. The~~–~~ C_{Air} ~~–~~ in the ^{222}Rn monitor was recorded at a 10-minute interval~~s~~,. The air inside the measurement set-up had ~~con~~maintained a certain ^{222}Rn concentration right before ~~injecting~~ the water sample injection (C_{System}, Bq/m^3). It is generally assumed that the

already existing C_{System} can be ~~ignored~~dignored accordingly when C_{System} is around or lower than 80 Bq/m³. In this study, ~~and~~ more than four intervals were conducted to ensure that the C_{System}~~²²²Rn concentration in the measuring set-up before sampling (background) (C_{System}, Bq/m³)~~ was less than 80 Bq/m³.~~ ~~ The measurement range of C_{Air} was 2–2,000,000 Bq/m³ with a measurement precision of 3%. The ~~above measured C_{Air} value was not yet the ²²²Rn concentration in the measured water sample (C_{water}), because the ²²²Rn driven out had been diluted by the air within the ²²²Rn monitor and a small part ortion of the ²²²Rn remained diluted in the watery phase. The~~C_{water} ~~c~~ ~~C_{Water} c~~an be calculated as:

$$C_{Water} = \frac{C_{Air} \times \left(\frac{V_{System} - V_{Sample}}{V_{Sample}} + k\right) - C_{System}}{1000} \tag{1}$$

where V_{System} is the interior volume of the measuring set-up (ml), which is 1122 ml in this study. V_{Sample} is the volume of water sample (ml). k is the ²²²Rn distribution coefficient of water/air (–), which can be set as 0.26 within the specified temperature range around a mean room temperature of 20 ℃ (Clever, 1985).

In this study, the average residence time (T_{res}, day) of recharged groundwater ~~recharged~~ from ~~the~~ river water ~~to the underlying aquifer and/or riverbank~~ was ~~also~~ identified based on the ²²²Rn isotopes (Hoehn and Von Gunten, 1989), which was described as follows:

$$T_{res} = \frac{1}{\lambda} \times \ln\left(\frac{C_e - C_r}{C_e - C_g}\right) \tag{2}$$

where λ represents the decay coefficient (0.181 day⁻¹) (Hoehn and Von Gunten, 1989). C_e represents the ²²²Rn concentration of background groundwater when the equilibrium between radon production and decay is reached. ~~(7400 Bq/m³ in this study);~~ The measuring ²²²Rn concentration of groundwater in aquifers more than 100 m away from the riverbank remains constant in this study (with an average value of 7400.0 ± 35.4 Bq/m³), suggesting that C_e can be defined as 7400.0 Bq/m³.~~ ~~C_r represents the ²²²Rn concentration of river water (Bq/m³); C_g represents the ²²²Rn concentration of riparian groundwater (Bq/m³).

2.4 Determination of RWC to riparian trees

~~Riparian trees at a certain distance away from the riverbank rarely used river water directly, as their lateral roots could not reach the river (Mensforth et al., 1994; Thorburn and Walker, 1994). Nevertheless, riparian trees could continuously absorb river water that merged into riparian deep water (including groundwater and deep soil water within the capillary fringe) when their deep roots tapped into the water table.~~ In this study, stable water ~~stable~~ isotopes (δ²H and δ¹⁸O) ~~integrated with the MixSIAR model~~ were integrated within the MixSIAR model and an

250   iteration method ~~and an iteration method~~ w~~er~~eas proposed to identify the ~~original (before and during the observation period)~~ contributions of the indirect river water that ~~merged~~ recharged into riparian deep water to riparian *S. babylonica* trees (Fig~~s~~. 4 and 5). Firstly, the direct water source (including soil water in different layers and groundwater) contributions to riparian trees ~~root water uptake patterns~~ were determined via δ^2H and $\delta^{18}O$ in different waters and the MixSIAR model~~,~~. ~~without considering river water as a direct water source for riparian~~

255 ~~trees.~~ Secondly, the proportional contributions of river water to riparian deep water (i.e., riparian groundwater and deep soil water in the 80−170 cm layer) were ~~figured~~ determined ~~out~~ by the MixSIAR model and water isotopes. Finally, the proposed iteration method was used to quantify the proportions of the indirect river water source taken up by ~~RWC to~~ riparian trees (Fig~~s~~. 4 and 5).

    The MixSIAR model is a Bayesian mixing model which can be integrated with ~~the~~ stable isotopes to quantify

260 the proportions of source contributions to a mixture (Stock and Semmens, 2013). The input data of the MixSIAR model include mixture data, source data, and discrimination data. In this study, the mean and standard deviation (SD) of the isotopic values of each water source for riparian trees/riparian deep water were input as source data into the MixSIAR, while the measured isotopic values of xylem water/riparian deep water were input as raw mixture data into the MixSIAR. The discrimination data for both δ^2H and $\delta^{18}O$ were set to zero, because the input

265 δ^2H and $\delta^{18}O$ values in the MixSIAR were non-fractionated or δ^2H-corrected. The Markov Chain Monte Carlo parameter was set to the run length "very long". Both the trace plots and three diagnostic tests (i.e., Gelman–Rubin, Heidelberger–Welch, and Geweke) were used to determine whether the MixSIAR model converged or not (Stock and Semmens, 2013). Then, the mean and SD values of different water source contributions ~~(median values)~~ could be estimated with the MixSIAR model.

270 **2.4.1 Quantifying proportional ~~direct water source~~ contributions of direct water sources to riparian trees**

~~In this study,~~ S~~s~~oil water at different depths ~~, which was mixed proportionally with precipitation, old soil water, or even river water and groundwater,~~ was taken up by riparian *S. babylonica* directly. We measured soil water isotopes at 11 depths in the three plots. In order to reduce errors in the analytical procedure, four soil layers (0−30

275 cm, 30−80 cm, 80−170 cm, and 170−300 cm) were ~~divid~~used to identify the main root water uptake depth of riparian trees according to seasonal variations in the SWC, water isotopes and WTD. The average soil water

isotopes values at depths of 0−5 cm, 5−10 cm, 10−20 cm, and 20−30 cm were calculated for the 0−30 cm soil layer, because the water isotopes went through strong evaporation and the SWC varied significantly seasonally. The soil water isotope values at depths of 40−60 cm and 60−80 cm were averaged for the 30-80 cm soil layer, and those values at 90−110 cm and 150−170 cm depths were averaged for the 80−170 cm soil layer assince the water isotopes and SWC were relatively stable. The average isotopic values of soil water at deep depths (190−210 cm, 250−270 cm, and 280−300 cm) were calculated for the 170−300 cm soil layer, which varied with the fluctuations of the groundwater levels. Groundwater also could be regarded as a relatively direct stable water source for phreatophyte riparian trees (Dawson and Ehleringer, 1991; Busch et al., 1992). In terms of seasonal variations in the SWC, water isotopes and WTD, four soil layers (0−30, 30−80, 80−170, and 170−300 cm) were divided to identify the main root water uptake depth of riparian trees in the three plots (Figs. 2, 3 and S1). As the isotopic composition of soil water in the 170−300 cm layer was similar to that of groundwater, they were considered to be one water source (groundwater). Mensforth et al. (1994) and Thorburn and Walker (1994) characterized the outer projected edge of canopy as the extension range of lateral roots, which could indicate whether riparian trees take up river water directly or not. In this study, the outer projected edge of canopy was less than 5 m for riparian *S. babylonica* tree closest to the river (5 m away from the riverbank). It indicated that the lateral roots of *S. babylonica* trees could not tap into the river. Therefore, the river water was not considered as a direct potential water source for tree water uptake, while groundwater and soil water in the 0−30, 30−80, and 80−170 cm layers, and groundwater were determined used as the direct potential water sources for riparian *S. babylonica*.

In this study, the δ^2H offsets between the xylem water in riparian trees and its corresponding potential source waters were observed, which could be resulted by thefrom δ^2H fractionation in the plant water use processes (Li et al., 2021; Cernusak et al., 2022). These δ^2H offsets could lead to biglarge errors in estimating the water source contributions using the MixSAIR model. IDue-n order to eliminate the δ^2H offsets of stem xylem water from its potential water sources, the measured stem xylem water δ^2H values were corrected via the potential water source line (PWL) proposed by Li et al. (2021). The PW-excess (PW-excess = δ^2H − $a_p\delta^{18}$O − b_p; a_p and b_p were the slope and the intercept of the PWL, respectively) was calculated to indicate the δ^2H deviation from the PWL, which was subsequently subtracted from the measured xylem water δ^2H values. The corrected δ^2H and raw δ^{18}O and corrected δ^2H in stem xylem water were set as the mixture data in the MixSIAR model to quantify the direct water source contributions of direct water sources to riparian *S. babylonica*. The parameter settings of the MixSIAR

305 ~~model have been described in detail by Stock and Semmens (2013) and Li et al. (2021). The contributions of riparian deep soil water in 80−170 cm layer to riparian trees (P_s) and the groundwater contributions to riparian trees (P_g) could be determined in particular to evaluate the RWCs to riparian trees.~~

2.4.2 ~~Identifying~~ Quantifying water source contributions ~~for~~ to deep soil water and groundwater

310 ~~Riparian deep soil water and groundwater could be continuously recharged by river water when the groundwater levels lied below the riverbeds (i.e., losing rivers).~~ The MixSIAR model in conjunction with water isotopes (δ^2H and δ^{18}O) were ~~applied~~ used to quantify the proportional contributions of current (between previous sampling time t-1 and current sampling time t) river water to riparian deep water (i.e., deep soil water in the 80−170 cm layer or groundwater). ~~RWCs to riparian deep water. As shown in Fig. S2a, the~~ The potential water sources of

315 riparian deep soil water in the 80−170 cm layer at ~~current sampling time (t)~~ included the in-situ (i.e., water that is already in the deep soil layer or groundwater) soil water in this layer at ~~previous sampling time (~~t-1~~)~~, soil water in the 0−80 cm layer at t-1, river water between t-1 and t, precipitation between t-1 and t, and groundwater between t-1 and t (Fig. 4a). The potential water sources for riparian groundwater at t were considered as the in-situ groundwater at t-1, soil water in the 0−170 cm layer at t-1, river water between t-1 and t, and precipitation between

320 t-1 and t (Fig. ~~S2b~~4b). The δ^2H and δ^{18}O values in riparian deep water ~~(deep soil water in 80−170 cm layer or groundwater)~~ at t were set as the mixture data in the MixSIAR model, while the water isotopes of their potential water sources were considered as the source data.

~~.~~

~~In this study, the average residence time (T_res) of groundwater recharged from the river to the underlying~~

325 ~~aquifer and/or riverbank was also identified based on the ²²²Rn isotopes, which was described as follows:~~

~~$$T_{res} = \frac{1}{\lambda} \times \ln\left(\frac{C_e - C_r}{C_e - C_g}\right) \qquad (2)$$~~

~~where λ represents the decay coefficient (0.181 d⁻¹); C_e represents the ²²²Rn concentration when the equilibrium between radon production and decay is reached (7400 Bq/m³ in this study); C_r represents the ²²²Rn concentration of river water (Bq/m³); C_g represents the ²²²Rn concentration of groundwater (Bq/m³).~~

330 2.4.3 An iteration method to determine RWC~~s~~ to riparian trees

The proportional contributions of the river water between t-1 and t to riparian trees could be quantified when

riparian deep-water contributions to trees and the RWC~~s~~ to riparian deep water were both ~~figured out~~determined.

It was worth not~~ing~~ed that ~~R~~riparian deep soil water (80-170 cm) and groundwater ~~could~~an be ~~continuously~~ recharged by river water continuously when the groundwater levels lied below the riverbeds (i.e., losing rivers).

335   Therefore, the proportional contribution of the old river water (before t-1) to riparian deep water should not be ignored. The total RWC to riparian deep water should be quantified explicitly during the entire period of the river losing flow to riparian deep zone since 2007. ~~the riparian in-situ deep water (i.e., in situ 80−170 cm soil water and in-situ groundwater) were also merged by old river water before t-1. In this study,~~ We assumed that the contributions of old river water ~~before t-1~~ to riparian in-situ deep water were ~~assumed to be~~identical to~~consistent with~~ those ~~proportions~~contributions of current river water (between t-1 and t) to riparian in-situ deep water ~~(i.e., "s$_r$" and "g$_r$")~~. An iteration method was proposed to quantify the ~~original~~total RWC to riparian *S. babylonica* trees near~~by~~ the losing rivers, which was described as follows:

$$RWC = P_s * S_r + P_g * G_r$$

$$= P_s*(s_r^t \pm s_r^{t-1} ~~s_r + s_r^\theta~~) + P_g*(g_r^t \pm g_r^{t-1} ~~g_r + g_r^\theta~~)$$

345

$$= P_s*(s_r^t \pm s_r^t*s_s^{t-1} \pm s_r^t*(s_s^{t-1})^2 \pm s_g^t*g_r^t \pm s_g*g_r^t*g_g^{t-1} \pm s_g^t*g_r^t*(g_g^{t-1})^2 ~~s_r + s_r*s_s + s_r*s_s^2 + s_g*g_r + s_g*g_r*g_g + s_g*g_r*g_g^2~~)$$
$$+ P_g*(g_r^t \pm g_r^t*g_g^{t-1} \pm g_r^t*(g_g^{t-1})^2 ~~g_r + g_r*g_g + g_r*g_g^2~~)$$

$$~~= P_s*s_r*(1+s_s+s_s^2) + P_s*s_g*g_r*(1+g_g+g_g^2) + P_g*g_r*(1+g_g+g_g^2)~~$$

$$= (P_s*s_r^t + P_g*g_r^t + P_s*s_g^t*g_r^t ~~P_s*s_r + P_g*g_r + P_s*s_g*g_r~~) + (P_s*s_r^t*s_s^{t-1} + P_g*g_r^t*g_g^{t-1} + P_s*s_g^t*s_r^t*g_g^{t-1} ~~P_s*s_r*s_s + P_g*g_r*g_g$$
$$+ P_s*g_r*s_g*g_g~~) + (P_s*s_r^t*(s_s^{t-1})^2 \pm P_g*g_r^t*(g_g^{t-1})^2 \pm P_s*s_g^t*g_r^t*(g_g^{t-1})^2 ~~P_s*s_r*s_s^2 + P_g*g_r*g_g^2 + P_s*s_g*g_r*g_g^2~~)$$

