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Water use sources of desert riparian *Populus euphratica* forests

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Abstract Desert riparian forests are the main body of natural oases in the lower reaches of inland rivers; its growth and distribution are closely related to water use sources. However, how does the desert riparian forest obtains a stable water source and which water sources it uses to effectively avoid or overcome water stress to survive? This paper describes an analysis of the water sources, using the stable oxygen isotope technique and the linear mixed model of the isotopic values and of desert riparian *Populus euphratica* forests growing at sites with different groundwater depths and conditions. The results showed that the main water source of *Populus euphratica* changes from water in a single soil layer or groundwater to deep subsoil water and groundwater as the depth of groundwater increases. This appears to be an adaptive selection to arid and water-deficient conditions and is a primary reason for the long-term survival of *P. euphratica* in the desert riparian forest of an extremely arid region. Water contributions from the various soil layers and from groundwater differed and the desert riparian *P. euphratica* forests in different habitats had dissimilar water use strategies.

Keywords Ecohydrology · Stable isotope · Groundwater depth · Water use strategy

Introduction

Arid and semiarid ecosystems cover about 50 % of the earth's land surface (Bailey 1996) and water, the most important limiting factor, decides the structure and function of these ecosystems. The ways in which limited water resources and large interannual and annual variations alter how riparian plants use their water sources for survival is an issue of common concern (Wang et al. 2010). As such, an in-depth study on the water sources used by plants in arid regions is needed (Chu 2007).

Desert riparian forests are the main elements of natural oases in the lower reaches of inland rivers. With increasing disturbances to hydrological processes in the arid region, the problem of degradation of desert riparian forests becomes more prominent (Chen et al. 2004; Han et al. 2011). The growth and distribution of desert riparian forests are closely related to water use (Li et al. 2008), it is generally recognized that as groundwater levels decrease, desert riparian forests cannot effectively use the water source and, therefore, cannot maintain healthy growth (Schachtschneider and February 2010; Hao et al. 2010). But not all of the plant only uses groundwater to maintain its healthy growth. Thorburn and Walker (1994) and Kolb et al. (1997) have shown that, to different degrees, riparian plants during the growing season use precipitation and soil water for survival. What is not known is how the desert riparian

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forest obtains a stable water source and which water sources it uses to effectively avoid or overcome water stress to survive. Especially in the arid region of water shortage, more study is needed to understand how to rationally allocate limited water resources, ensure effective uptake and use of water by plants, and avoid the deterioration of the eco-environment.

Currently, the stable isotopic technique is used to determine the water use strategies of different plants (Ehleringer et al. 1991; Dawson 1998; Rietti-Shati et al. 2000; Drake and Franks 2003; Zhang et al. 2004; Sun et al. 2005; Huang and Pang 2010; Schachtschneider and February 2010; Wang et al. 2010). Due to the presence of isotope fractionation processed, different water sources in nature have different isotopic composition; stable hydrogen and oxygen isotope fractionation generally do not happen in the water uptake processes of root system from soil (White et al. 1985). Therefore, the isotopic composition in plant xylem water can reflect the stable isotopic information of the different water sources used by plants.

Soil water, groundwater, and river water are potential water sources for riparian plants. According to the general speculation, riparian plants mainly use river water; however, that was not the case. Some studies have shown that riparian plants do not absorb river water or use it rarely, relying instead on groundwater. For example, only small riverside trees use river water while mature, large trees rarely use river water in the riparian *Acer* forests in western USA (Dawson and Ehleringer 1991). The study by Busch et al. (1992) of *Populus fremontii* and *Salix gordejevii* in western Arizona found that both use groundwater rather than river water during the growing season. Even the trees washed by river water do not use it as a principal source. Thorburn and Walker (1993) found that the isotope composition in the sap of trees washed by river water in an Australian alluvial plain is similar to that of nearby trees not washed by river water with the ratio of groundwater used by trees increasing from 40 to 63 % with increasing surface soil aridity. Mensforth et al. (1994) also confirmed this in the trees far from the river. Thorburn and Walker (1994) found that riparian plants use mixed water sources that include groundwater, surface runoff, and shallow soil water. Up to 50 % of the water used by *Eucalyptus camaldulensis* growing on riversides is groundwater or soil water; even when water is flowing in the seasonal river, the maximum use of river water by this species reaches only 30 %. In areas where the depth of phreatic water is 4 m or more, *Salix gordejevii* do not absorb shallow soil water, but use only groundwater during the summer rainy period. Hygrophytes growing at the side of seasonal rivers can absorb 26–33 % of shallow soil water during the rainy season and mainly absorb groundwater in other seasons (Snyder and Williams 2000). Zhao et al. (2008) found that trees and shrubs use groundwater more frequently, while herbs mainly use surface water. In the dry season, *Nitraria tangutorum* uses mostly shallow soil water, *Haloxylon ammodendron* uses deep subsoil water, and *Calligonum mongolicum* uses groundwater (Chu 2007). As such, the modes of riparian plant water usage are not entirely consistent and predicting the water absorption and use of riparian forests is difficult. A clear understanding of the water sources used by desert riparian plants will help guide the design of regional-scale models in areas where water is a limiting factor for plant growth. It will also contribute to water balance assessments and efforts to restore and protect the riparian forest vegetation.

