Analysis of Plant Water Sources in the Urumqi River Basin and Its Implications for Identifying Groundwater-Dependent Ecosystems in Arid Areas

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Abstract

Water resources are a core factor affecting ecosystem stability and vegetation growth and development in arid regions. Analyzing plant water sources at the watershed scale is of great significance for understanding ecohydrological processes in arid regions. Taking the Urumqi River Basin, a typical Groundwater-Dependent Ecosystems (GDEs), as the study area, this study combined hydrogen and oxygen isotope tracing, the direct comparison method, the stable isotope mixing model (IsoSource), and the stable isotope Bayesian mixing model framework (MixSIAR) to quantitatively assess the relative contributions of atmospheric precipitation, surface water, soil water, and groundwater to plant xylem water, and to explore their implications for GDEs. The results showed that the Local Meteoric Water Line (LMWL) was $ 2H = 6.96 $18O+4.44 (R2=0.95). The isotopic values of plant xylem water fell entirely within the distribution ranges of soil water and groundwater, and the direct comparison method revealed niche differentiation in water source utilization between herbs and shrubs. Based on Bias and mean absolute error (MAE) to evaluate model performance at the category level, the MixSIAR model was more stable than the IsoSource model, while the latter showed a significant systematic negative bias of -8.481‰ in predicting $ $2H for shrubs. The model results indicated that shrubs utilized deep soil water (2.5~3 m) and groundwater at a combined rate as high as 48.4%, reflecting their dependence on deep water sources. This also means that sharp fluctuations in deep soil water and groundwater would directly threaten shrub survival and may further trigger the degradation or even collapse of GDEs. Therefore, the water-use status of shrubs can serve as an important sensitive indicator of GDEs health. By placing plant water source analysis within the framework of GDEs conservation, this study establishes a research system of "water sources-vegetation strategies-GDEs health," providing a scientific basis for vegetation restoration and water resource management in the Urumqi River Basin, the delineation of ecological groundwater levels, and the protection of GDEs, thereby supporting the sustainable conservation of ecological barrier functions in arid regions.

Full Text

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Analysis of Plant Water Sources in the Urumqi River Basin and Its Implications for Identifying Groundwater-Dependent Ecosystems in Arid Areas

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Abstract: Water resources are a core factor influencing ecosystem stability and vegetation growth in arid regions. Conducting analyses of plant water sources at the watershed scale is of great significance for understanding ecohydrological processes in arid areas. Taking the Urumqi River Basin, a typical groundwater-dependent ecosystem (Groundwater-Dependent Ecosystems, GDEs), as the study area, this study combined hydrogen and oxygen isotope tracing techniques, the direct comparison method, the stable isotope mixing model IsoSource, and the stable isotope Bayesian mixing model framework MixSIAR to quantitatively evaluate the relative contributions of atmospheric precipitation, surface water, soil water, and groundwater to plant xylem water, and to explore their impacts on GDEs. The results showed that the local meteoric water line (Local Meteoric Water Line, LMWL) was: $\delta^2H = 6.96\delta^{18}O + 4.44$ ($R^2 = 0.95$). The isotopic values of plant xylem water fell entirely within the distribution ranges of soil water and groundwater. The direct comparison method revealed ecological niche differentiation between herbaceous plants and shrubs in water-source utilization. Model performance at the categorical level was evaluated based on bias (Bias) and mean absolute error (MAE); the MixSIAR model was more stable than the IsoSource model, while the latter showed a significant systematic negative bias of $-8.481‰$ in predicting δ^2H of shrub xylem water. The model results indicated that the total utilization rate of deep soil water (2.5–3 m) and groundwater by shrubs reached 48.4%, reflecting their dependence on deep water sources. This means that when deep soil water and groundwater fluctuate sharply, shrub survival will be directly threatened and may further trigger degradation or even collapse of GDEs. Therefore, shrub water-use status can serve as an important sensitive indicator of GDE health. By placing plant water-source analysis within the GDE protection framework, this study constructs a research system of "water source–vegetation strategy–GDE health," providing a scientific basis for vegetation restoration and water-resource management in the Urumqi River Basin, for the delineation of ecological groundwater levels, and for the protection of GDEs, thereby supporting the sustainable conservation of ecological barrier functions in arid regions.