350   (3)

where S$_r$ and G$_r$ represent ~~original~~total~~(before and during the observation period)~~ RWC~~s~~ to riparian deep soil water in the 80−170 cm layer and groundwater, respectively. The P$_s$ and P$_g$ represent the contributions of riparian deep soil water in the 80−170 cm layer and groundwater to riparian trees, respectively. The s$_r^{t-1}$ and g$_r^{t-1}$ ~~and g$_r^\theta$~~ represent the proportional contributions of the old river water (before t-1) to riparian deep soil water in the 80−170 cm layer and groundwater, respectively. The ~~s$_s^{t-1}$, s$_r^t$, and s$_g^t$~~ s$_s$, s$_r$, and s$_g$ represent the proportional contributions of in-situ soil water in the 80−170 cm layer at t-1, river water during t-1 to t, and groundwater during t-1 to t for riparian deep soil water in the 80−170 cm layer at t, respectively. The g$_g^{t-1}$ and g$_r^t$ ~~g$_g$ and g$_r$~~ represent the proportional contributions of in-situ groundwater at t-1 and river water from t-1 to t for riparian groundwater at t, respectively. The expression of "~~P$_s$*s$_r^t$ + P$_g$*g$_r^t$ + P$_s$*s$_g^t$*g$_r^t$~~P$_s$*s$_r$ + P$_g$*g$_r$ + P$_s$*s$_g$*g$_r$" in

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Equation (3) was proposed to determine the current river water (between t-1 and t) contributions to riparian trees. The second iteration ($\underline{P_s*s_r^t*s_s^{t-1} + P_g*g_r^t*g_g^{t-1} + P_s*g_r^t*s_g^t*g_g^{t-1}}$ ~~$P_s*s_r*s_s + P_g*g_r*g_g + P_s*g_r*s_g*g_g$~~) and the third iteration ($\underline{P_s*s_r^t*(s_s^{t-1})^2 + P_g*g_r^t*(g_g^{t-1})^2 + P_s*s_g^t*g_r^t*(g_g^{t-1})^2}$ ~~$P_s*s_r*s_s^2 + P_g*g_r*g_g^2 + P_s*s_g*g_r*g_g^2$~~) were used to quantify the proportional contributions of old river water ~~before t-1~~ that ~~merged~~ recharged~~into~~ riparian in-situ deep water to trees (Fig. 5~~4~~). Only three iterations were applied in this study, because the differences between the RWCs in the third iteration and the next iteration were less than 0.1%. Using this proposed iteration method, we estimated the ~~complete~~ total proportions of old and current river water ~~recharged~~ in the riparian ~~deep water~~trees ~~could be estimated~~.

2.5 ~~Data~~Statistical analysis

One-way analysis of variance (ANONA) incorporating with the Kolmogorov-Smirnov, Levene's and post-hoc Tukey's tests ($p < 0.05$) were used to investigate the statistic differences of different variables. The variables included ~~The statistic differences in~~the WTD~~s~~, SWC, δ^2H and $\delta^{18}O$ in different water ~~bodie~~ source~~s~~ and xylems, ^{222}Rn concentration of river water and groundwater, contributions of different ~~potential~~ water source~~s~~ to riparian deep water or trees ~~contributions~~, and leaf $\delta^{13}C$ values ~~among~~ in the three plots in 2019 and 2021 ~~were analyzed by~~. The linear regression model was fitted to the whole dataset in both ~~two~~ years to get the general relationships ~~(not only available for the observation periods)~~ between the WTD, leaf $\delta^{13}C$ values and the RWC to riparian trees.~~One-way analysis of variance incorporating with Kolmogorov-Smirnov, Levene's and post-hoc Tukey's tests ($p < 0.05$). The relationships between the WTD, leaf $\delta^{13}C$ values and RWCs to riparian trees were determined by the regression analysis method.~~ The statistical analysis was performed in the Excel (v2016) a~~s well as~~nd SPSS (24.0, Inc., Chicago, IL, USA).

3 Results

3.1 Hydro-meteorological conditions

The observation period in 2021 was wet with a total precipitation of 802.5 mm, which was 1.8 times higher than for the drier year 2019 (445.6 mm) (Fig. 2a). The precipitation amount during rainy season accounted for 75.4% and 97.0% in 2019 and 2021, respectively. The annual mean temperature during the observation period in 2019 and 2021 was 22.4 °C and 21.8 °C, respectively. The daily mean VPD and ET_0 increased during the observation

period, reaching a peak in June and May, respectively (Fig. S1). The average daily VPD during the observation period was significantly higher in dry 2019 (1.1 KPa) than in wet 2021 (0.9 KPa) ($p < 0.05$) (Fig. S1a and b). There was a significant difference in the average daily ET_0 from June to September between dry 2019 (5.0 mm/day) and wet 2021 (4.3 mm/day) ($p < 0.05$), but no significant difference was observed during the remaining observation period between the two years ($p > 0.05$) (Fig. S1c and d). No significant difference in the daily mean net radiation during the observation period was found between dry 2019 and wet 2021 ($p > 0.05$) (Fig. S1 c and d).

The river water level fluctuated between 27.9 m and 28.9 m in 2019 and between 27.7 m and 29.3 m in 2021 (Fig. 3). The mean WTD across the three plots was significantly ($p < 0.05$) ~~high~~deeper in 2019 (2.7 ± 0.3 m) than in 2021 (1.7 ± 0.5 m). The WTD increased with increasing distances from the riverbank in both 2019 and 2021 (Fig. 3). The river water continuously recharged the groundwater system ("losing" river) during the observation periods in 2019 and 2021, indicated by a lower groundwater level than the river water level (Fig. 3). Significantly higher SWC was observed in 2021 compared to 2019 ($p < 0.05$) (Fig. S2). ~~Significantly higher SWC was observed in 2021 compared with that~~to in 2019 ($p < 0.05$) (Fig. S1~~2~~). The SWC ~~of~~of each ~~all four~~ soil layers at D45 was significantly lower than ~~that~~ at D05 and D20 in 2021 ($p < 0.05$), while no pronounced difference in the SWC ~~of~~in the 0−30 cm layer was observed among the three plots in 2019 ($p > 0.05$) (Fig. S1~~2~~).

3.~~1~~ 2 Direct water source contributions to ~~Water uptake patterns of~~ riparian trees

~~It was evident in Fig. 5 that the δ²H and δ¹⁸O in precipitation~~ Precipitation was significantly more depleted in δ^2H and $\delta^{18}O$ in 2021 (−52.9‰ ± 30.2‰ for δ^2H and −8.1‰ ± 3.8‰ for $\delta^{18}O$) than ~~those~~ in 2019 (−29.2‰ ± 18.8‰ for δ^2H and −4.1‰ ± 3.0‰ for $\delta^{18}O$) ($p < 0.05$) (Fig. 6). The ~~significantly larger~~ slope of the ~~Local~~ local ~~Meteoric~~ meteoric ~~Water~~ water ~~Line~~ line in 2021 (7.8) was significantly higher ~~with respect~~than ~~to that~~ in 2019 (5.5) ($p < 0.05$), which ~~also~~ suggested that the falling raindrops undergone stronger sub-cloud evaporation in 2019 (Zhao et al., 2019)~~more depleted precipitation isotopes in 2021 ($p < 0.05$)~~. ~~Significantly higher SWC was observed in 2021 compared with that in 2019 ($p < 0.05$) (Fig. S1). The SWC of all four soil layers at D45 was significantly lower than that at D05 and D20 in 2021 ($p < 0.05$), while no pronounced difference in SWC of 0−30 cm layer was observed among three plots in 2019 ($p > 0.05$) (Fig. S1).~~ The δ²H and δ¹⁸O in the ~~superficial~~surface soil water ~~in~~ (above 0−30 cm ~~layer~~depth) ~~in 2021~~ were significantly ~~more depleted~~lower and more variable in 2021 than ~~those~~ in 2019 ($p < 0.05$) (Fig. 5~~6~~). ~~Nevertheless~~In contrast, there were slightly ~~enriched~~ higher water ~~isotopes~~isotopic

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compositions in the 30−170 cm soil layer in 2021 compared ~~with those~~to in 2019. No significant difference in the

isotopic compositions of the soil water below 170 cm depth and groundwater ~~was~~were observed between 2019

and 2021 (*p* > 0.05). The δ²H and δ¹⁸O in soil water in the 80−170 cm layer were significantly lower than

groundwater in 2019 (*p* < 0.05), while no significant difference was observed between soil water isotopes in the

80−170 cm layer and groundwater isotopes in 2021 (*p* > 0.05). ~~As shown in Fig. 5, the isotopes in g~~Groundwater

~~were~~was significantly more depleted in δ²H and δ¹⁸O ~~than~~compared to ~~those in~~river water in both two years (*p*

< 0.05) (Fig. 6). The δ²H and δ¹⁸O in ~~stem~~xylem water during the observation periods in 2019 and 2021 were not

significantly different (*p* > 0.05), but they were gradually ~~depleted~~lower with the increasing distance~~s~~ from the

riverbank~~in riparian zone~~.

The contributions of the ~~superficial~~surface soil water ~~(above 30 cm depth)~~ to transpiration ~~flux~~ of riparian

trees in 2019 (20.1% ± 9.7%) were similar to ~~those in~~2021 (19.0% ± 10.5%).~~As shown in Fig. 6, n~~ No significant

difference in the soil water contributions to riparian *S. babylonica* was also observed in the 30−80 cm layer

between the two years (*p*>0.05)~~As shown in~~(Fig. 6̶7). The *S. babylonica* tree species principally relied on riparian

deep water below the 80 cm depth in both 2019 (55.9%) and 2021 (57.1%). There was no significant difference

in the riparian deep-water contributions to ~~the~~transpiration ~~flux~~ of *S. babylonica* trees between the three distances

from the riverbank (*p* > 0.05) (Fig. 7). Nevertheless, ~~t~~The soil water contributions in the 80−170 cm layer to

riparian trees ~~reduced~~decreased with ~~the~~increasing distance ~~away~~from the riverbank in both years, whereas the

proportions of groundwater ~~contributions~~taken up by riparian trees increased from D05 to D45 in both 2019 (from

27.6% to 32.1%) and 2021 (from 17.0% to 32.2%) (Fig. 6̶7). It was found that the groundwater contributions to

riparian *S. babylonica* trees increased ~~evidently~~significantly (*p* < 0.05) from April to July~~;~~. ~~Nevertheless,   but~~

~~t~~They plummeted significantly (*p* < 0.05) and reached minimum in September in 2021.

3.~~2~~3 Water source contributions to riparian deep soil water and groundwater

~~Significant seasonal and interannual variations of different water source contributions to riparian deep soil water~~

~~in 80−170 cm layer were found during the observation periods in the study area (*p* < 0.05). R~~The primary water

sources of riparian deep soil water in the 80-170 cm layer ~~w~~ere ~~as primarily recharged by~~ the in-situ soil water in

this layer (mean of 33.1%) and groundwater capillary rise (mean of 25.3%) in 2019 (Fig. 7̶8). In comparison, the

in- situ soil water in the 80-170 cm layer (mean of 23.9%), groundwater capillary rise (mean of 24.6%), and river

water (mean of 24.4%) contributed evenly to riparian deep soil water in 2021. The in--situ soil water contribution

to riparian deep soil water ~~in 2019~~ was significantly higher in 2019 than ~~that~~ in 2021 ($p < 0.05$). However, the river water contributed less to riparian deep soil water in 2019 (mean of 15.7%) compared ~~with~~ to 2021 ($p < 0.05$). The RWC to riparian deep soil water was the lowest in August in 2019 (11.3% ± 4.5%) ~~but~~ and in June in 2021 (13.6 ± 3.8%), respectively. The in-situ soil water contributions to riparian deep soil water showed a significant increase with increasing distance ~~away~~ from the riverbank, while the RWC~~s~~ to riparian deep soil water decreased from D05 to D45 in both years ($p < 0.05$) (Fig. ~~7~~8).

~~There were significant differences in interannual and seasonal water source contributions to riparian groundwater in three plots in dry 2019 and wet 2021 ($p < 0.05$).~~ The in-situ groundwater ~~was the main source of riparian groundwater in both years (Fig. 8~~9), contribution ~~but its contribution~~ was significantly higher in 2019 (mean of 56.0% ± 11.2%) than ~~that~~ in 2021 (37.1% ± 16.7%) (p < 0.05) (Fig. 9). The average contribution of the river water to riparian groundwater was ~~recharged by river water with mean of~~ 28.1% ± 12.1% during the observation period. There was a significantly higher RWC to riparian groundwater in 2021 (mean of 35.1% ± 11.9%) than ~~that~~ in 2019 (mean of 21.1% ± 7.2%) ($p < 0.05$). The lowest RWC (13.0% ± 1.2%) showed in August with the lowest ~~water table~~ ~~WTD~~ groundwater level of 3.1 m in 2019, whereas river water contributed the ~~most~~ highest (47.1% ± 13.2%) to riparian groundwater in July with a higher ~~water table~~ groundwater level of 1.8 m in 2021 (Figs. 3 and 9). The proportional contribution of the in-situ groundwater ~~contributions to~~ for riparian groundwater increased with the increasing distance~~s~~ from the riverbank during the observation periods, while the RWC~~s~~ to riparian groundwater decreased significantly from D05 to D45 ($p < 0.05$) (Fig. ~~8~~9). ~~As shown in Table 2, t~~There was a significant increase of ^{222}Rn ~~activities~~ activity in groundwater from D05 (~~494.5~~610.1 ± 107.5 Bq/m^3) to D45 (787.4 ± 153.2 Bq/m^3) ($p < 0.05$) (Table 1). The T$_{res}$ of recharged groundwater from river water ~~that recharged by river to the underlying aquifer and/or riverbank~~ increased from D05 (~~0.09 ± 0.09~~0 days) to D45 (0.15 ± 0.13 days) (Table ~~2~~1). These also indicated that the river recharge~~d to~~ riparian deep strata ~~was~~ rapid~~ly~~ and frequent~~ly~~, particularly more ~~evident~~ significant in the plots closer to the riverbank.