This paper describes an analysis of the water sources, using the stable oxygen isotope (δ^{18}O) technique, of desert riparian *Populus euphratica* forests growing at sites with different groundwater depths and conditions. The aim is to provide a scientific basis for the water allocation and management of the desert riparian forests.

Materials and methods

Description of study area

The study area is located in the Ejina Oasis of Inner Mongolia, on the lower reaches of the Heihe River Basin, China (Fig. 1). The climate of this area is one of the most extreme dry areas in China. It is characterized by sparse precipitation, high evaporation, frequent blowing sand events, and long periods of sunshine. The multiyear mean precipitation is 42 mm, the multiyear mean evaporation of 3,755 mm. Overall, the evaporation rate is 89 times greater than the precipitation. Most precipitation (about 70 to 80 % of the annual total) falls from June to September. Vegetation is dominated by *P. euphratica* and associated *Tamarix chinensis* shrubs distributed on both banks of the desert river. The two plant species are tolerant to drought and blowing sand and play important roles in maintaining the ecological balance in the region, enabling agricultural and livestock production in the oasis.

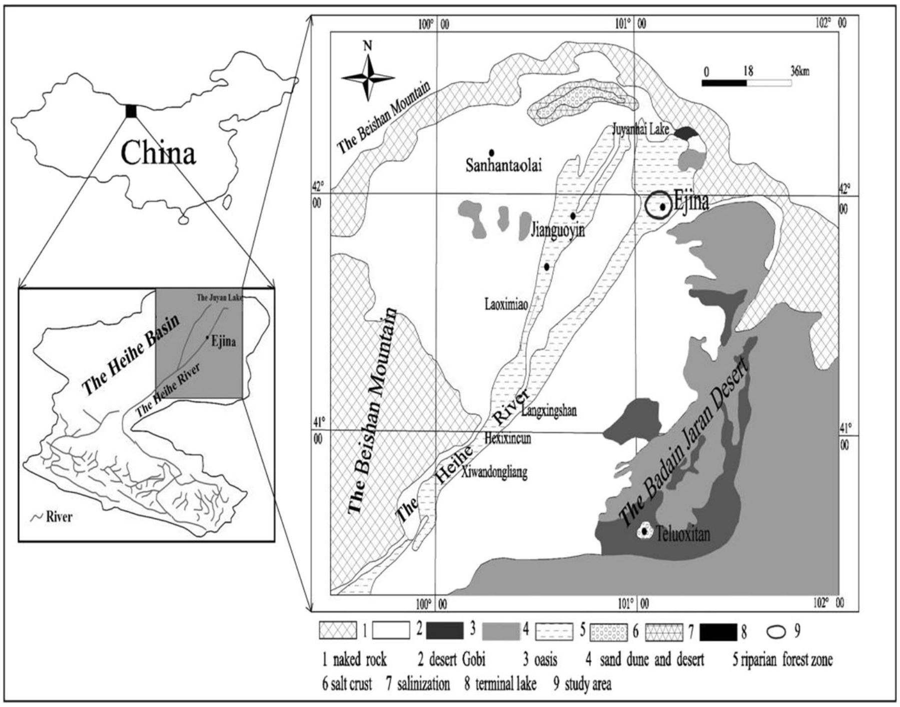

Fig. 1 Location map showing the Heihe Basin and the Ejina area

Experimental design

The depth to groundwater in the Ejina Oasis ranges from 1.5 to 4 m. This study examined *P. euphratica* growing in areas with different groundwater depths: 1.80, 2.00, 3.25, and 3.80 m. For each groundwater depth, xylem water samples of *P. euphratica* and soil water samples from different layers were analyzed to determine the variations in xylem water δ^{18}O relative to each potential water source. For groundwater depths of 1.80 and 2.00 m, the soil profiles were divided into 20-cm intervals to calculate the water contribution. For groundwater depths of 3.25 and 3.80 m, contributions of soil water and groundwater were calculated at 40-cm intervals.

In order to clarify *P. euphratica* water use sources in different site conditions, we selected three typical site types which were the groundwater depth around the 2.0 m for the sample plots: *Populus euphratica* communities on the riverside lowlands, sand dune, and Gobi. *Populus euphratica* communities on the riverside lowlands were dominated by mature trees with saplings at the edge of the forest. The primary-associated species on the riverside lowlands were *T. chinensis* and *Sophora sphaerocarpa*. Sand dune plots included *P. euphratica* communities on sand dunes and degraded *P. euphratica* forests on highly undulated and severely desertified sand dunes. The *P. euphratica* in these sample plots grew poorly. The associated species in the sand dune plots included *T. chinensis*, *Nitraria sphaerocarpa*, *Zygophyllum xanthoxylon*, and *Alhagi sparsifolia*. For the Gobi plots, we selected *P. euphratica* communities that were far from the river channel and that had no river water irrigation throughout the year. Associated species in the Gobi plots included *T. chinensis*, *Artemisia desertorum*, *Alhagi sparsifolia*, *C. mongolicum*, *Reaumuria soogorica,* and *Ephedra*. From each plot, samples of *P. euphratica* xylem water, soil water, and groundwater were collected for δ^{18}O determination. The δ^{18}O values helped identify the water sources used by *P. euphratica* under different site conditions.