Keywords: plant water-source analysis; groundwater-dependent ecosystems

(GDEs); hydrogen and oxygen isotopes; direct comparison method; MixSIAR model; Urumqi River Basin

Water resources in arid regions are the core element maintaining ecosystem stability and vegetation survival, and are a key factor affecting plant growth. Spatiotemporal differences in the sources of plant xylem water directly determine species distribution patterns and ecological functions[1]. In recent years, as pressure on water resources in arid regions has intensified, research on groundwater-dependent ecosystems (Groundwater-Dependent Ecosystems, GDEs) has received increasing attention. GDEs refer to ecosystems whose species composition, structure, and ecological processes depend partly or wholly on groundwater during their life cycle[2]. From riparian forests and desert springs to inland riparian oases worldwide, GDEs maintain key biodiversity and ecosystem service functions, but their health is facing severe threats from climate change and human activities. As a typical inland river basin in an arid region, the Urumqi River Basin has scarce precipitation, strong evaporation, complex topography, and distinctive hydrological processes, causing the xylem water use of plants in the basin to depend heavily on multiple recharge sources, including atmospheric precipitation, surface water, soil water, and groundwater, thereby increasing the complexity of plant xylem water sources. Among these, groundwater and deep soil water are the most stable water sources in arid regions[3–4] and play an irreplaceable role in maintaining GDEs, especially the stability of deep-rooted shrub communities. In recent years, changes in precipitation patterns and rising temperatures caused by global climate change have further affected regional hydrological cycles and threatened vegetation survival and ecological barrier functions[5]. Against this background, accurately analyzing plant water sources—especially identifying key plant groups highly dependent on deep water sources—is of crucial importance for ecological restoration and sustainable water-resource management in China' s arid regions[6].

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At present, a variety of technical approaches are used to investigate the sources of plant water uptake. These include root excavation based on direct observation[7], physiological-characteristic methods that reflect plant water status[8], stem sap-flow methods for measuring transpiration water consumption[9], and stable hydrogen–oxygen isotope techniques. Among them, stable hydrogen–oxygen isotope techniques can quantitatively distinguish the utilization proportions of different water sources, and, owing to their unique capacity for precise analysis, have become the most effective and widely applied research method at present. Their theoretical basis is that, during root water uptake and xylem water transport in most terrestrial plants, hydrogen and oxygen isotopes undergo no significant fractionation; therefore, the hydrogen and oxygen isotope composition of plant xylem water can indicate the characteristics of environmental water sources[10]. Based on this property, by comparing the isotopic differences between plant xylem water and potential water sources—including atmospheric precipitation, surface water, soil water, and groundwater—and applying binary or multi-source isotope mixing models, the relative contribution of each water source can be determined, thereby effectively revealing plant water-use strategies. Among these models, the stable-isotope mixing model IsoSource and the Bayesian stable-isotope mixing-model framework MixSIAR are the most widely used[11]. The former is intuitive to calculate but cannot quantify uncertainty and is prone to failure when multiple water sources are mixed; the latter, although computationally more complex, presents results in probabilistic form and effectively evaluates uncertainty. Therefore, compared with traditional hydrological methods, the use of these models can more accurately distinguish the mixing effects among water sources and improve analytical precision[12-13]. In addition, this technique has been widely applied in riparian forests and desert ecosystems[14-15].

Scholars in China and abroad have conducted extensive research on the analysis of plant xylem-water sources. In terms of different plant life forms, trees, shrubs, and herbs differ in their use of water: trees and shrubs mainly use deep soil water—water that has infiltrated below the root zone—or groundwater, whereas herbs primarily use surface water or shallow soil water within the active root zone[16-17]. In terms of differences in root-length distribution, compared with a single vegetation-structure type, plants with more lateral roots have higher soil-water use efficiency, and shallow-rooted and deep-rooted plants exhibit vertical ecological-niche complementarity[18]. However, for different life-form plants—especially shrubs and herbs—in arid regions, there is still a lack of systematic understanding of their degree of dependence on deep water sources, water-use strategies, and ecological-indicator significance. On this basis, using the Urumqi River basin as an example, this study analyzes plant water sources and focuses on revealing ecological-niche differentiation in the water-use strategies of different life-form plants. From the perspective of protecting GDEs, it discusses the implications of the findings for ecological conservation and sustainable water-resource management in arid regions.