3.~~3~~ 4 Seasonal variations in RWC to riparian trees

~~Significant differences in the seasonal RWCs to riparian S. babylonica were found between dry 2019 and wet 2021 ($p < 0.05$). As shown in Fig. 9, t~~The proportional contributions of river water to riparian *S. babylonica* trees were significantly ~~more~~ higher in 2021 (mean of 23.8% ± 7.8%) than ~~those~~ in 2019 (mean of 16.8% ± 4.7%) ($p < 0.05$). ~~In particular, riparian S. babylonica took up significantly more river water in July (35.2 ± 7.0%) and~~

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470 ~~November (29.0 ± 5.0%) in 2021 than that in July (15.4 ± 1.7%) and November (14.8 ± 1.6%) in 2019 (*p* < 0.001). The least absorption of river water for *S. babylonica* was 17.7 ± 2.7% in 2021 (in September), which was larger than that of 13.2 ± 1.9% in 2019 (in August). The most absorption of river water occurring in July in 2021 was also larger than that of 24.2 ± 3.0% observed in June in 2019.~~ Specifically, the most significantly monthly difference in the RWC to riparian *S. babylonica* trees between dry 2019 and wet 2021 was up to 19.8% (*p* < 0.001).

475 The monthly maximum RWC to *S. babylonica* trees was significantly higher in wet 2021 (35.2% ± 7.0%) compared to dry 2019 (24.2% ± 3.0%) (*p* < 0.05).

The riparian *S. babylonica* took up the most river water in July (35.2 ± 7.0%) in 2021, whereas the highest RWC to riparian trees occurred in June (24.2% ± 1.6%) in 2019. The minimum river water uptake for riparian *S. babylonica* in 2021 was in September (17.7% ± 2.7%), while trees took up the least river water in August 2019

480 (13.2% ± 1.9%). Although the precipitation amount in rainy season was much higher than in drought season (*p* < 0.001), no significant difference in the RWC to riparian *S. babylonica* trees was observed between the rainy and drought seasons in a same year (*p* > 0.05) (Figs. 2 and 9). The difference values of the RWC to riparian trees between the rainy ~~(−4.0%)~~ and dry ~~(−4.4%)~~ seasons were not significantly different (*p* > 0.05) in both 2019 (−4.0%) ~~−~~and 2021 (−4.4%) (Fig. 9). These showed that there were no significant~~ly~~ seasonal variations in the

485 RWC to riparian trees ~~in a same~~within a year (*p* > 0.05).

The water uptake of river water by riparian *S. babylonica* was significantly different ~~among~~ between the three plots in 2019 ~~and 2021~~ (*p* < 0.05), while no difference was observed between the three plots in 2021 (*p* > 0.05) (Fig. 10). Specifically, ~~T~~the RWC to riparian trees decreased significantly by 6.9% from D05 (20.0%) to D45 (13.1%) in 2019 (*p* < 0.05), whereas the~~re corresponding value reduced little by 2.6% (from 25.3% to 22.72%)~~

490 ~~along the distances~~ was no significant difference in 2021 (*p* > 0.05) (Fig. 10).

3.~~4~~ 5 Relationships ~~of~~ between leaf δ¹³C~~,~~ ~~with~~ RWC~~s~~ to riparian trees and WTD

~~The seasonal leaf δ¹³C of riparian *S. babylonica* in three plots varied significantly in 2019 and 2021 (*p* < 0.05).~~ The leaf δ¹³C of riparian *S. babylonica* trees ~~in 2019 (−27.7 ± 1.0 ‰)~~ was ~~remarkably larger~~significantly higher in 2019 (−27.7‰ ± 1.0 ‰) than ~~that~~ in 2021 (−29.7‰ ± 0.7 ‰) (*p* < 0.05) (Table ~~1~~2). There was a significant~~ly~~

495 increase of ~~the~~ leaf δ¹³C from D05 (−28.8‰) to D45 (−27.0‰) in 2019 (*p* < 0.05), while no significant difference in ~~the~~ leaf δ¹³C was observed ~~among~~ between the different distances in 2021 (*p* > 0.05). The ~~smallest~~ lowest leaf δ¹³C value of riparian trees ~~showed~~ occurred on Aug~~ust~~ 15 in 2019 and Jul~~y~~ 14 in 2021, before ~~when~~ intense

rainfall occurred in both years.

There was a significantly negative relationship between the RWC~~s~~ to riparian trees and ~~the~~ WTD (R^2 = 0.57; *p* =~~<~~ 0.000~~0~~1) (Fig. ~~10a~~11a). The leaf δ^{13}C of riparian *S. babylonica* was found to be negatively correlated with the RWC~~s~~ to riparian trees (R^2 = 0.61; *p* =~~<~~ 0.000~~0~~1) but positively related to ~~the~~ WTD (R^2 = 0.37; *p* =~~<~~ 0.000~~0~~1) in linear functions ~~(p < 0.001)~~ (Fig. ~~10b~~11b and c). These indicated that deeper WTD (2.7 ± 0.3 m) resulted in ~~and less~~lower RWCs to riparian *S. babylonica* and ~~resulted in~~ higher leaf-level WUE in the ~~dry~~ drier year ~~of~~ 2019. In comparison, the riparian *S. babylonica* under relatively shallower WTD (1.7 ± 0.5 m) led to ~~greater~~higher RWCs but ~~smaller~~ lower leaf-level WUE in 2021. ~~It seemed that the riparian S. babylonica could consume the least amount of river water for transpiration to achieve the maximum WUE when the WTD was 4.0 m.~~

4 Discussion

4.1 Advantages and limitations of MixSIAR model and the iteration method~~River recharge to riparian deep soil water and groundwater~~

The iteration method in combination with the MixSIAR model and stable water isotopes is particularly useful for separating and quantifying the proportional contributions of ~~the indirect~~ river water ~~source~~ to transpiration ~~flux~~ of riparian trees near~~by~~ a losing river. This integration of methods is ~~superior~~more accurate than ~~to~~ previous studies (Alstad et al., 1999; Zhou et al., 2017; White and Smith, 2020), which only considered ~~the~~ river water as a direct water source of riparian trees without considering their distances from the riverbank and extents of the lateral roots. The primary advantage ~~is that~~ of the combined method is that it explicitly identifies the direct and indirect water sources of riparian trees according to the distance from the riverbank, the extents of lateral roots, and the process of river recharging riparian deep water. Both the trace plots and three diagnostic tests (i.e., Gelman–Rubin, Heidelberger–Welch, and Geweke) were used to ~~Both the trace plots and three diagnostic tests are used to check~~ensure that the MixSAIR model has converged (Stock and Semmens, 2013). Moreover, the MixSIAR model has explicitly considered the uncertainties in the isotopic values and the estimates of source contributions compared to the simpler linear mixing models (Stock and Semmens, 2013; Ma et al., 2016~~; Stock and Semmens, 2013~~). The strength of the newly proposed multi-iteration method is that it can determine the total contributions of the indirect river water source to riparian trees ~~nearby a losing river~~. The multi-iteration will not stop~~s~~ until there is no significant difference between the results of the last two iterations, which reduces the

525 calculation errors of the RWC to riparian trees. ~~This study quantified the RWCs to riparian deep soil water within the capillary fringe and groundwater nearby a losing river. Approximately one third of the riparian groundwater was recharged by river water, while 46.5% of riparian groundwater was not exchanged with river water or other water sources (Fig. 8). A short residence time (no more than 0.28 days) of groundwater recharged by river water in 2021 indicated that there were rapid and frequent interactions between river water and riparian groundwater~~

530 ~~(Table 2). These contradictions might be due to that the seepage of river water exchanged with mobile groundwater quickly but not mixing with water held tightly in the soil pores (Brooks et al., 2010; Evaristo et al., 2015; Allen et al., 2019). It was consistent with previous studies that the lateral seepage of river water or rising water table could briefly saturate riparian soils but not replace/flush immobile waters or isotopically homogenize different water pools (Sprenger et al., 2019).~~

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However, the riparian deep-water sources were identified using the water isotopic data collected between two campaigns (an interval of about one month). The riparian soil water movement was complex,~~icated~~ and the water isotopes might not be uniform between two campaigns along the losing river. Assuming the isotopic uniformity over such a time interval may cause uncertainties in estimating the RWC to riparian deep water. In addition, we

540 assumed that the contributions of old river water (before initial time (t-1)) to riparian in-situ deep water were identical with those contributions of current river water (during the observation period between t-1 and t) to riparian in-situ deep water in this study. This could ~~increase~~nduce some uncertainties on the estimations of the RWC to riparian deep water and the RWC to riparian trees. To minimize this issue, w~~W~~ater samples need to be collected more frequently to quantify the contributions of river water to riparian deep water and trees. ~~There was~~

545 ~~a significant decline of water table (0.8 m) between June and August in 2019, while the water table increased by 1.3 m from June to November in 2021. Changes in water tables significantly affected the interactions between riparian deep water and river water. This study confirmed that the rising water tables stimulated riparian deep water to exchange with river water. The river water contributed significantly more to riparian deep water in wet 2021 with shallower WTD of 1.7 m than that in dry 2019 with deeper WTD of 2.7 m (Figs. 7 and 8). It agreed~~

550 ~~well with the report of Wang et al. (2021) that the amount of surface water recharge to riparian groundwater increased with reducing WTD (ranging from 16.3 m to 2.6 m) in Baiyangdian wetland, China. The impacts of river water on riparian deep water weakened significantly with the increase of distance from the river. It could be~~

4.2 RWC to riparian trees and effects of the distance from the river on RWC

In this study, deep-rooted riparian trees nearby the losing river were identified to use a small proportion of river water (less than 25%) for transpiration (Fig. 10). The small RWC to riparian trees may be caused by three non-exclusive processes: fFirstly, the lateral roots of riparian trees further than 5 m away from the riverbank rarely took up river water directly when their outer projected edges of canopy (less than 5 m in our study) were out of reach of the river (Busch et al., 1992; Thorburn and Walker, 1994). Instead, they took up riparian deep soil water/groundwater recharged by river water, which was likely to restricted the RWC to transpiration flux of riparian trees. Secondly, the ecohydrologyical separation (Brooks et al., 2010; Evaristo et al., 2015; Allen et al., 2019; Sprenger et al., 2019) might result in large isotopic discrepancies between fast-moving water flow and immobile water for plant water uptake. Although the residence time of recharged groundwater from river water was extremely short (no more less than 0.28 days) (Table 1), only one third of riparian groundwater was replaced by the lateral seepage of river water (Fig. 9). This probably indicated that river water recharged mobile groundwater quickly but could not completely replace water held tightly in the soil pores (Brooks et al., 2010; Evaristo et al., 2015; Allen et al., 2019). It was consistent with Sprenger et al. (2019) who found that the lateral seepage of river water or rising groundwater level could briefly saturate riparian soils but not entirely replace/flush immobile waters or isotopically homogenize different water pools. Thirdly, several recent studies showed that the tree species even phreatophytic/deep-rooted trees predominantly extended roots into fine pores to take up immobile soil water (Evaristo et al., 2015; Maxwell and Condon, 2016; Evaristo et al., 2019). As mentioned above,

580 the immobile water could not be completely replaced by infiltrating river water, which eventually resulted in a small contribution of river water to deep-rooted riparian trees. This ecohydrologicaly separation perspective that plant accessible water pools were separated from the fast-moving water can also be supported by the findings that no significant difference in RWCs to riparian trees between rainy and drought seasons was observed in both dry

585 and wet years (Fig. 9). Because riparian *S. babylonica* trees preferred to rely on immobile water in fine soil pores and they would not change the river water uptake patterns when the fast-moving precipitation input increased (Brooks et al., 2010; Sprenger et al., 2019).

In contrast, Alstad et al. (1999) found that riparian *Salix* trees nearby a losing river on the northeast side of the Rocky Mountain National Park, Colorado relied on rivers for approximately 80% of its transpiration flux. It is probably due to the fact that only river water and precipitation were considered as potential water sources for

590 riparian *Salix* in their study. The RWC to riparian *Salix* trees calculated by Alstad et al. (1999) could be overestimated because it was supposed tolikely included all proportions of the indirect river water, in-situ soil water and in-situ groundwater contributions to riparian *Salix* trees. In fact, river water seeped into the saturated/vadose zone across the riparian riverbank and it was taken up by riparian trees indirectly in the form of river-recharged deep soil water/groundwater. In our study, we separated the contributions of indirect river water

595 source (i.e., river-recharged deep soil water in the 80−170 cm layer and groundwater) for riparian trees. The accurate quantification of the indirect RWC to deep-rooted riparian trees could help to determine the effect of riparian plant water use on river runoff along a losing river.