Sample collection

Xylem, soil, and groundwater samples were collected in the selected sample plots. At least three *P. euphratica* xylem samples were collected from each plot to help eliminate interference from possible isotopic enrichment caused by stomatal evapotranspiration. Shoots ranging from 0.3 to 0.5 cm in diameter and 3 m to 5 cm in length were collected from stems more than 2 years old; the outer bark and phloem of the shoots was removed to obtain the xylem samples. For soil water sampling, a soil profile was excavated in each sample plot and soil samples were taken, beginning in the top 20 cm to the depth of the groundwater table, at 20-cm intervals. Two samples were taken from each soil layer: one sample was used for isotope determination; another sample was used for soil moisture determination. All samples that were used for isotope determination were placed in small glass bottles sealed with parafilm, refrigerated, and transported to the laboratory.

Analysis of samples

Prior to the determination of isotopes, plant and soil samples were chilled to −20 °C and water samples were refrigerated at 4 °C. Water was extracted from xylem and soil using a cryogenic vacuum distillation approach. The process of cryogenic vacuum distillation extracts all the water from a sample and freezes it into a collection tube. During this process, all the compounds that are volatile under the sample-tube conditions (vacuum and high temperature) are co-distilled with the water. A Finnigan DELTAplus XP isotope ratio mass spectrometer (Thermo Fisher Scientific Inc., Waltham, MA), located in the Basin Key Laboratory of the Cold and Arid Regions Environmental and Engineering Research Institute, was used for isotopic determination.

The ratio of stable isotopes can be expressed as:

$$\delta^{18}\mathrm{O} = (R_{\mathrm{sam}}/R_{\mathrm{std}} - 1) \times 1000 \qquad (1)$$

where δ^{18}O (‰) refers to the isotopic difference of the sample relative to the Vienna Standard Mean Ocean Water (VSMOW), R_{sam} is the ratio of heavy and light element richness in the sample ($^{18}\mathrm{O}_{\mathrm{sam}}/^{16}\mathrm{O}_{\mathrm{sam}}$), and R_{std} is the ratio of heavy and light element richness of the national universal reference material ($^{18}\mathrm{O}_{\mathrm{std}}/^{16}\mathrm{O}_{\mathrm{std}}$). To calculate the relative use state of different water sources, the linear mixed model of the isotopic values of the potential water use sources by desert riparian forests was used, calculation model is as follows

$$\delta^{18}O_p = \sum_{i=1}^{n} f_i \times \delta^{18}O_i \qquad I = \sum_{i=1}^{n} f_i \qquad (2)$$

Where $\delta^{18}\mathrm{O}_{\mathrm{p}}$ represents the δ^{18}O value in water of the plant body, $\delta^{18}\mathrm{O}_{\mathrm{i}}$ represents the δ^{18}O value of different water sources, and I represents the ratio of plants to water source, i. As the potential water sources of plants are less than 3, a unique solution for f_{i} can be determined. Phillips and Gregg (2003) developed the IsoSource software to define the upper and lower limits of the contribution of various potential water sources that exceeds 3. In this study, the contribution ratio of different water sources to the desert riparian forest was determined using IsoSource software.

Results

Variations of δ^{18}O of *Populus euphratica* at different groundwater depths

Fig. 2 is the variations of δ^{18}O in the soil water, groundwater, and *P. euphratica* xylem water at different groundwater depths. In areas with a groundwater depth of 1.80 m, the soil water δ^{18}O from 0–80-cm depth increases with increasing depth, from −7.07±0.04 to −5.49±0.05 ‰. Below 80 cm, the δ^{18}O values are similar, ranging from −5.63±0.20 to −5.35±0.22 ‰, but are significantly positive than the groundwater δ^{18}O of −6.47±0.17 ‰ (Fig. 2a). Where the groundwater depth is 2.0 m, the soil water δ^{18}O gradually increases with increasing depth, from −9.56±0.27 to −7.72±0.11 ‰. Soil water δ^{18}O at 180 cm (−7.67±0.12 ‰) was similar to the groundwater δ^{18}O (Fig. 2b). Where groundwater depth was 3.25 m, the soil water δ^{18}O fluctuated with depth: at 20–40-cm δ^{18}O increased from −8.36±0.27to −7.72±0.11 ‰ and from 40–160-cm δ^{18}O decreased with depth, ranging from −6.91±0.24 to −7.75±0.14 ‰. The groundwater δ^{18}O was −7.23±0.30 ‰ (Fig. 2c). In locations with groundwater depth of 3.80 m, the general trend of variation of soil water δ^{18}O was similar to that of the 3.25 m groundwater depth, δ^{18}O varied between −9.05±0.15 and −5.29±0.20 ‰. A significant variation of the soil water δ^{18}O occurred at a depth of 240 cm. The groundwater δ^{18}O was 6.67±0.03 ‰ (Fig. 2d). The xylem water δ^{18}O levels were −5.20±0.07, −7.62±0.06, −7.26±0.10, and −6.78±0.07 ‰ at groundwater depths of 1.80, 2.00, 3.25, and 3.8 m, respectively (Fig. 2).