1 Materials and Methods

1.1 Overview of the Study Area

The Urumqi River basin is located in central Xinjiang, in the middle section of the northern foot of the Tianshan Mountains, with a drainage area of 9182 km^2. The terrain relief is pronounced; temperature differences are large; cold and hot conditions change sharply; precipitation is low; and in mountainous areas air temperature decreases with increasing elevation, with the greatest lapse rate in summer. In the downstream plain, the annual mean air temperature is 5–7 °C; January is the coldest month and July the warmest. The basin belongs to a typical mid-temperate continental arid climate. Annual precipitation in the basin is 70–500 mm. In mountainous areas, precipitation is concentrated mainly from May to August, whereas in the plains it is concentrated from April to July. The distribution pattern of precipitation is characterized by greater amounts in the east than in the west, greater amounts in mountains than in plains and in plains than in valleys, and less than 100 mm in the northern desert[19]. From upstream to downstream, the basin passes through five hydraulically connected yet independent hydrogeological units: the bedrock fissure-water area; the Quaternary pore-water area of the Chaiwopu Basin; the bedrock fissure-water and Urumqi River valley Quaternary pore-water area in low mountains and hills; the Quaternary pore-water area of the piedmont sloping plain; and the Quaternary pore-water area of the downstream fine-soil plain (Fig. 1).

1.2 Sample Collection and Testing

To investigate the effects of different geological and geomorphic structures and plant types, sampling was carried out on sunny days in mid-October 2023 in plain, basin, and river-valley areas. A total of 21 sampling sites were established, and plant, soil, and water samples were collected.

1.2.1 Plant sample collection A total of 13 plant species, including herbs and shrubs, were sampled. The herbaceous plants included upland cotton (*Gossypium hirsutum*), *Stipa capillata*, *Halogeton arachnoideus*, and *Phragmites australis*; the shrub plants included *Alhagi camelorum*, *Haloxylon ammodendron*, *Ambrosia artemisiifolia*, *Reaumuria songorica*, *Ephedra przewalskii*, *Populus alba*, *Tamarix chinensis*, *Caragana sinica*, and *Nitraria tangutorum*. For each species, three individuals with good growth and similar crown width, height, and basal stem diameter were selected. For herbaceous plants, the non-green portions at the root–stem junction and the main root system 2–3 cm below the ground surface were collected; for shrubs, gray branches with diameters of 0.3–0.5 cm were collected at approximately 50 cm above the ground. After the bark was rapidly removed, the samples were immediately sealed in plastic bags and stored in a low-temperature freezer[20]. A total of 21 plant samples were obtained.

1.2.2 Soil sample collection Soil profiles were excavated beneath each selected plant sample, and soil samples were collected by layer. Surface soil from 0–0.2 m was excavated with a soil shovel, passed through a 2 mm sieve, and sampled after plant residues and stones were removed. Soil samples from depths of 0.2–0.5 m, 0.5–1 m, 1–2 m, and 2–3 m were collected using a hand auger. Three replicate samples were collected from each layer; each set was fully mixed separately and then placed in sealed plastic bags, and stored cold in a foam box at −5 °C. A total of 105 soil samples were obtained.

1.2.3 Water sample collection Groundwater samples were collected from wells near the 21 sampling sites. The sampling bottles were rinsed three times in advance, then directly filled and

Visible text in Fig. 1 (translated)

Legend: plant sampling point; surface-water sampling point; groundwater sampling point; precipitation sampling point; water system; reservoir; hydrogeological unit; fine-soil plain; gravel plain; valley area; bedrock area; Chaiwopu Basin.
Map labels: fine-soil plain; gravel plain; bedrock area; valley area; Chaiwopu Basin.
Inset legend: study area; Xinjiang.
Scale bars: 0–20 km; 0–220 km.

Fig. 1 Schematic diagram of the geographical location of the study area and distribution of sampling points

Fig. 1 Geographical location of the study area and sampling points distribution

sealed; surface-water samples were collected from springs or rivers near the sampling points, and the bottles were likewise rinsed three times and rapidly sealed after sampling. Thirteen precipitation sampling points were established. Standard rain gauges were installed at the sites, and samples were collected immediately after rainfall ended, transferred into HDPE plastic bottles, sealed with Parafilm sealing film, and brought back to the laboratory for frozen storage.