We observed substantially variations in the RWC to riparian trees at interannual (between two years) and spatial (between three distances from the riverbank) scales (Fig. 10). The RWC to riparian *S. babylonica* trees in

600 wet 2021 was 1.4 times higher on average than in dry 2019 (Fig. 10). This is mainly because that the higher water tablegroundwater level in wet year induced higher RWC to riparian deep water, while riparian *S. babylonica* trees presented similar root architecture (i.e., phreatophyte) associated with similar water source proportions between dry and wet years (Figs. 10). Thus, the indirect RWC to riparian phreatophyte trees in wet year was higher than in dry year. Although there was no significant difference in the deep water (below the 80 cm layer) contributions

605 to riparian trees between three plots, we observed substantial effect of the declining water tablegroundwater level with increasing distance from the riverbank on the decreased indirect RWC to riparian trees in dry 2019 (Fig. 10). Therefore, the interannual and spatial variabilities of the RWC to riparian *S. babylonica* trees were generally

attributed to the various RWCs to riparian deep water rather than the water use patterns of riparian trees. Our result is in contrasts to a previous study by Qian et al. (2017) who reported a significant increase of the RWC to *G. biloba* trees in response to the ~~water table~~groundwater level decline. This discrepancy was ascribed to the fact that riparian *G. biloba* had a dimorphic root system and shifted their main water sources from shallow soil layer to deeper soil layer. Nevertheless, the potential root growth rate of riparian phreatophyte *S. babylonica* trees can reach 1-13 mm/day, which allows the riparian *S. babylonica* trees to remain in contact with a rising/declining ~~water table~~groundwater level and ~~keep~~maintain constant water uptake proportions from deep strata below the 80 cm depth (Naumburg et al., 2005)." ~~This study identified that deep-rooted riparian trees nearby a losing river used a smaller proportion of river water (less than 25%), even though the water uptake from deep soils and groundwater recharged by river water were considered (Fig. 9). This finding was similar to the results reported on riparian trees nearby the perennial stream (Busch et al., 1992; Thorburn and Walker, 1994). It underlined that other water sources rather than river water played dominant roles in riparian tree water uptake. Global studies also concluded that 89% of plant transpiration relied on precipitation during the growing season or that stored in the substrates from past season (Miguez-Macho and Fan, 2021).~~

~~As the outer projected edge of canopy were out of reach of river, the lateral roots of riparian trees further than 5 m away from the riverbank could not directly absorb river water (Busch et al., 1992; Thorburn and Walker, 1994). The RWC to riparian trees mainly depended on the river water recharge to deep soil water and groundwater (less than 30%). The river water exchanged rapidly and frequently with riparian mobile deep soil water/groundwater, but rarely with bound water in fine pores (Brooks et al., 2010; Evaristo et al., 2015; Allen et al., 2019; Sprenger et al., 2019). Nevertheless, the riparian trees predominantly extended roots into fine pores to take up bound water (Evaristo et al., 2015; Maxwell and Condon, 2016; Evaristo et al., 2019). The mobile deep soil water/groundwater was alternative water source for riparian trees especially under drought conditions. These discrepancies between fast-moving river water seepage and immobile water for plant water uptake probably led to the small contribution of river water to riparian trees.~~

~~The temporal and spatial variations in the RWCs were significantly affected by various water tables in this study. Shallower water table could increase the river water recharge to riparian deep water which riparian trees mainly relied on. It was evident that riparian deep-rooted *S. babylonica* absorbed significantly more river water in 2021 with 1 m shallower WTD than that in 2019 (Fig. 9). The decreasing RWCs along the gradient of distance~~

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in both dry and wet years also confirmed that the water table decline could make riparian phreatophyte trees less dependent on river water (Zhou et al., 2017). In contrast to the findings in this study, riparian dimorphic *G biloba* shifted from shallow soil layer to deeper soil layer with significantly increasing absorption of river water when the water table declined more than 1 m (Qian et al., 2017). This indicated that riparian dimorphic trees could increase the proportions of river water absorption in response to the water table decline, while the RWCs to riparian phreatophytic/deep-rooted trees decreased with the water table decline.

4.3 Link between RWC/WUE/WTD and itsthe implicationsResponses of WUE to riparian tree uptake of river water and WTD

The water uptake patterns of riparian *S. babylonica* trees generally remainfollowed the characteristics of a phreatophyte. We observed that the leaf WUE of all *S. babylonica* trees across three plots in both dry and wet years were negatively correlated with the indirect RWC to riparian trees and positively related to the WTD, respectively (Figs. 10, 11b, and 11c). These relationships are in consistent with previous studies (Behzad et al., 2022; Cao et al., 2020; Ding et al., 2020; Behzad et al., 2022). Higher leaf WUE associated with lower RWC to riparian trees and lower groundwater levels are likely due to thatbecause the water stress restricts the stomatal conductance and further reduces transpiration rate of riparian trees. Specifically, dry 2019 was characterized as higher water demand (indicated by higher VPD) and lower water availability compared to wet 2021, but the energy resource (indicated by net radiation) for riparian trees was similar between two years (Figs. S1 and S2). We supposargued that the water limitation rather than the energy limitation regulated the leaf-level stomatal conductance of riparian *S. babylonica* trees. The high water demands but low river water availability in dry year probably resulted in stomatal closure of riparian trees to minimize the water loss, which could eventually lead to a decrease of transpiration rate and even photosynthetic rate (Fabiani et al., 2021; Behzad et al., 2022; Fabiani et al., 2021). Aguilos et al. (2018) further found that the water stress would enhance radiation-normalized WUE, because the lack of water availability induced a morestronger reduction in transpiration than photosynthesis. On account ofWith no difference in the average net radiation between dry and wet years, the lower river water availability in the dry year probably resulted in an increase of the leaf WUE. It can be inferred that riparian *S. babylonica* trees took up more river water and probably showed a consumptive river-water-use pattern in the wet year compared to the dry year. This agreed well with previous studies that the woody plants showed lower leaf WUE and consumptive water-use patterns in rainy season, while they showed higher leaf WUE and conservative

water-use patterns with lower soil water availability in dry season (Horton and Clark, 2001; ~~Behzad et al., 2022;~~ Cao et al., 2020; Behzad et al., 2022 ~~Horton and Clark, 2001~~). However, consumptive river water taken up by riparian trees could result in a great loss of river water ~~the consumptive river water use by riparian trees could result in an overconsumption of river water~~, which should be avoided in the riparian zone of a losing river restored by "ecological water" ~~There was a balance and coordination between the soil water availability and river water absorption as well as leaf level WUE of riparian trees, because obvious differences in the RWCs and leaf δ^{13}C values were found in three plots between dry and wet years in this study (Fig. 9 and Table 2). The riparian S. babylonica grew more reliance on river water and the WUE significantly decreased with frequent precipitation and rising groundwater level in wet year ($p < 0.05$) (Figs. 9, 10a and 10b). This might be ascribed to that the high water availability could stimulate riparian trees to maximize their transpiration rate and show a profligate water use strategy with growing water extraction from river. It agreed well with previous studies that woody plants showed profligate water-use patterns and relatively lower WUE in rainy season, whereas they had higher WUE and conservative water use patterns as the soil water availability decreased in dry season (Horton and Clark, 2001; Cao et al., 2020). However, the profligate water use strategy of riparian trees could result in overconsumption of river flow, which indicated that rising water tables would not be recommended in this shallow WTD area. These leaf-level ecophysiological characteristics (i.e., water use efficiency and transpiration rate) of riparian trees responded quickly to the changing water tables.~~

~~It was evident that the WTD played a critical role in river water acquisition and WUE of riparian trees nearby losing rivers (Mensforth et al., 1994; Horton and Clark, 2001; Qian et al., 2017; Zhou et al., 2017). This study indicated that the increasing WTD linearly reduced the reliance of riparian trees on river water sources, mainly due to the diminishing water exchanges between river water and riparian groundwater with the water table decline (Figs. 7, 8 and 10a). In comparison, the declining water table proportionally increased the leaf δ^{13}C of riparian S. babylonica (Fig. 10b), which was consistent with previous studies that an exponential growth function existed between the leaf δ^{13}C of riparian Salix gooddingii and WTD (δ^{13}C = 2.76 − 24.78×exp$^{-0.02WTD}$, 0 < WTD <10 m) (Horton and Clark, 2001). In this study, the 4 m of WTD seemed to be optimal to coordinate the riparian plant water relations, when the riparian S. babylonica consumed the least amount of river water for transpiration and showed highest WUE. This benefited for balancing the relationship between the riparian tree growth and river flow reservation. Nevertheless, there were some controversial views that the WUE of plant species firstly~~

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increased and then decreased with increasing WTD, and the maximum WUE occurred when WTD was 1.44 m (Xia et al., 2018) or 6 m (Antunes et al., 2018). The knee point of WTD was not observed in this study, suggesting that further investigations should be conducted under deeper water tables (> 4 m) to quantify the relationships among water tables, WUE and RWCs to riparian trees.

The WTD played a critical role in the river water uptake of riparian trees near a~~by~~ losing river~~s~~ (Mensforth et al., 1994; Horton and Clark, 2001; Qian et al., 2017; Zhou et al., 2017). We observed that the proportional contributions of the river water source to riparian trees decreased linearly in response to groundwater level decline, leading to a proportional increase in leaf WUE (Fig. 11a and b). It was consistent with Horton and Clark (2001) who found an exponential increase of the leaf WUE of riparian *Salix gooddingii* with increasing WTD. As mentioned above, we emphasized the key role of reduced water availability ~~to account for the control of~~on decreasing transpiration rate ~~on~~thus enhancing leaf WUE in this study. Nevertheless, there were some controversial views that ~~the~~ leaf WUE of plant species increased firstly and then decreased with ~~the~~ increasing WTD (Antunes et al., 2018; Xia et al., 2018). This could be due to the fact that riparian trees could tolerate reduced water availability only within a species-specific threshold, beyond which xylem cavitation and even crown mortality occurs (Naumburg et al., 2005). These indicated that ~~the~~ optimal WTD for plant species was related to the highest leaf WUE, under that condition plant species could consume l~~ower~~ess ~~transpiration~~ water for transpiration to maximize CO_2 assimilation (Antunes et al., 2018; Xia et al., 2018). The break point of WTD was not observed in this study (Fig. 11a and b). Further investigations need to be conducted under deeper ~~water table~~groundwater levels (WTD > 4 m) to optimize the WTD and riparian plant-water relations.

Our results have important implications for untangling the trade-offs between riparian tree water use and river runoff management. ~~Considering various meteorological conditions, water resources and the leaf WUE of riparian trees, t~~The proportion of the RWC to riparian trees has been compared between dry and wet years to investigate the effects of river water availability on the water use characteristics of riparian trees. The riparian *S. babylonica* trees ~~remain~~showed the highest WUE and the lowest river water uptake proportion under the lowest groundwater level condition (with the WTD of 4 m). ~~While t~~The rising ~~water table~~groundwater level would trigger riparian trees to show a consumptive river-water-use pattern, which ~~e~~should not be recommended in the revegetated riparian zone beside an ecological-water-recharged losing river. Therefore, the relationships between the RWC to riparian trees, leaf-level physiological characteristics (e.g., leaf WUE) and hydro-meteorological

720 conditions are critical ~~and helpful~~ to protect the revegetated riparian zones and maintain river runoff sustainability.

~~**4.4 Further scopes**~~

~~Riparian trees could only indirectly absorb river water that merges into riparian deep water when they grow at a certain distance away from the riverbank. Inaccurate estimation of the RWCs to riparian trees nearby the losing rivers would be resulted once river water is identified as a separate source, but it can be resolved by the newly developed iteration method in this study. When river water merging into riparian deep water is utilized by riparian trees, the iteration method could accurately separate and quantify the indirect contributions of river water to riparian trees. The iteration method has been proven to be available for quantifying the RWCs to those riparian trees growing under shallow WTD conditions along the losing river in this research. However, it still requires further improvements under more cases with deeper WTDs. Moreover, the proportions of old river water merging into riparian deep water before the initial time need more investigation by collecting prior water samples. It is evident that quantifying the relationships among the RWCs to riparian tree species, WTD and WUE provides critical insights into coordinating and balancing the river water conservation and riparian plant transpiration in losing rivers.~~

5 Conclusions

735 In ~~T~~this study, we presented a new iteration method together with the MixSIAR model and stable water isotopes (δ^2H and δ^{18}O) ~~and the MixSIAR model~~ to separate and quantify the proportional ~~indirect~~ contributions of ~~the indirect~~ river water ~~source~~ to riparian *S. babylonica* in dry 2019 and wet 2021 along a losing river in Beijing, China. It was found that ~~T~~the infiltrating river water ~~could quickly~~ exchanged with riparian mobile water quickly~~(with a proportion of 24.1%)~~ but not completely mixing with waters held tightly in the fine pores. Riparian

740 trees near~~by~~ a ~~perennial stream~~losing river generally extended roots into fine pores to access the ~~o slow-moving~~immobile water sources~~,~~. The isotopic discrepancies between the fast-moving water flow and the immobile water taken up by the roots led to a small RWC (20.3%) to transpiration ~~flux~~ of riparian trees~~only taking up a small amount of fast-moving river water (20.3%)~~. The water deficit in the dry year probably induced stomatal closure and larger reduction in transpiration compared to the photosynthesis of riparian trees, thus leading to an

745 evident increase of ~~the~~ WUE than in the wet year.~~More river water could be absorbed and lower leaf δ^{13}C was resulted in wet year when the WTD was 1 m shallower than that in dry year. The RWCs to riparian trees decreased~~

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along the distance away from the riverbank. Increasing WTD linearly reduced the reliance of riparian trees on river water sources (*p* < 0.001). It was found thatThe leaf δ¹³CWUE showed a negatively correlation with the RWCs to riparian trees but was positively related to the WTD in linear functions (*p* < 0.001). Riparian *S. babylonica* trees maintained the highest WUE and the lowest river water uptake proportion under deep groundwater condition (with the WTD of 4 m) in this study. These suggested that rising water tablegroundwater level would promote triggered riparian trees to show a profligate water use strategy and increase the river water acquisitions uptake and show a consumptive river-water-use pattern, which wshould not be recommended for the water resources management of a losing river restored by ecological water. . The maximum WTD of 4 m seemed to be optimal for riparian plant-water relations, maintaining highest water use efficiency and minimizing the plant transpiration. This study provides valuable insights into riparian afforestation related to water use and healthy riparian ecosystem healthenhancement.

Data availability: The data that support the findings of this study are available from the corresponding author upon request.

Author contributions: YL: Investigation, Methodology, Formal analysis, Writing - original draft, Writing - review & editing; YM: Methodology, Formal analysis, Conceptualization, Writing - review & editing; XFS: Supervision, Writing - review & editing, Project administration; QZ: Methodology. LXW: Writing - review & editing.

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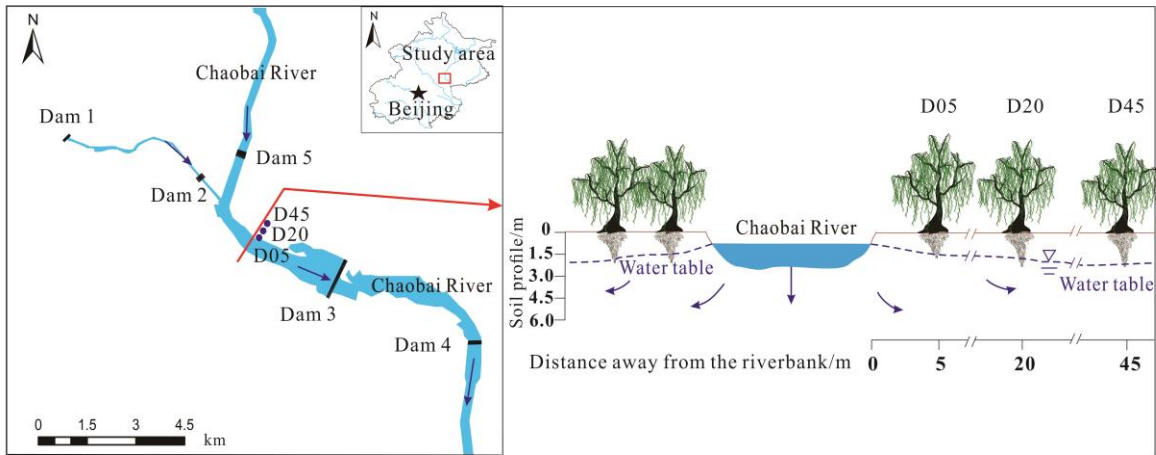920   river. Journal of Desert Research. 37, 124-131, 2017. (in Chinese).