Contribution of potential water sources to the water use of *Populus euphratica*

At a groundwater depth of 1.80 m, the *P. euphratica* xylem water δ^{18}O was most similar to the soil water δ^{18}O of the 120-cm soil layer (mean contribution of

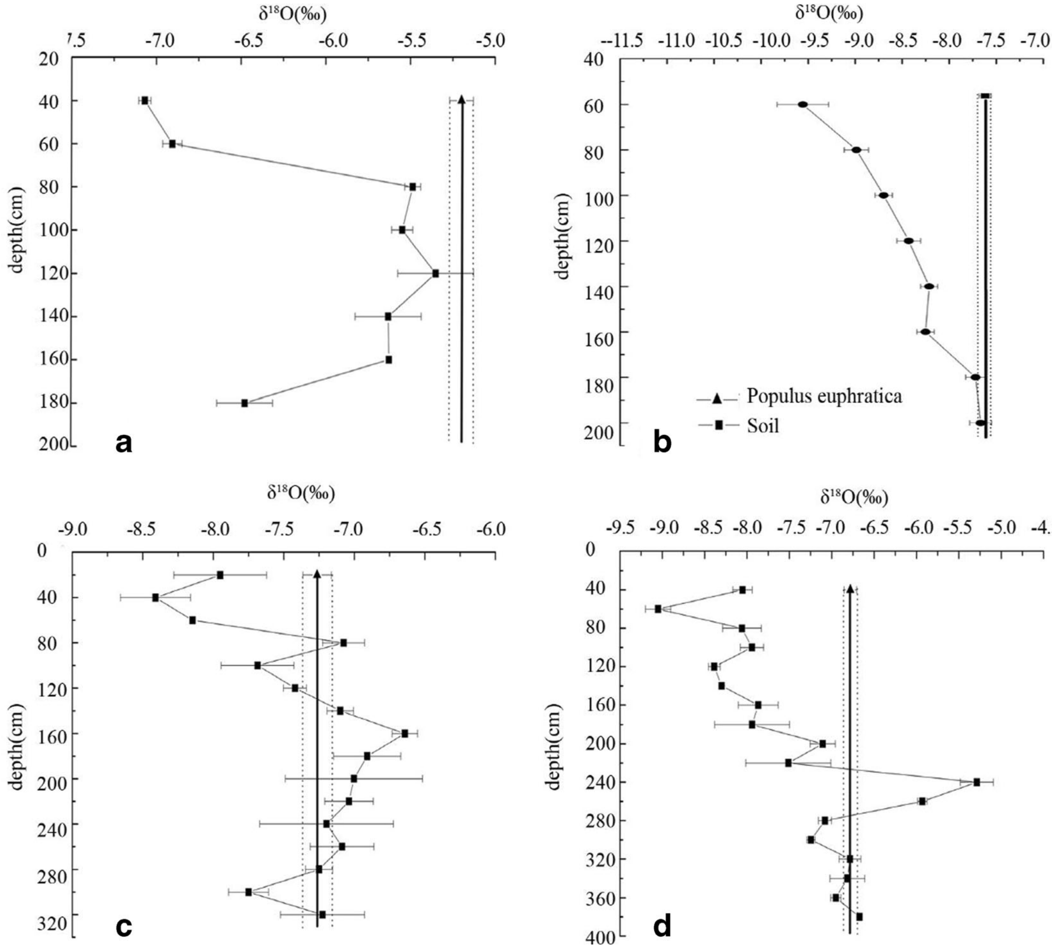

Fig. 2 Variations of δ^{18}O in the soil water, groundwater, and *P. euphratica* xylem water at different groundwater depths. **a, b, c,** and **d** represent groundwater depths of 1.80, 2.00, 3.25, and 3.80 m

82.4 %), followed by the contribution of the 80-cm soil layer (6.9 %). The mean contribution of groundwater at this depth was only 0.2 %, suggesting that *P. euphratica* absorbs water primarily from the 120-cm soil layer (Fig. 3a). At a groundwater depth of 2.00 m, the largest water contribution was from groundwater (53.3 %), followed by the soil water of the 180-cm soil layer (33 %) (Fig. 3b). At a groundwater depth of 3.25 m, the contributions were diverse, with soil water from the 140–180-cm soil layer providing the largest contribution (19.8 %); Soil water from the 200–240- and 260–300-cm soil layers and groundwater contributed 19, 16.7, and 18.1 %, respectively (Fig. 3c). At a groundwater depth of 3.8 m, the water source of *P. euphratica* was deep subsoil water and groundwater. The 200–240-cm soil layer provided the largest contribution (24.9 %), followed by groundwater (23.7 %). Soil water from the 260–300- and 320–360-cm soil layers contributed to 21.2 and 18.2 %, respectively (Fig. 3d). The total contribution of soil water of the 200–360-cm soil layer and groundwater was 88 %. It is thus clear that as the groundwater depth increases, the water source of *P. euphratica* changes from soil water, from a single soil layer, to deep subsoil water (below 200 cm), and groundwater. The contribution of these water sources increases with depth (Fig. 3).