Moisture in all samples was extracted using a vapor water isotope analyzer (Eco) (Picarro-L1115-I). This technique is based on the principle of ultra-low-pressure vacuum-distillation cryogenic extraction: water is evaporated (sublimated) under ultra-low pressure and condensed in a low-temperature environment, thereby removing impurities and salts from the water samples; it is then extracted without fractionation or loss and collected by freezing. The extracted water then enters a liquid-water isotope analyzer, where wavelength-scanned cavity ring-down spectroscopy is used to determine the δ^2H and δ^{18}O isotopes of all samples. At least two internationally certified standard water samples with known δ values, such as VSMOW and SLAP, were used for multipoint linear calibration, establishing an accurate conversion relationship between the raw instrumental measurement signal and the true δ value. The measurement signals of all unknown samples were automatically calculated using this calibration curve, thereby strictly tracing their δ values to the VSMOW international standard. The specific formula is as follows:

$$\delta = \left[\left(\frac{R_{-\text{sample}}}{R_{-\text{V}-\text{SMOW}}}\right) - 1\right] \times 1000 \tag{1}$$

where $R_{-\text{sample}}$ is the isotope ratio of the sample (^{2}H/^{1}H or ^{18}O/^{16}O); $R_{-\text{V}-\text{SMOW}}$ is the corresponding ratio of the international standard material "Vienna Standard Mean Ocean Water."

1.3 Research methods and data processing

1.3.1 Direct comparison method

This study is based on a fundamental premise: during the process by which water is absorbed by roots and transported to the xylem, the hydrogen and oxygen isotope composition does not undergo significant fractionation [20]. Therefore, the isotope values of xylem water can be regarded as a direct reflection of the water sources absorbed by the plant. According to the principle of isotope mass balance, by comparing the δ^2H and δ^{18}O values of xylem water with those of each potential water source, when the isotope data point of xylem water falls within the distribution range of the isotope values of a certain potential water source, it can be preliminarily inferred that the plant may have used that water source.

1.3.2 IsoSource model and MixSIAR model

Two stable-isotope mixing models were used to analyze plant water sources: the frequency-distribution-based IsoSource model and the Bayesian-framework-based MixSIAR model. The IsoSource model iteratively calculates all potential combinations of water-source proportions that satisfy mass balance—that is, combinations whose weighted mean isotope values fall within a small tolerance interval around the isotope value of the mixture—and generates the frequency distribution of the contribution rate of each water source. The results are expressed as possible intervals and central tendencies. The model inputs are the mean δ^2H and δ^{18}O values of plant xylem water and each potential water source. MixSIAR is a Bayesian mixing model based on the R language; its inputs include δ^2H and δ^{18}O data for plant xylem water, as well as the mean values and standard deviations of the isotopes of each potential water source. The model assumes no isotope fractionation during plant water uptake, and therefore the fractionation factor was set to zero. Long-chain iterations were performed using a Markov chain Monte Carlo (MCMC) algorithm, supplemented by Gelman and Geweke diagnostic methods to ensure the posterior distri-

···converge, thereby improving the accuracy and stability of contribution-rate estimation.

By combining the preliminary judgment from the direct comparison method with the quantitative results of the IsoSource and MixSIAR models, the water-use strategies of plants for different water sources and the corresponding contribution proportions can be evaluated more comprehensively, thus providing a quantitative basis for determining the degree of plant dependence on groundwater.

1.4 Uncertainty Analysis

Accurately quantifying the average utilization proportions (f_i) of different water sources by plants—such as soil water, groundwater, and precipitation—is crucial for understanding hydrological processes in ecosystems. However, these contribution rates usually cannot be directly observed and can only be calculated using isotope mixing models such as IsoSource and MixSIAR. Based on the principle of mass balance, the model regards the stable isotope value (O_i, ‰) measured in plant xylem water as being composed of the isotope values δ_{Ai} of the potential water sources according to their contribution rates f_i. At the category level, the predicted value of the model ($\bar{P}_i$, ‰) is calculated as:

$$\bar{P}_i = \sum_{i=1}^{n} f_i \delta_{Ai} \tag{2}$$

The uncertainty of model estimation mainly originates from model structure and parameterization, input-data errors, and limitations in the resolution of source partitioning.