Figure 1: Schematic diagram of the study area and the three sampling plots (D05, D20, and D45). D05, D20, and D45 are the plots at distance of 5 m, 20 m, and 45 m away from the riverbank, respectively.
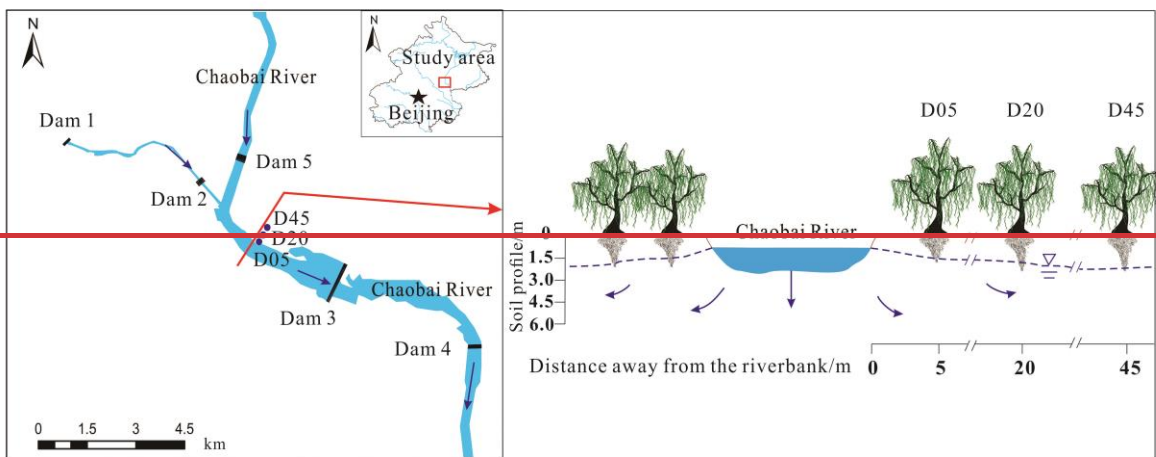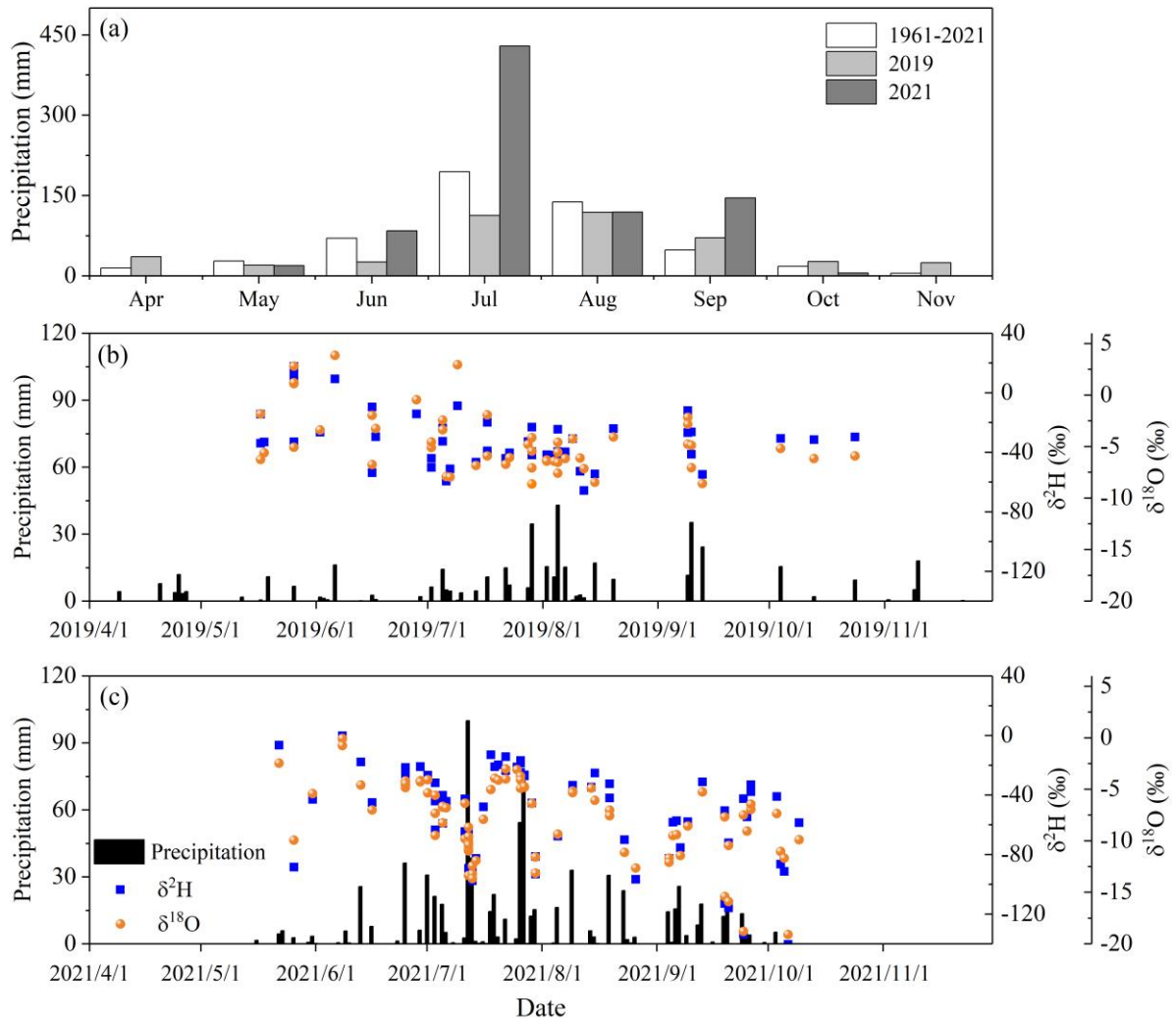

Figure 1：Schematic diagram of the study area and the three sampling plots (D05, D20, and D45). D05, D20, and D45 are the plots at distance of 5 m, 20 m, and 45 m away from the riverbank, respectively.

Figure 2: Changes in monthly average precipitation amount from 1961 to 2021 and monthly total precipitation amount for the observation years 2019 and 2021 (a), daily precipitation amount and precipitation isotopes during 2019 (b) and 2021 (c).

Figure 2: Changes in (a) average monthly precipitation between April and November from 1961 to 2021 and that in the observation years (2019 and 2021), and daily variations in the precipitation and their isotopic compositions in (b) 2019 and (c) 2021.
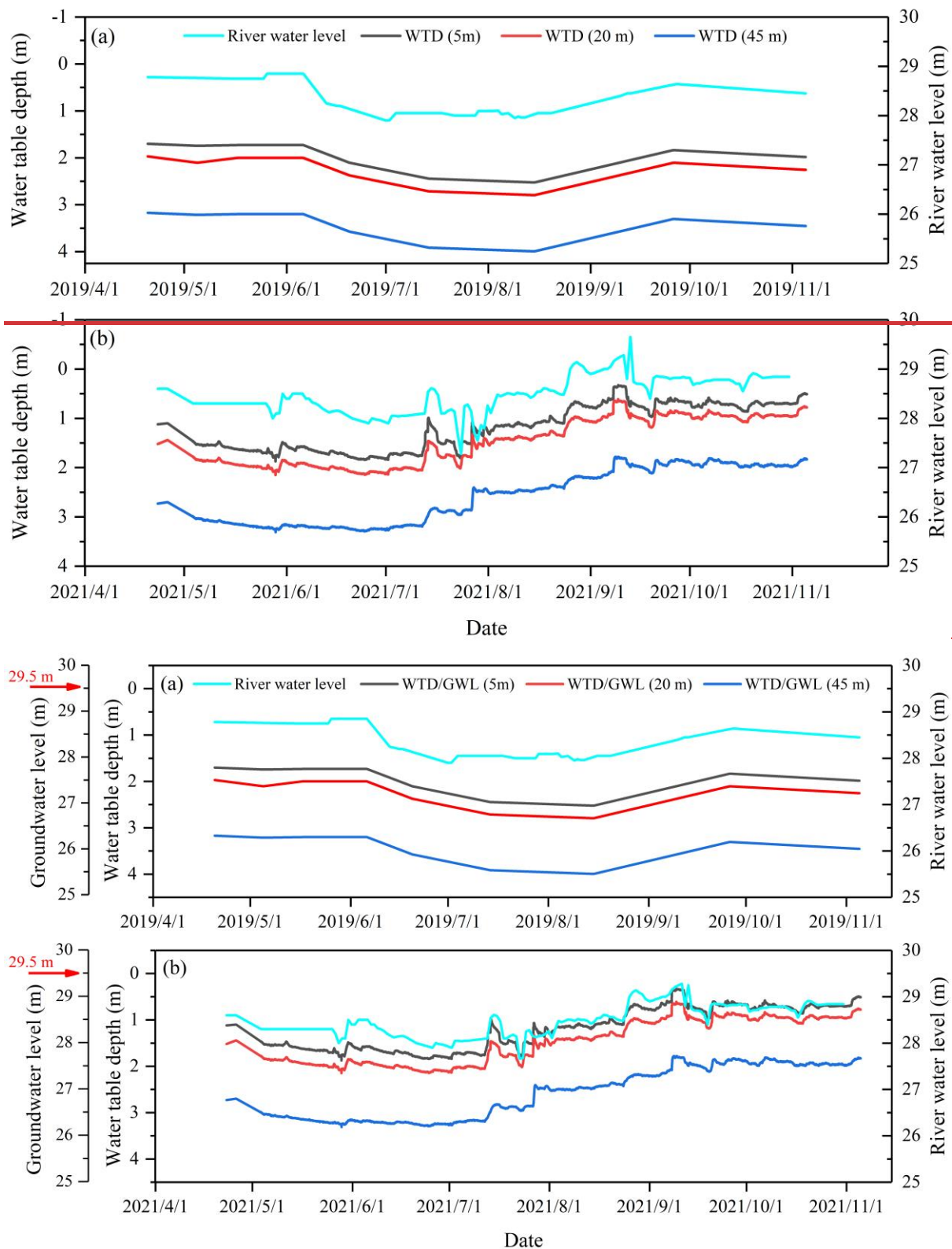
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Figure 3: Seasonal variations of the river water level and ~~the~~ ~~depth to the water table~~water table depth ~~depth~~ (WTD)/ groundwater level (GWL) at distances of 5 m, 20 m, and 45 m away from the riverbank during the observation period in ~~(a)~~ 2019 (a) and ~~(b)~~ 2021 (b). The red arrow

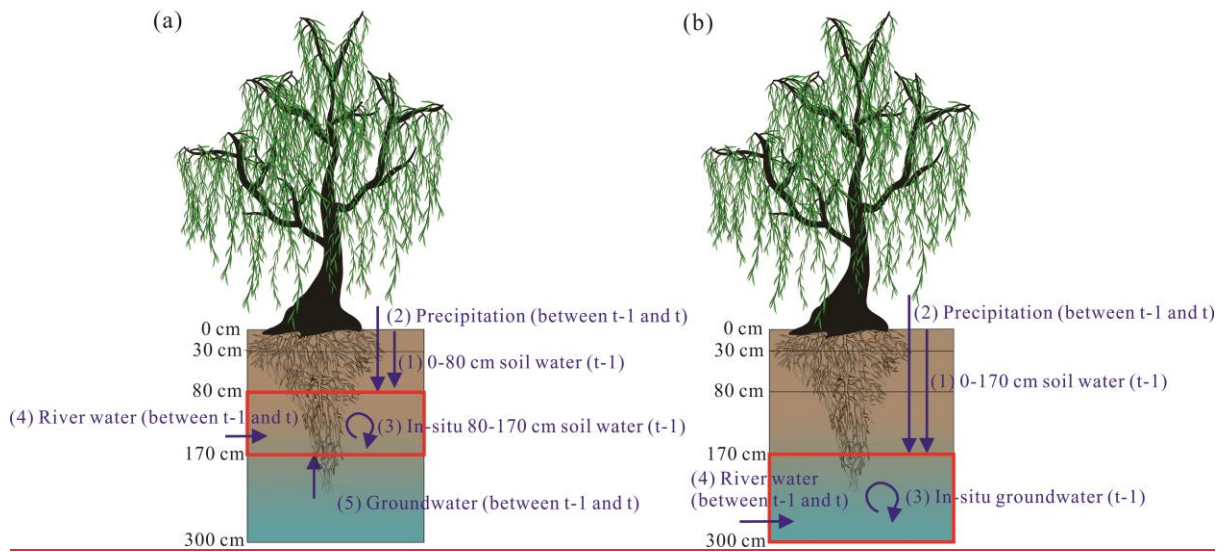**indicates the riparian ground surface level (29.5 m). The riverbed level is 26 m.**

940

Figure 4: Schematic diagram for potential water sources of –riparian deep soil water in the 80−170 cm layer (a) and groundwater (b).