Populus euphratica water sources under different habitat condition

The xylem δ^{18}O of *P. euphratica* growing in riverside lowlands was near the δ^{18}O of soil water from 1.6- to 2.0-m layer and that of groundwater, moreover, the δ^{18}O of soil water from 1.6- to 2.0-m layer was close to that of groundwater, indicating that xylem water may be related to water recharged by rising capillary water. The xylem water δ^{18}O at this location was very different from that of river water, indicating that the water sources for *P. euphratica* forests are deep subsoil water and groundwater rather than river water (Fig. 4a). The δ^{18}O of xylem water of the degraded *P. euphratica* on the dune field was close to that of groundwater, multi-layer soil water, and river water, suggesting that groundwater and multi-layer soil water were the water sources and that the groundwater was effectively recharged by river water (Fig. 4b). The δ^{18}O of xylem water of *P. euphratica* on the Gobi was similar to that of groundwater and multi-layer soil water, indicating that groundwater and multi-layer soil water are the primary water sources (Fig. 4c).

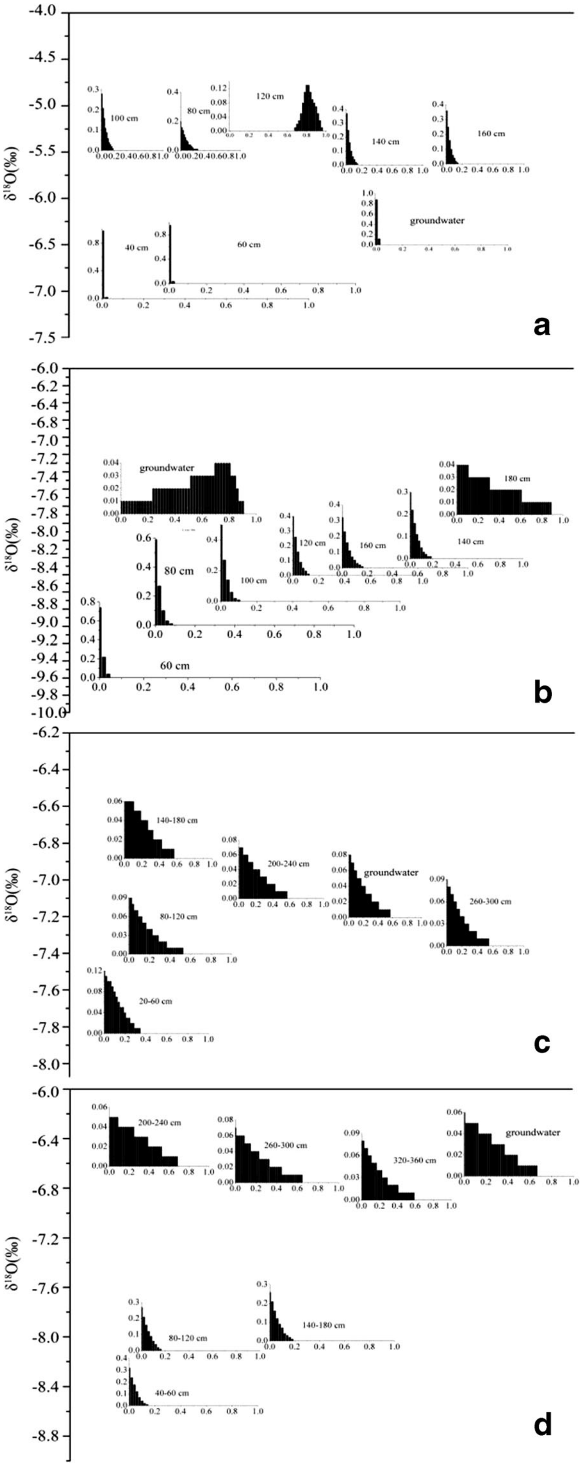

Fig. 3 Histograms showing the analyzed results of multi-source mass conservation Histograms show the estimated range of potential contribution of soil water of different soil layers to the plant water source. **a**, **b**, **c**, and **d** represent groundwater depths of 1.80 m, 2.00 m, 3.25 m, and 3.80 m