Because the true category-average water-use proportions cannot be obtained directly, this study adopted an indirect validation strategy: at the scale of category means, the model-predicted values ($\bar{P}_i$) were compared with the observed mean values ($\bar{O}_i$) to evaluate the effectiveness of the model in estimating the contribution proportions of water sources. To comprehensively evaluate model performance in terms of systematic bias and absolute error, bias (Bias) and mean absolute error (Mean Absolute Error, MAE) were selected as evaluation metrics. Bias is used to identify the direction and magnitude of systematic deviation in predicted values; the closer it is to zero, the more unbiased the model is. MAE reflects the absolute deviation between predicted and observed values; the smaller its value, the higher the prediction consistency of the model at the category level.

$$\text{Bias}_k = \bar{P}_k - \bar{O}_k \tag{3}$$

$$\text{MAE} = \frac{1}{n} \sum_{k=1}^{n} \left| \bar{P}_k - \bar{O}_k \right| \tag{4}$$

where $\bar{P}_k$ is the mean isotope value predicted by the model for a plant type; $\bar{O}_k$ is the observed mean isotope value for that plant type; and n is the number of plant functional-type categories ($n = 2$ in this study, i.e., shrubs and herbs). This method is suitable for separately evaluating the simulation performance for δ^2H and δ^{18}O isotopes.

2 Results and Analysis

2.1 Distribution Characteristics of Stable Isotopes in Plant Water

The δ^2H isotope value (-78.55 ± 4.17)‰ and δ^{18}O isotope value (-9.63 ± 1.98)‰ of shrub xylem water were, overall, slightly more positive than those of herbaceous plants, for which δ^2H was (-80.47 ± 4.38)‰ and δ^{18}O was (-9.94 ± 1.53)‰. This trend was more consistent for δ^2H. For δ^{18}O, the mean and median values of shrubs were higher than those of herbs, and their observed range (-12.63‰ ~ -5.68‰) was wider than that of herbs (-12.12‰ ~ -7.44‰), also including data points slightly lower than the minimum value for herbs (Fig. 2). Therefore, numerically, the isotopes in shrub xylem water were overall more positive than those in herbs, indicating that shrubs may have experienced stronger isotopic enrichment during evaporation; this is consistent with the characteristics of deep-rooted plants using relatively depleted, deep, stable water sources that are less affected by evaporation.

2.2 Relationship Between Plant Water and Other Water Bodies

Based on analysis of precipitation samples from 13 sampling sites, the local atmospheric precipitation had a δ^2H range of -88.71‰ ~ -36.30‰, with a mean value of (-65.02 ± 17.85)‰; the δ^{18}O range was -13.18‰ ~ -5.40‰, with a mean value of

Figure labels visible in Fig. 2: herbs; shrubs; median; mean; outlier; (a) δ^2H, y-axis δ^2H/‰; (b) δ^{18}O, y-axis δ^{18}O/‰; x-axis: plant type.

Fig. 2 Distribution of δ^2H and δ^{18}O in plant xylem water

(-9.97 ± 2.51)‰. Regression analysis yielded the local meteoric water line (LMWL) for the study area as $\delta^2\text{H} = 6.96\delta^{18}\text{O} + 4.44$ ($R^2 = 0.95$). Compared with the global meteoric water line (GMWL: $\delta^2\text{H} = 8\delta^{18}\text{O} + 10$), both the slope and intercept of the LMWL were lower (Fig. 3a). The lower slope (6.96) indicates that precipitation underwent intense evaporation, while the lower intercept (4.44) reflects the dry continental climatic characteristics of the study area.

The isotope values of surface water were all located above the LMWL. In addition to indicating relatively weak evaporation during its formation, this is also closely related to the basin’ s distinctive recharge characteristics and seasonal hydrological processes (Fig. 3b). The δ^2H and δ^{18}O values of plant xylem water, soil water, and groundwater at all sampling points were distributed near or below the meteoric water line (LMWL) (Fig. 3c), reflecting their recharge source (precipitation) and varying degrees of evaporative enrichment. Further analysis showed that the δ^2H and δ^{18}O values of plant xylem water [for herbaceous plants, δ^2H was (-80.47 ± 4.38)‰ and δ^{18}O was (-9.94 ± 1.53)‰; for shrubs, δ^2H was (-78.55 ± 4.17)‰ and δ^{18}O was (-9.63 ± 1.98)‰] all fell within the isotopic distribution ranges of soil water and groundwater (herbaceous-plant soil water: δ^2H from -94.27‰ to -65.54‰ and δ^{18}O from -12.85‰ to -3.61‰; shrub soil water: δ^2H from -94.13‰ to -45.48‰ and δ^{18}O from -13.19‰ to -2.39‰; groundwater: δ^2H from -99.74‰ to -64.23‰ and δ^{18}O from -15.35‰ to -9.28‰), indicating that plants mainly use soil water and groundwater as sources of xylem water.