Water source contributions to riparian trees:
- 0−30 cm soil water
- 30−80 cm soil water
- 80-170 cm soil water (P_s)
- Groundwater (P_g)

→ Riparian deep water that fed by river water

Water source contributions to riparian 80-170 cm soil water at t
- In-situ soil water in 80−170 cm layer at t-1 (s_s^{t-1})
- Soil water in 0−80 cm layer at t-1
- River water from t-1 to t (s_r^t)
- Precipitation from t-1 to t
- Groundwater from t-1 to t (s_g^t)

Water source contributions to riparian groundwater at t
- In-situ groundwater at t-1 (g_g^{t-1})
- Soil water in 0−170 cm layer at t-1
- River water from t-1 to t (g_r^t)
- Precipitation from t-1 to t

$$P_s*s_r^t*(1+ s_s^{t-1} +(s_s^{t-1})^2)+ P_s*s_s^{t-1}*g_r^t*(1+ g_g^{t-1} +(g_g^{t-1})^2)$$

$$P_g * g_r^t*(1+ g_g^{t-1} +(g_g^{t-1})^2)$$

1st iteration **2nd iteration** **3rd iteration**

$$P_s*s_r^t + P_g*g_r^t + P_s*s_g^t*g_r^t$$

$$P_s*s_r^t*s_s^{t-1}+ P_g*g_r^t*g_g^{t-1}+ P_s*g_r^t*s_g^t*g_g^{t-1}$$

$$P_s* s_r^t*(s_s^{t-1})^2 + P_g*g_r^t*(g_g^{t-1})^2 + P_s*s_g^t*g_r^t*(g_g^{t-1})^2$$

Proportional contributions of river water to riparian trees nearby losing rivers

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Water uptake patterns of riparian trees:
- 0−30 cm soil water
- 30−80 cm soil water
- 80-170 cm soil water (P_s)
- Groundwater (P_g)

→ Riparian deep water that recharged by river water

Water source contributions for riparian 80-170 cm soil water at t
- In-suit soil water in 80−170 cm layer at t-1 (s_s)
- Soil water in 0−80 cm layer at t-1
- River water from t-1 to t (s_r)
- Precipitation from t-1 to t
- Groundwater from t-1 to t (s_g)

Water source contributions for riparian groundwater at t_2
- In-suit groundwater at t-1 (g_g)
- Soil water in 0−170 cm layer at t-1
- River water from t-1 to t (g_r)
- Precipitation from t-1 to t

$$P_s*s_r*(1+s_s+s_s^2)+ P_s*s_g*g_r*(1+g_g+g_g^2)$$

$$P_g*g_r*(1+g_g+g_g^2)$$

1st iteration **2nd iteration** **3rd iteration**

$$P_s*s_r + P_g*g_r + P_s*s_g*g_r$$

$$P_s*s_r*s_s + P_g*g_r*g_g + P_s*g_r*s_g*g_g$$

$$P_s*s_r*s_s^2 + P_g*g_r*g_g^2 + P_s*s_g*g_r*g_g^2$$

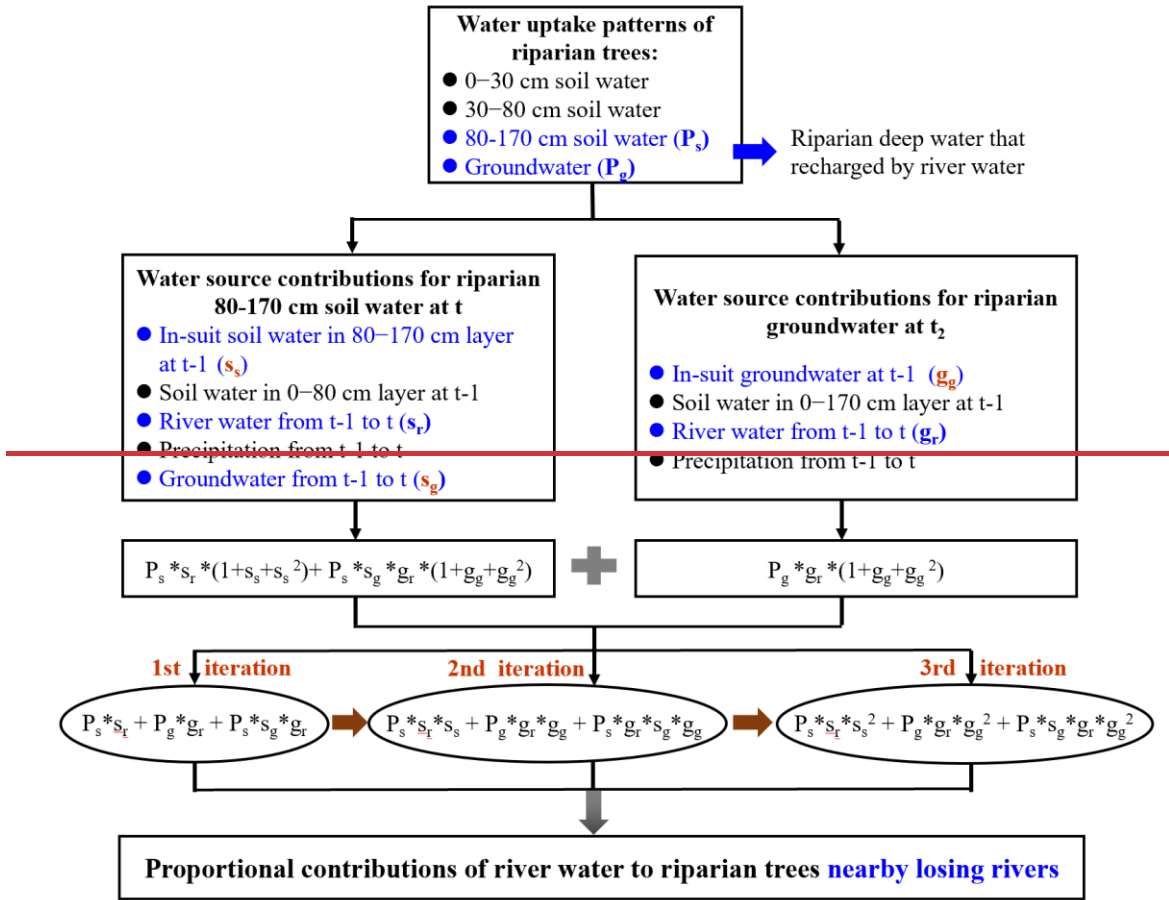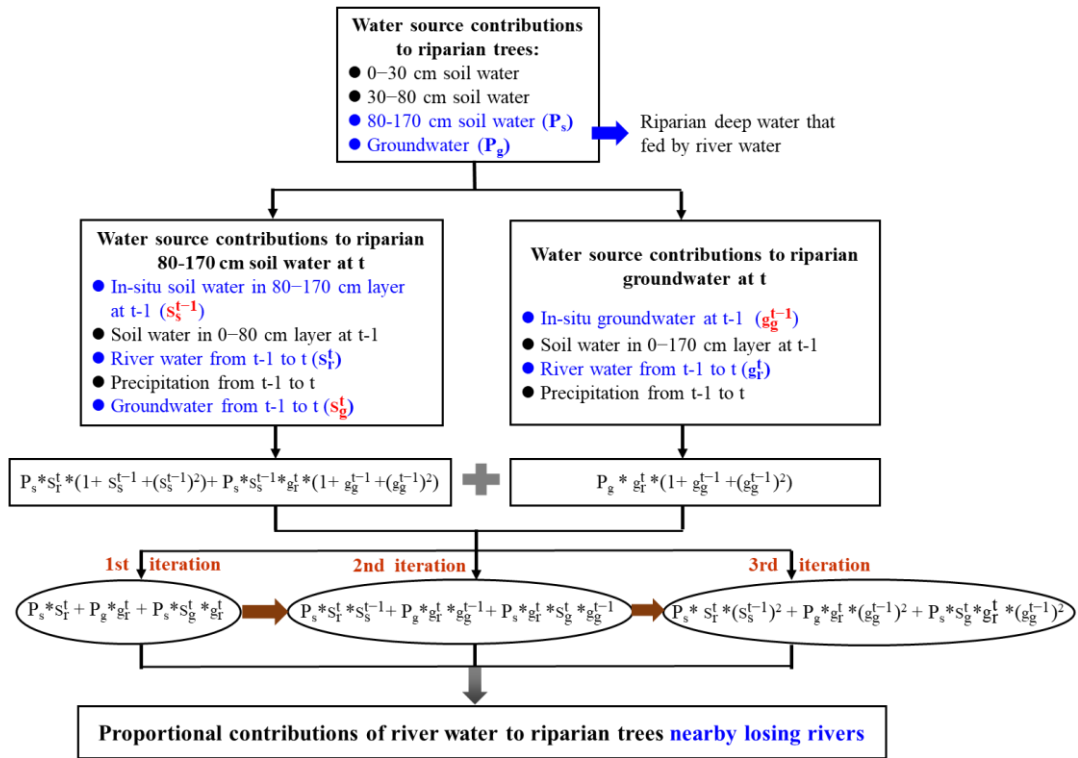**Proportional contributions of river water to riparian trees nearby losing rivers**

Figure 4: Flowchart for quantifying the proportional contributions of river water to riparian trees.

Figure 5: Flowchart for quantifying the proportional contributions of river water to riparian trees. The P_s and P_g represent the contributions of riparian deep soil water in the 80−170 cm layer and groundwater to riparian trees, respectively. The s_r^{t-1} and g_r^{t-1} represent the proportional contributions of the old river water (before t-1) to riparian deep soil water in the 80−170 cm layer and groundwater, respectively. The s_s^{t-1}, s_r^t, and s_g^t represent the proportional contributions of in-situ soil water in the 80−170 cm layer at t-1, river water during t-1 to t, and groundwater during t-1 to t for riparian deep soil water in the 80−170 cm layer at t, respectively. The g_g^{t-1} and g_r^t represent the proportional contributions of in-situ groundwater at t-1 and river water from t-1 to t for riparian groundwater at t, respectively.
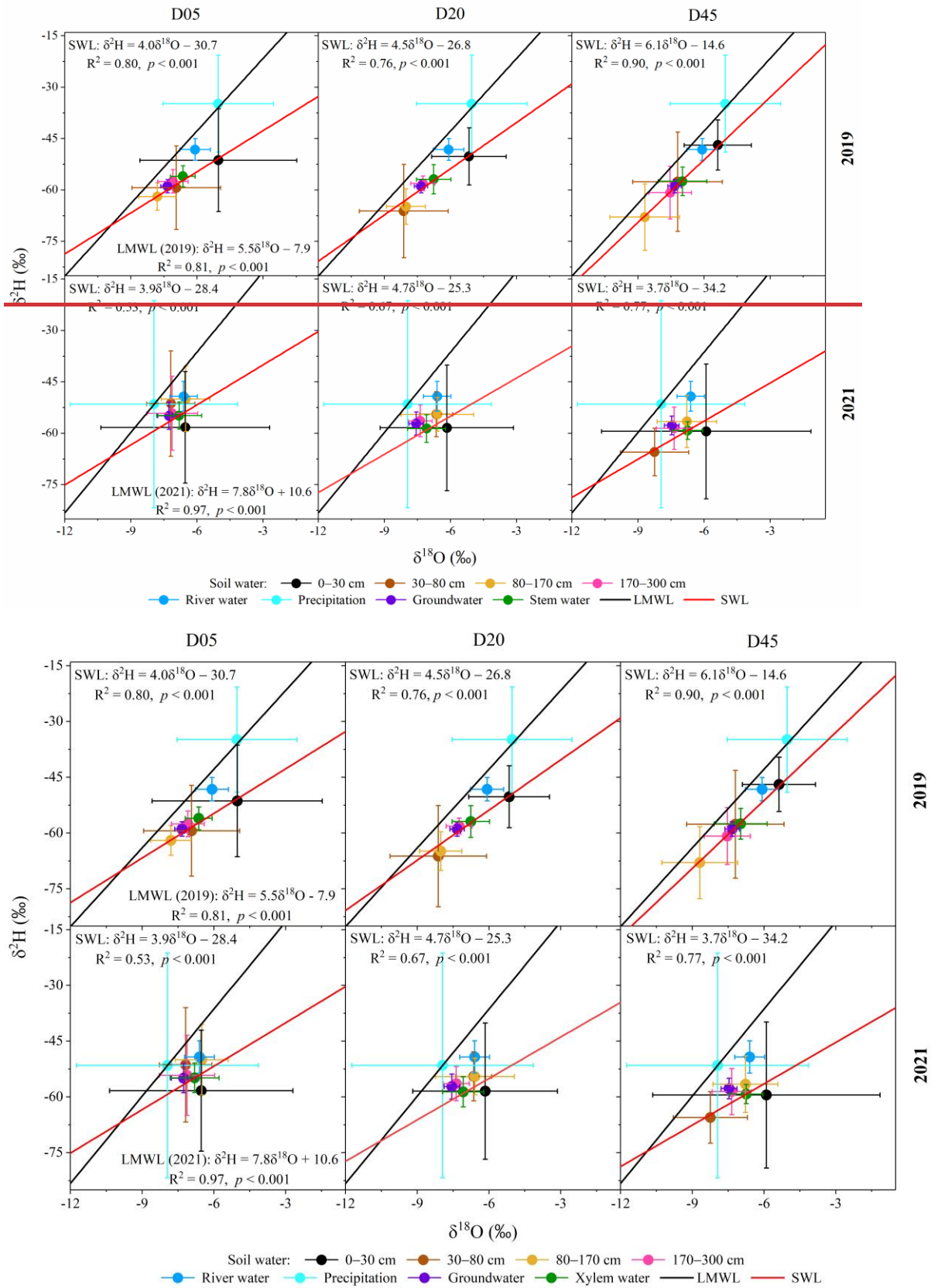
Figure 6: Dual-isotope (δ²H and δ¹⁸O) biplots of different water bodies in the three plots (D05, D20, and D45) ~~during the observation period~~ <u>in</u><u>for the observation years</u> **2019 and 2021. The**

~~Local~~ local ~~Meteoric~~ meteoric ~~Water~~ water ~~Line~~ line (LMWL) was fitted by the precipitation isotop~~ic valu~~es ~~of precipitation in~~for each year. The soil water line (SWL) was fitted by the soil

965   water isotopes in ~~all~~ the four~~soil~~ layers ~~in~~ across ~~the~~ three plots (D05, D20, and D45) ~~in~~ for each year. D05, D20, and D45 are the plots at distance of 5 m, 20 m, and 45 m away from the riverbank, respectively. The error bars indicate standard deviations.