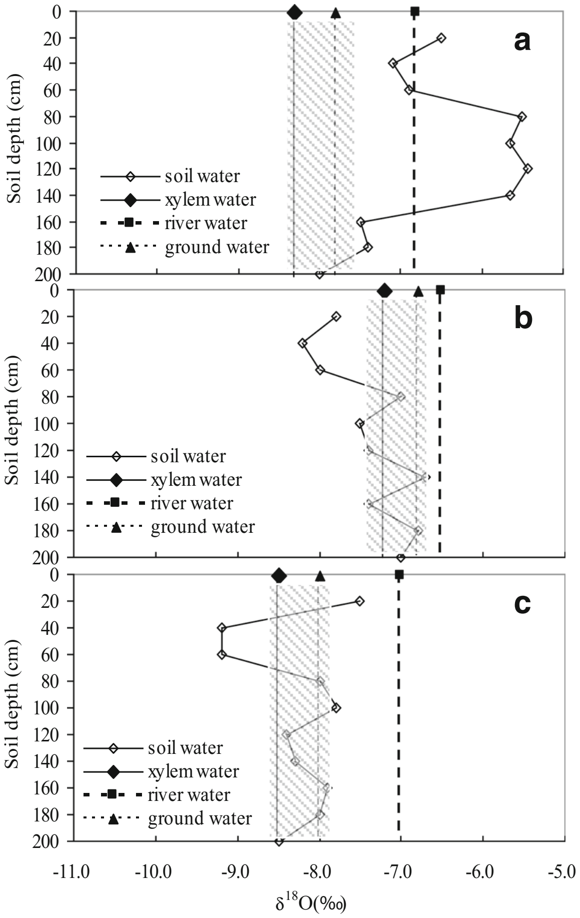

Fig. 4 Comparison of δ^{18}O values of xylem water of *P. euphratica*, soil water, groundwater, and river water. **a, b, c** represents riverside lowlands, degraded, and Gobi *Populus euphratica*, respectively. *Shadowed sections* represent water sources close to xylem water of *Populus euphratica*

Discussion

In the extremely arid region of the lower reaches of the Heihe River, precipitation often completely evaporates before infiltrating into the soil, and the sparse precipitation has no practical significance to plant growth and development (Chen et al. 2003; Zhao et al. 2008). Therefore, in this study, the effect of precipitation on soil water and the isotopic composition of soil water and groundwater are negligible.

At locations with different groundwater depths, significant variation in δ^{18}O of soil water occurs in the 80-, 160-, and 240-cm layers (Fig. 2). This is related to the intense evaporation and soil texture in the extreme arid environment of the study region (Zhao et al. 2008). These results are consistent with those of Asbjornsen et al. (2007) in the savanna and forest zone of the mid-western USA, which showed significant variation in δ^{18}O of soil water at the 80–100-cm (forest) and 60–80-cm (savanna) layers, respectively. However, we found significant δ^{18}O of soil water variation deeper, likely because of the co-mingling of soil water with different δ^{18}O values causing the mixing of isotopes. The intense evaporation in the surface soil layer (0–60 cm) causes the enrichment of heavy isotopes and leads to general increases in soil water δ^{18}O. At shallower groundwater depths (≤2.0 m), the soil water δ^{18}O decreases due to persistent rising phreatic water recharging soil water. As the groundwater depth increases (>3.0 m), δ^{18}O of soil water varies significantly due to the effects of atmospheric evaporation and phreatic water recharge. Above the significant variation layer, soil water in different layers mutually complements and oxygen isotopes in soil water continuously mixes; therefore, δ^{18}O values of soil water increases with depth. Below the significant variation layer, soil water is continuously recharged by groundwater and the exchange between groundwater and soil water is active; therefore, δ^{18}O values of soil water decreases with increasing depth and is similar to groundwater δ^{18}O. The variations of soil water δ^{18}O values demonstrate that soil water is recharged by groundwater.

It is generally accepted that δ^{18}O value does not change in the processes of water uptake by root systems and its transfer to plant leaves. As such, the δ^{18}O in the water of a plant body can be viewed as a mixture of the δ^{18}O of various water sources (White et al. 1985; Turner et al. 1987). Comparing the δ^{18}O of xylem water of *P. euphratica*, soil water, and groundwater (Fig. 3), we found that at a groundwater depth of 1.8 m, *P. euphratica* obtains water mainly from the 120-cm soil layer. At a groundwater depth of 2.0 m, the main water source is groundwater. At a groundwater depth of 3.25-m *P. euphratica* obtains water mainly from the 80-, 120–140-, and 200–280-cm soil layers and groundwater. At a groundwater depth of 3.80 m, *P. euphratica* obtains water mainly from the 200–220-and 280–360-cm soil layers. According to the general speculation, riparian plants mainly use river water; however, that was not the case, riparian plants do not absorb river water or use it rarely, relying instead on groundwater and soil water, especially large trees and trees of relatively far away from the river (Dawson and Ehleringer 1991; Busch et al. 1992). The proportion of groundwater that is used by plants increases with the dryness of surface soil layer (Thorburn and Walker 1993). The use of groundwater and uncertain water sources may be an adaptive selection of trees for surviving long-term drought conditions (Dawson and Ehleringer 1991; Dawson and Pate 1996). As the groundwater depth increases, the water source of *P. euphratica* changes from soil water from a single soil layer to deep subsoil water and groundwater. This appears to be an adaptive selection to arid and water-deficient conditions and improves the long-term survival of the desert riparian forest in an extremely arid region.

Seasonal rivers recharge groundwater and thereby become an important factor affecting the growth and distribution of *P. euphratica*. Based on our results, river water δ^{18}O value varies between −6.2 and −7.0 ‰ and groundwater δ^{18}O value varies between −6.5 and −8.0 ‰, indicating that river water recharges groundwater. However, due to the effects of channel distance and recharge time, isotope fractionation takes place in the groundwater recharge processes. For example, during the river water infiltration processes, evaporation occurs and water is redistributed in the soil profile (Zimmermann et al. 1967). The process of converting river water to groundwater enriches the heavy isotopes (δD and δ^{18}O) increasing the concentrations of δD and δ^{18}O (Clark and Fritz 1997; Kendall and Caldwell 1998).