2.3 Quantitative analysis of plant water sources based on the IsoSource and MixSIAR models

When exploring the water-uptake mechanisms of xerophytic plants, hydrogen isotopes exhibit significant fractionation, whereas oxygen isotope fractionation during water uptake is relatively weak; therefore, δ^{18}O values are usually used directly to determine plant water sources. By comparing the δ^{18}O values of xylem water from different vegetation types in the Urumqi River basin with those of different water sources, it was found that the intersections between xylem water and soil water differed slightly between herbaceous plants and shrubs. Xylem water of herbaceous plants intersected with soil water at 1-2 m and 2-3 m, while shrubs intersected with soil water at 2-3 m, indicating that herbaceous plants mainly absorb soil water from depths of 1-3 m, whereas shrubs mainly absorb soil water from depths of 2-3 m (Fig. 4).

To further quantify the contribution proportions of different water sources and to focus on evaluating plant dependence on groundwater, this study applied the IsoSource and MixSIAR models. Based on the means and standard deviations of δ^2H and δ^{18}O, the contribution rates of each potential water source to plant xylem water were calculated (Fig. 5). The results of both models indicate that herbaceous plants and shrubs show clear niche differentiation and dependency hierarchies in their use of soil water from different layers and groundwater. According to the more reliable MixSIAR model results, the direct utilization rates of groundwater by herbaceous plants and shrubs were very similar (16.9% and 17.1%, respectively), but this does not fully reflect their true dependence. A detailed analysis of the soil-water utilization profile showed that water use by herbaceous plants was concentrated in the shallow to middle layers of 0-2 m, and their utilization proportion decreased slowly with increasing depth, indicating susceptibility to the effects of precipitation and evaporation.

Fig. 3 The δ^2H-δ^{18}O relationship of the atmospheric precipitation line, potential water sources, and plant xylem water in the study area

Visible panel labels and legends in Fig. 3:

- **(a) Atmospheric precipitation line**
  - Precipitation
  - GMWL: $\delta^2\mathrm{H} = 8\delta^{18}\mathrm{O} + 10$
  - LMWL: $\delta^2\mathrm{H} = 6.96\delta^{18}\mathrm{O} + 4.44$
  - Axes: δ^2H/‰; δ^{18}O/‰
- **(b) Surface water**
  - Surface water
  - GMWL: $\delta^2\mathrm{H} = 8\delta^{18}\mathrm{O} + 10$
  - LMWL: $\delta^2\mathrm{H} = 6.96\delta^{18}\mathrm{O} + 4.44$
  - Axes: δ^2H/‰; δ^{18}O/‰
- **(c) Soil water and groundwater**
  - Groundwater
  - Plant xylem water

- Soil 0–0.2 m
- Soil 0.2–0.5 m
- Soil 0.5–1 m
- Soil 1–2 m
- Soil 2–3 m
- GMWL: $\delta^2H = 8\delta^{18}O + 10$
- LMWL: $\delta^2H = 6.96\delta^{18}O + 4.44$
- Axes: δ^2H/‰; $\delta^{18}O$/‰

Figure 4 annotations. Legend: herbaceous-plant soil water; shrub-plant soil water; precipitation; surface water; groundwater; plant xylem water.
(a) Herbaceous plants. (b) Shrub plants.
Axes: soil depth/m; $\delta^{18}O$/‰.

Fig. 4 Relationship between plant xylem water and potential water sources based on $\delta^{18}O$
Fig. 4 Tracing the relationship between xylem water and potential water sources in plants based on $\delta^{18}O$

Figure 5 annotations. Legend: soil 0–0.2 m; soil 0.2–0.5 m; soil 0.5–1 m; soil 1–2 m; soil 2–3 m; groundwater.
(a) IsoSource model. (b) MixSIAR model.
Axes: water-use efficiency/%; plant type. Categories: herbaceous plants; shrubs.