Figure 5: Dual-isotope (δ^2H and δ^{18}O) biplots of different water bodies in three plots (D05, D20, and D45) during the observation period in 2019 and 2021. The Local Meteoric Water Line (LMWL) was fitted by the isotopic values of precipitation in each year. The soil water line (SWL) was fitted by the water isotopes in all soil layers in the three plots (D05, D20, and D45) in each year. D05, D20, and D45 are the plots at distance of 5 m, 20 m, and 45 m away from the riverbank, respectively. The error bars indicate standard deviations.
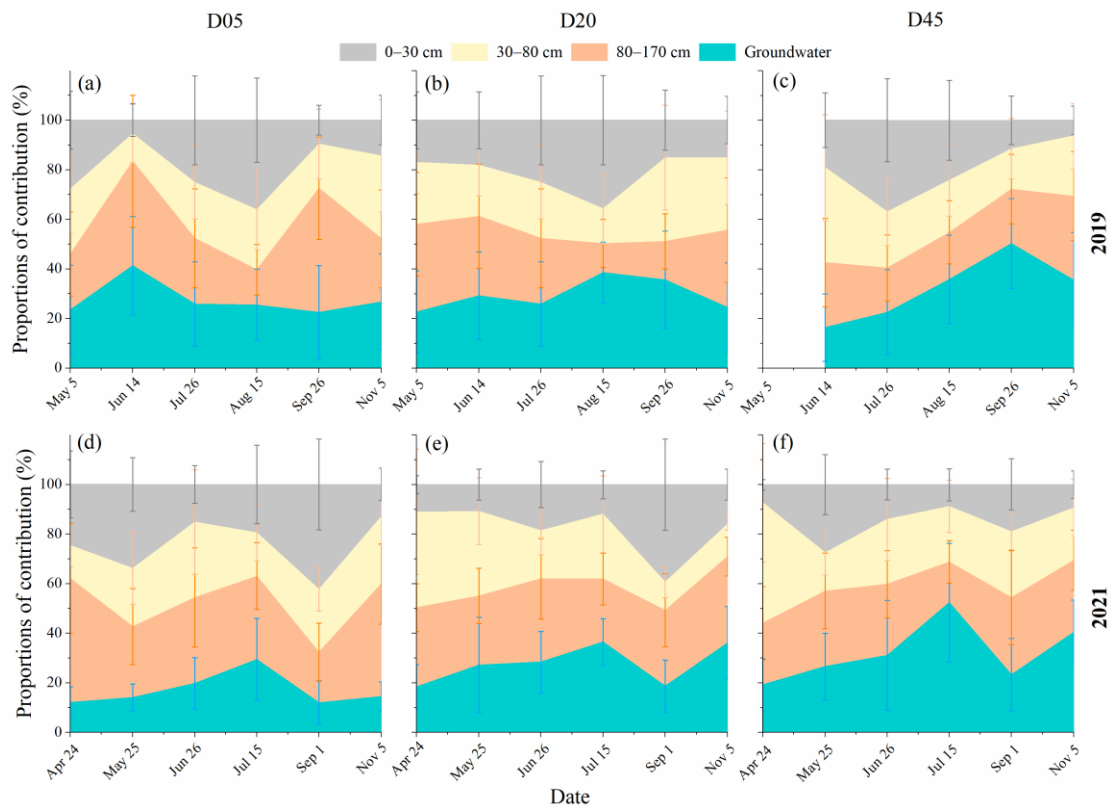
Figure 67: Seasonal ~~water uptake pattern~~variation**s** in the proportional contributions of ~~the direct water sources~~soil water and groundwater to ~~of~~ riparian ~~S. babylonica~~trees in ~~the~~ three plots (D05, D20, and D45) ~~during the observation period in~~for the observation years 2019 (a−c) and 2021 (d−f). D05, D20, and D45 are the plots at distance of 5 m, 20 m, and 45 m away from the riverbank, respectively. The error bars indicate standard deviations.
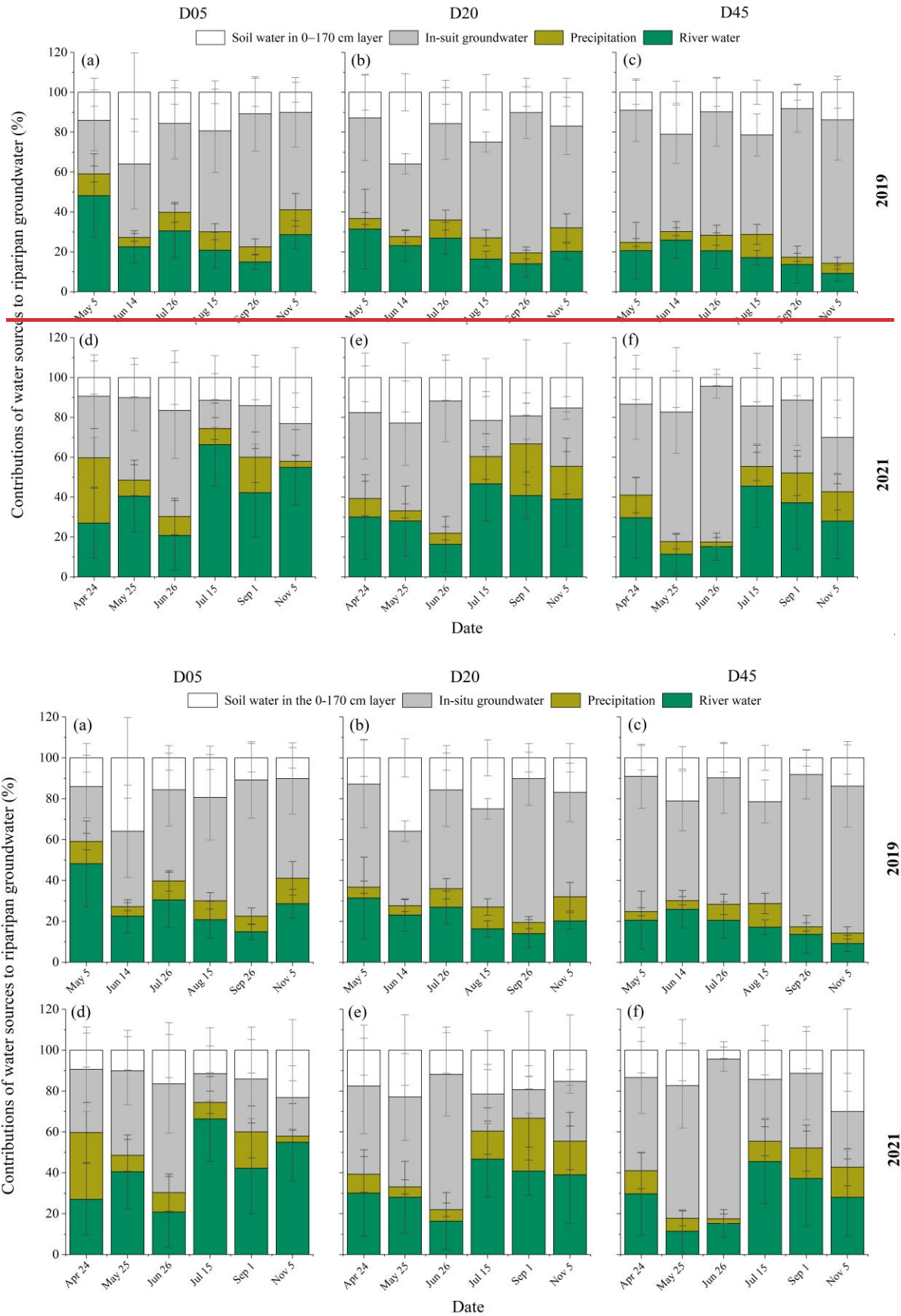
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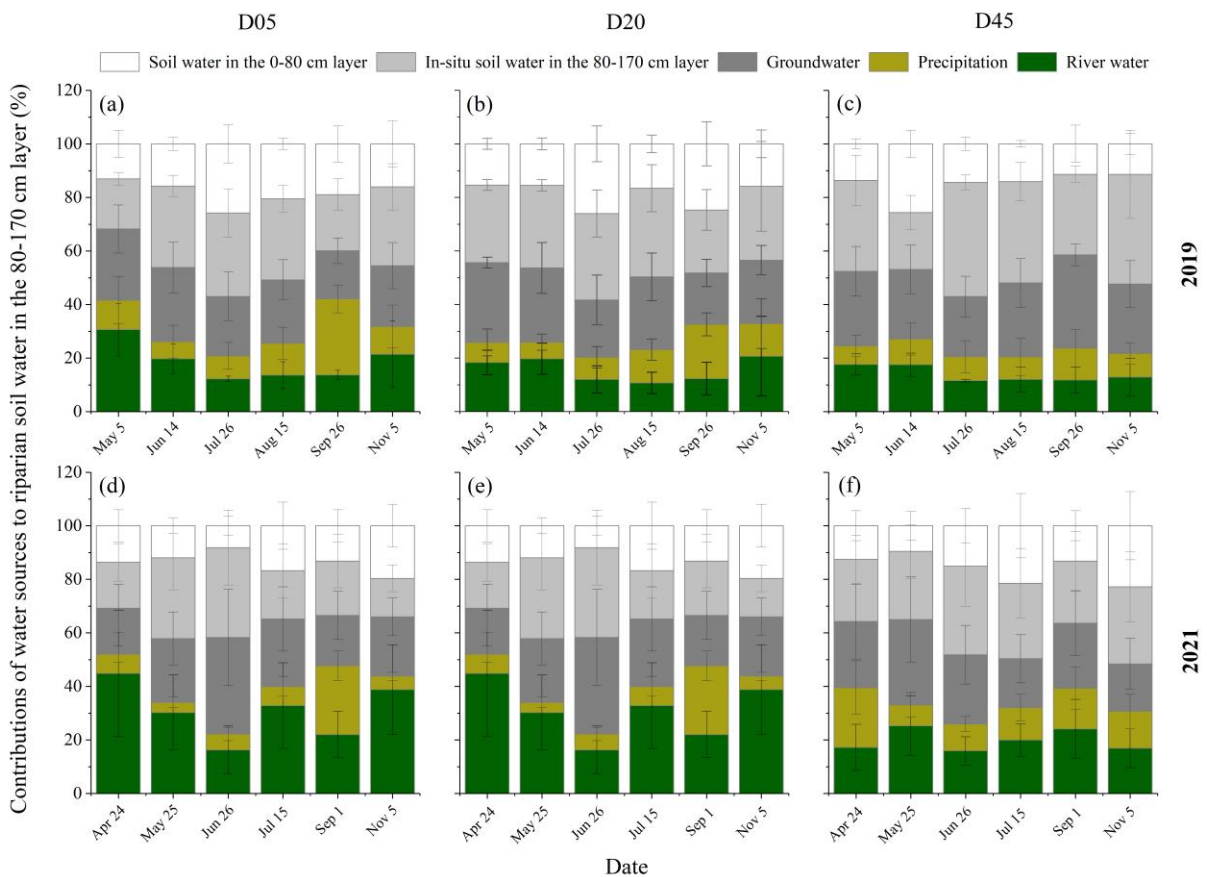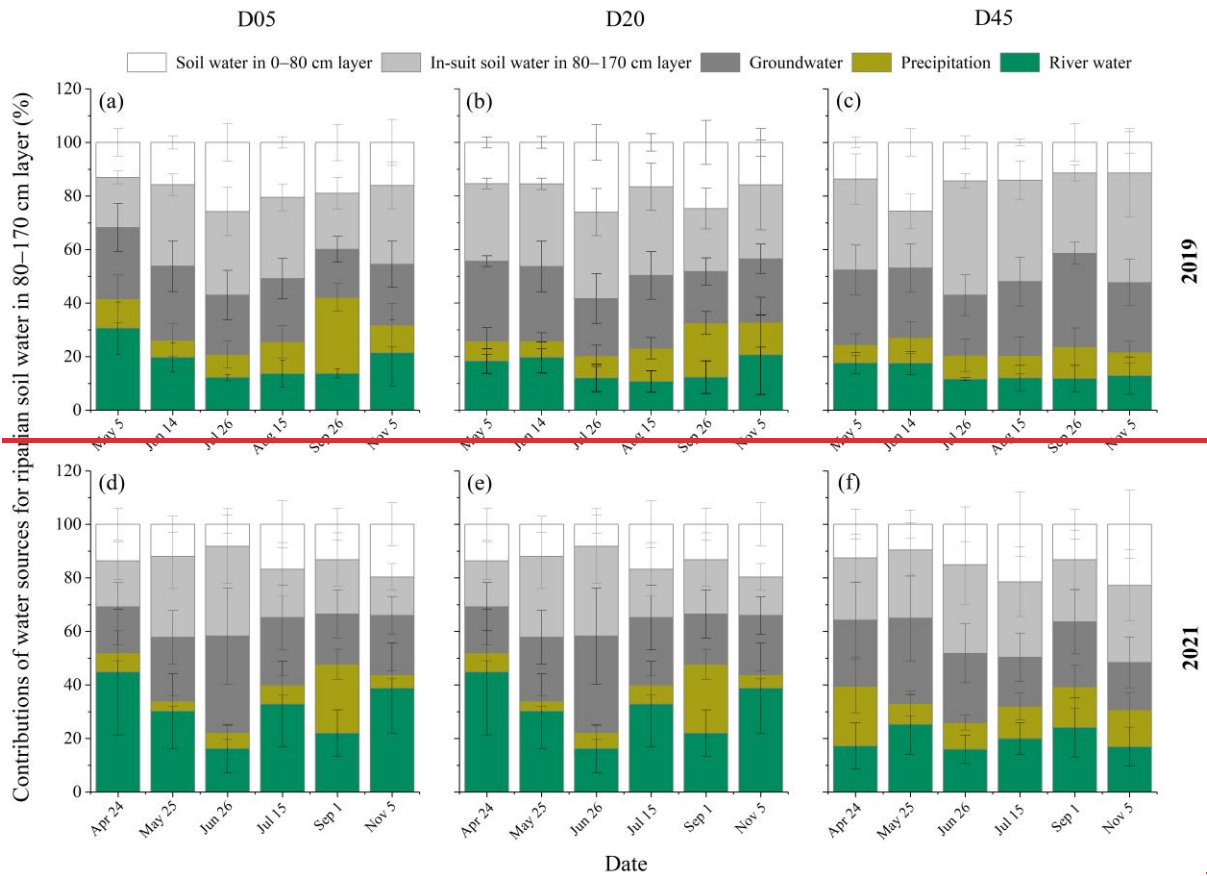
Figure ~~7~~8: Seasonal variations in the different water source contributions to riparian deep soil water

980 **in <u>the</u> 80−170 cm layer in <u>the</u> three plots (D05, D20, and D45) ~~during the observation period in~~<u>for the</u>**

<u>observation years</u> 2019 (a−c) and 2021 (d−f). D05, D20, and D45 are the plots at distance of 5 m, 20 m,