The same species in different habitats have different water use strategies. *P. euphratica* forests on riverside lowlands are near the river channel and its water source originates from groundwater and the deep subsoil layer rather than river water. The xylem water δ^{18}O of degraded *P. euphratica* on sand dunes is very close to that of groundwater, multi-layer soil water, and river water, indicating that groundwater and multi-layer soil water are likely water sources and that groundwater is effectively recharged by river water; Gobi *P. euphratica* away from the river channel, and it mainly use groundwater and multi-layer soil water.

Plant growth in arid desert regions is highly reliant on groundwater (Rodriguez-Iturbe 2000; Zhong et al. 2002). Groundwater depth directly affects soil water which is closely related to the growth of vegetation and determines the distribution, growth of vegetation, and population succession and existence or disappearance of desert oasis (Fan et al. 2004; Chen et al. 2006). Groundwater is the most important water source for the survival of vegetation in most desert regions (Snyder and Williams 2000; Smith et al. 1991; Busch et al. 1992; Dawson and Ehleringer 1991). Single surface water irrigation cannot alter the water conditions of desert vegetation, and maintaining the stability of groundwater is vital to maintain the normal growth of vegetation (Li and Zhang 2003).

Conclusions

As groundwater depth increases, significant variations of the δ^{18}O in the soil profile occur at 80, 160, and 240 cm. These variations demonstrate that soil water is recharged by groundwater and that its δ^{18}O is also affected by the groundwater δ^{18}O.

As the groundwater depth increases, the main water source of *P. euphratica* changes from soil water in a single soil layer or groundwater, to deep subsoil water below 2.00 m and groundwater.

Desert riparian *P. euphratica* in different habitats have different water use strategies. Water source of *P. euphratica* on the riverside lowland is groundwater and deep subsoil water, rather river water. Degraded *P. euphratica* on sand dunes use groundwater and multi-layer soil water recharged by river water, and Gobi *P. euphratica* mainly use groundwater and multi-layer soil water. Maintaining the stability of groundwater is vital to maintain the normal growth of vegetation.

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References

Asbjornsen, H., Mora, G., & Helmers, M. J. (2007). Variation in water uptake dynamics among contrasting agricultural and native plant communities in the Midwestern U.S. *Agriculture. Ecosystems and Environment, 121*, 343–356.

Bailey, R. G. (1996). *Ecosystem geography* (1st ed.). Berlin: Springer.

Busch, D. E., Ingraham, N. L., & Smith, S. D. (1992). Water uptake in woody riparian phreatophytes of the southwestern United States: a stable isotope study. *Ecological Applications, 2*, 450–459.

Chen, Y. N., Cui, W. C., Li, W. H., Chen, Y. P., & Zhang, H. F. (2003). Utilization of water resources and ecological protection in the Tarim River. *Acta Geographica Sinica, 58*, 215–222 (in Chinese).

Chen, Y. N., Li, W. H., Chen, Y. P., Zhang, H. F., & Zhuang, L. (2004). Physiological response of natural plants to the change of groundwater level in the lower reaches of Tarim River, Xinjiang. *Progress in Natural Science, 14*, 975–983 (in Chinese).

Chen, Y. N., Li, W. H., Chen, Y. P., Zhao, R. F., & Wan, J. H. (2006). Ecological response of dried channel water transfer of the lower Tarim River and Ecological restoration. *Arid Zone Research, 23*, 521–530 (in Chinese).

Chu, J. M. (2007). Study of selective water use of plants in arid zone. Beijing, Academy of Forestry Scientific Research, Beijing. Doctoral Dissertation.

Clark, I. D., & Fritz, P. (1997). *Environmental isotopes in hydrogeology*. Boca Raton: Lewis Publishers.

Dawson, T. E. (1998). Fog in the California redwood forest: ecosystem inputs and use by plants. *Oecologia, 117*, 476–485.

Dawson, T. E., & Ehleringer, J. R. (1991). Streamside trees that do not use stream water. *Nature, 350*, 335–337.

Dawson, T. E., & Pate, J. S. (1996). Seasonal water uptake and movement in root systems of Australian phraeatophytic plants of dimorphic root morphology: a stable isotope investigation. *Oecologia, 107*, 13–20.

Drake, P. L., & Franks, P. J. (2003). Water resource partitioning, stem xylem hydraulic properties, and plant water use strategies in a seasonally dry riparian tropical rainforest. *Oecologia, 137*, 321–329.

Ehleringer, J. R., Phillips, S. L., Schuster, W. S. F., & Sandquist, D. R. (1991). Differential utilization of summer rains by desert plants. *Oecologia, 88*, 430–434.

Fan, Z. L., Ma, Y. J., Zhang, H., Wang, R. H., Zhao, Y. J., & Zhou, H. F. (2004). Research of eco-water table and rational depth of groundwater of Tarim River drainage basin. *Arid Land Geography, 27*, 8–13 (in Chinese).

Han, L., Wang, H. Z., Chen, J. L., & Yu, J. (2011). Disturbance regimes and gaps characteristics of the desert riparian forest at the middle reaches of Tarim Rivers. *Acta Ecologica Sinica, 31*, 4699–4708 (in Chinese).

Hao, X. M., Chen, Y. N., Li, W. H., Guo, B., & Zhao, R. F. (2010). Hydraulic lift in *P. euphratica* from the desert riparian vegetation of the Tarim River Basin. *Journal of Arid Environments, 74*, 905–911.

Huang, T. M., & Pang, Z. H. (2010). Changes in groundwater induced by water diversion in the Lower Tarim River, Xinjiang Uygur, NW China: Evidence from environmental isotopes and water chemistry. *Journal of Hydrology, 387*, 188–201.

Kendall, C., & Caldwell, E. A. (1998). Fundamentals of isotope geochemistry. In C. Kendall & J. J. McDonnell (Eds.), *Isotope tracers in catchments hydrology* (pp. 5–86). Amsterdam: Elsevier Science B.V.

Kolb, T. E., Hart, S. C., & Amundson, R. (1997). Boxelder water source and physiology at perennial and ephemeral stream sites in Arizona. *Tree Physiology, 17*, 151–160.

Li, X. M., & Zhang, X. M. (2003). Water condition and restoration of natural vegetation in the southern margin of the Taklimakan Desert. *Acta Ecologica Sinica, 23*, 1449–1453 (in Chinese).

Li, W. H., Hao, X. M., Qin, X. W., Chen, Y. N., & Huang, X. (2008). Ecological process of desert riparian forest communities and its hydrological mechanism of inland river basin in arid area. *Journal of Desert Research, 28*, 1113–1117 (in Chinese).

Mensforth, L. J., Thorburn, P. J., Tyerman, S. D., & Walker, G. R. (1994). Source of water used by riparian *Eucalyptus camaldulensis* overlying highly saline groundwater. *Oecologia, 100*, 21–28.

Phillips, D. L., & Gregg, J. W. (2003). Source partitioning using stable isotopes: coping with too many sources. *Oecologia, 136*, 261–269.

Rietti-Shati, M., Yam, R., Karlen, W., & Shemesh, A. (2000). Stable isotope composition of tropical high-altitude freshwaters on Mt. Kenya, Equatorial East Africa. *Chemical Geology, 166*, 341–350.

Rodriguez-Iturbe, I. (2000). Ecohydrology: a hydrologic perspective of climate-soil-vegetation dynamics. *Water Resources Research, 36*, 3–9.

Schachtschneider, K., & February, E. C. (2010). The relationship between fog, floods, groundwater and tree growth along the lower Kuiseb River in the hyperarid Namib. *Journal of Arid Environments, 74*, 1632–1637.

Smith, S. D., Welling, A. B., Nachlinger, J. A., & Fox, C. A. (1991). Functional responses of riparian vegetation to streamflow diversions in eastern Sierra Nevada. *Ecological Applications, 1*, 89–97.

Snyder, K. A., & Williams, D. G. (2000). Water sources used by riparian trees varies among stream types on the San Pedro River, Arizona. *Agricultural and Forest Meteorology, 105*, 227–240.

Sun, S. F., Huang, J. H., Lin, G. H., Zhao, W., & Han, X. G. (2005). Application of stable isotope technique in the study of plant water use. *Acta Ecologica Sinica, 25*, 2362–2371 (in Chinese).

Thorburn, P. J., & Walker, G. R. (1993). The source of water transpired by *Eucalyptus camaldulensis*: soil, groundwater, or streams? In J. R. Ehleringer, A. E. Hall, & G. D. Farquhar (Eds.), *Stable isotopes and plant carbon-water relations* (pp. 511–527). San Diego: Academic Press.

Thorburn, P. J., & Walker, G. R. (1994). Variations in stream water uptake by *Eucalyptus camaldulensis* with differing access to stream water. *Oecologia, 100*, 293–301.

Turner, J. V., Arad, A., & Johnston, C. D. (1987). Environmental isotope hydrology of salinized experimental catchments. *Journal of Hydrology, 94*, 89–107.

Wang, P. Y., Liu, W. J., & Li, P. J. (2010). Advance in the study of plant water use strategy. *Guangxi Plants, 30*, 82–88 (in Chinese).

White, J. W. C., Cook, E. R., Lawrence, J. R., & Broecker, W. S. (1985). The D/H ratios of sap in trees: implications for water sources and tree ring D/H ratios. *Geochimica et Cosmochimica Acta, 49*, 237–246.

Zhang, G. X., He, Y., & Deng, W. (2004). Advance in the application of isotope D and ^{18}O in water environment study. *Arid Zone Research, 21*, 225–229 (in Chinese).

Zhao, L. J., Xiao, H. L., Cheng, G. D., Song, Y. Y., Zhao, L., Li, C. Z., et al. (2008). A preliminary study of water sources of riparian plants in the lower reaches of the Heihe Basin. *Acta Geoscientia Sinica, 29*, 709–718 (in Chinese).

Zhong, H. P., Liu, H., & Wang, Y. (2002). Relations between Ejina Oasis and water resources in the lower reaches of the Heihe River. *Advances in Water Science, 13*, 223–228 (in Chinese).

Zimmermann, U., Ehhalt, D. H., & Münnich, K. O. (1967). Soil water movement and evapotranspiration: changes in the isotopic composition of the water. In: Proceedings of the Symposium on Isotopes in Hydrology. International Atomic Energy Agency, Vienna, pp. 567–585.