**and 45 m away from the riverbank, respectively. The error bars indicate standard deviations.**

Figure 89: Seasonal variations in the different water source contributions to riparian

groundwater in ~~the~~ three plots (D05, D20, and D45)~~during the observation period in~~ for the observation years 2019 (a−c) and 2021 (d−f). D05, D20, and D45 are the plots at distance of 5 m, 20 m, and 45 m away from the riverbank, respectively. The error bars indicate standard deviations.
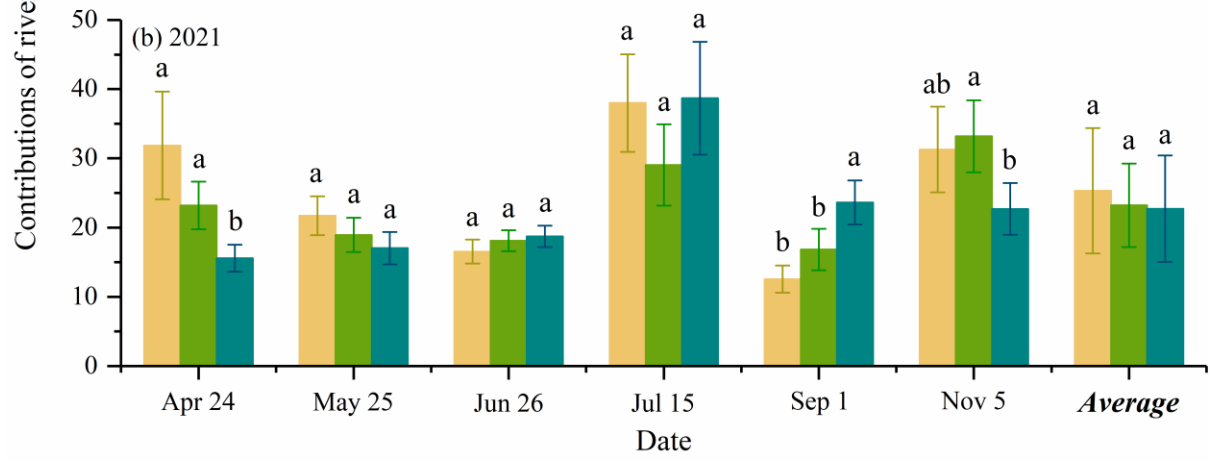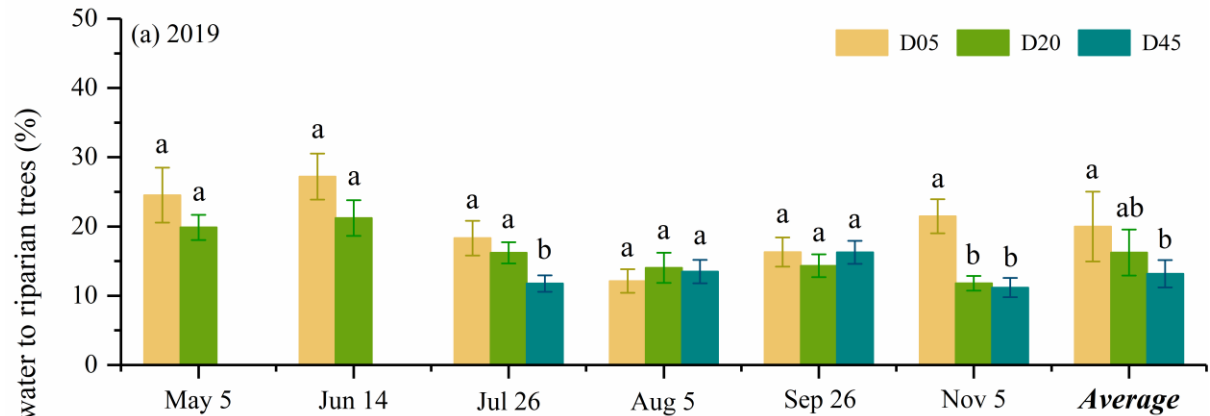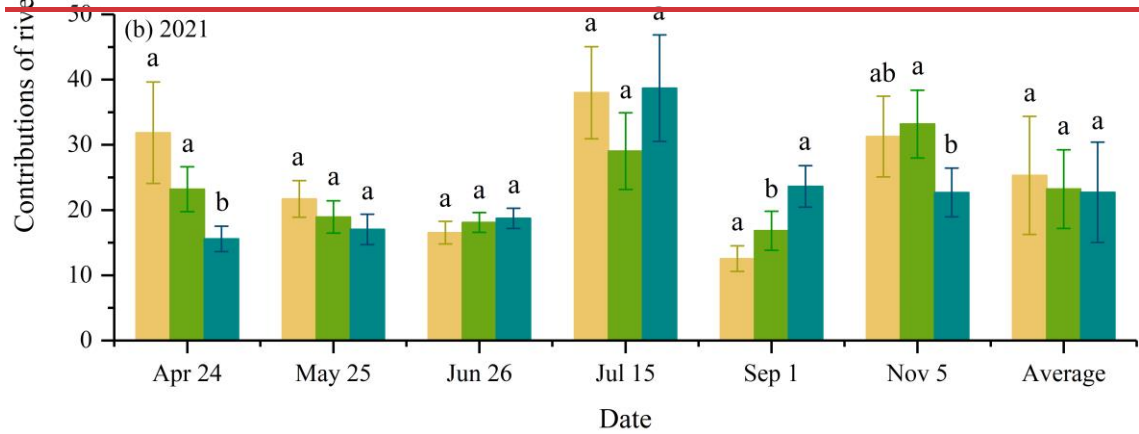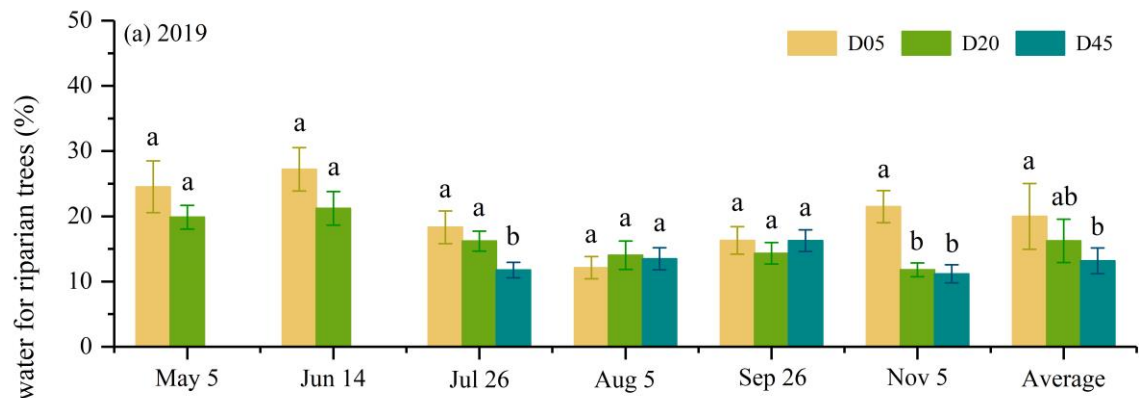
Figure ~~9~~10: ~~Rs~~easonal variations ~~of the r~~iver water contribution~~s (RWC)~~ to riparian ~~S.~~

babylonicatrees in the three plots (D05, D20, and D45) for each sampling campaign during the observation period infor the observation years (a) 2019 (a) and (b) 2021 (b). The dDifferent letters represent show a significant differences in the river water contributionsRWC to riparian S. babylonicatrees in between the three plots for each sampling campaign ($p < 0.05$). D05, D20, and D45 are the plots at distance of 5 m, 20 m, and 45 m away from the riverbank, respectively.
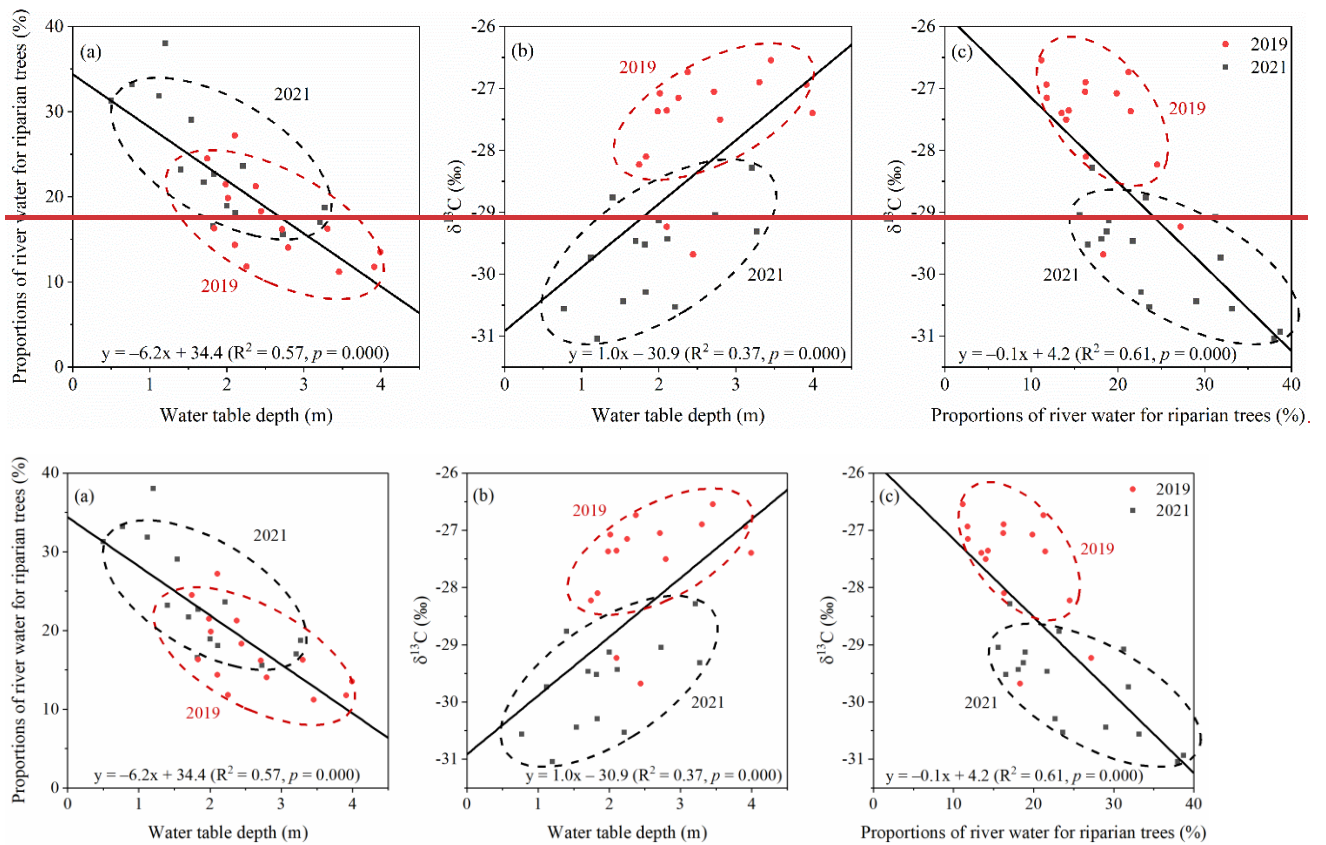
Figure ~~10~~11: Relationships between ~~(a)~~ the ~~river water contributions~~proportions of river water contributions for ~~to~~ riparian ~~S. babylonica~~trees and the water table depth~~water table depth~~ (a), between ~~(b)~~ the leaf δ¹³C values and the water table depth~~water table depth~~ (b), and between~~(c)~~ the leaf δ¹³C values and proportions of river water contributions for ~~river water contributions to~~ riparian ~~S. babylonica~~trees (c).

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Table 1: The ^{222}Rn values in river water, background groundwater and riparian groundwater in three plots (D05, D20, and D45), and the average residence time of recharged groundwater from river water (T_{res}, day) in 2021. The background groundwater represents groundwater in aquifers more than 100 m away from the riverbank.

	River water	Background groundwater	Riparian groundwater		
			D05	D20	D45
^{222}Rn value (Bq/m^3)	610.1 ± 212.3	7400 ± 35.4	610.1 ± 107.5	763.3 ± 118.3	787.4 ± 153.2
T_{res} (days)	0	Null	0	0.13 ± 0.1	0.15 ± 0.13

Notes: D05, D20, and D45 are the plots at distance of 5 m, 20 m, and 45 m away from the riverbank, respectively.

Table 2: Leaf δ¹³C values of riparian *S. babylonica* in the three plots (D05, D20, and D45) during the observation period in 2019 and 2021.

			Leaf δ^{13}C value (‰)					
			2019					
	May 5	Jun 14	Jul 26	Aug 15	Sep 26	Nov 5	Mean	STD
D05	−28.8	−29.2	−29.7	−30.4	−28.1	−27.4	−28.8	1.0
D20	−27.1	−26.7	−27.1	−27.5	−27.4	−27.2	−27.1	0.2
D45	Null	−27.2	−26.9	−27.4	−26.9	−26.5	−27.0	0.3
			2021					
	Apr 24	May 25	Jun 26	Jul 14	Sep 1	Nov 5	Mean	STD
D05	−29.7	−29.5	−29.5	−31.0	−29.5	−29.1	−29.7	0.6
D20	−28.8	−29.1	−29.4	−30.4	−30.1	−30.3	−29.7	0.7
D45	−29.0	−29.0	−29.4	−30.8	−30.1	−30.0	−29.7	0.9

Note: D05, D20, and D45 are the plots at distance of 5 m, 20 m, and 45 m away from the riverbank, respectively. STD represents standard deviations.

Table : The ^{222}Rn values in river water, background groundwater and riparian groundwater in three plots (D05, D20, and D45), and the average residence time of in 2021. The background groundwater represents groundwater in aquifers more than 100 m away from the riverbank.

	River water	Background groundwater	Riparian groundwater		
			D05	D20	D45
^{222}Rn value (Bq/m^3)	610.1 ± 212.3	7400	494.5 ± 107.5	763.3 ± 118.3	787.4 ± 153.2
T_{res} (days)	0	Null	−0.09 ± 0.09	0.13 ± 0.1	0.15 ± 0.13

Notes: D05, D20, and D45 are the plots at distance of 5 m, 20 m, and 45 m away from the riverbank, respectively.