Fig. 5 Plant water-use efficiency under the IsoSource and MixSIAR models
Fig. 5 Water use efficiency of model plants under IsoSource and MixSIAR conditions

⋯effect. In contrast, the proportion of water used by shrub plants increased significantly with soil depth; their utilization rates for the 0.5–1 m, 1–2 m, and 2–3 m soil layers were 14.8%, 23.5%, and 31.3%, respectively. This indicates that the core water-uptake zone of shrubs lies in deeper soil layers where moisture is more stable and more closely connected with groundwater. Therefore, through their well-developed deep root systems, shrub plants indirectly use deep soil water maintained by upward groundwater recharge or capillary action at high intensity, thereby exhibiting stronger niche specificity than herbaceous plants and a more integrated dependence on the groundwater system.

3 Discussion

3.1 Model selection and performance evaluation

This study combined stable-isotope tracing techniques with quantitative models, clearly revealing fundamental differences in the overall water-use strategies of herbaceous and shrub plants in the Urumqi River Basin. The results not only accurately resolved the composition of water sources for plants of different life forms, but also, from the perspective of plant water-use patterns, deepened understanding of the structure and function of groundwater-dependent ecosystems within the basin. Bias and mean absolute error (MAE) were used to evaluate model performance at the category level. The model performance evaluation showed (Table 1) that the IsoSource and MixSIAR models each had advantages and disadvantages in predictive accuracy. The IsoSource model had slightly lower error when predicting δ^{18}O in herbaceous plants, but it showed a significant systematic negative bias in predicting δ^{2}H in shrub plants (−8.481‰), indicating its instability under certain scenarios. In contrast, the MixSIAR model performed more consistently across all scenarios. Although its mean absolute error for δ^{18}O was higher than that of the IsoSource model, for δ^{2}H the error of the IsoSource model was far higher than that of the MixSIAR model. Although the IsoSource model showed extremely high predictive accuracy, it produced a large bias in predicting δ^{2}H in shrub plants; in actual

Table 1 Model evaluation results

Tab. 1 Model evaluation results

Model category	Plant type	Bias/‰ δ^{18}O	Bias/‰ δ^{2}H	Mean absolute error (MAE)/‰ δ^{18}O	Mean absolute error (MAE)/‰ δ^{2}H
IsoSource	Herbaceous	0.001	0.003	0.002	4.239
IsoSource	Shrub	0.003	−8.481		
MixSIAR	Herbaceous	0.351	1.639	0.415	1.657
MixSIAR	Shrub	0.480	1.675		

may bring risks in practical applications. Therefore, based on overall stability, and because the Bayesian framework can quantify uncertainty in contribution rates, this study selected MixSIAR for subsequent analysis.

According to the MixSIAR model results, the proportions of soil water used by the two life-form plants both showed a clear upward trend. However, compared with herbaceous plants, shrubs exhibited a stronger dependence on deeper soil water. In the shallow layer (0–0.5 m), the water-use proportion of herbaceous plants (24.1%) was nearly twice that of shrubs (13.3%); in the middle layer (0.5-2 m), the water-use proportion of herbaceous plants tended to be stable (18.3%-20%), whereas that of shrubs continued to increase rapidly (from 14.8% to 23.5%), indicating that their root systems could effectively absorb water at this depth; in the deep layer (2–3 m), the utilization proportion of shrubs reached 31.3%, exceeding their dependence on groundwater. Although the direct utilization proportions of the two for groundwater were similar (about 17%), shrubs showed a significant dependence on deep soil water, reflecting a niche-differentiation strategy based on deep root systems

. Herbaceous plants mainly relied on shallow and middle soil water, whereas shrubs obtained deeper and more stable water sources through developed root systems, thereby reducing competition with herbaceous plants for shallow-layer water. This divergence may stem from differences in root-system structure and ecological adaptation strategies among different plants. Herbaceous plants have relatively shallow and densely distributed root systems, enabling them to rapidly absorb shallow and middle soil water to support their own growth

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. During the growing season, if extreme precipitation events occur, large amounts of infiltration may be generated, and deep soil layers may retain a considerable proportion of soil water; the well-developed deep root systems of shrubs can penetrate several meters of soil to obtain more stable deep water sources, forming a unique hydrological niche and producing higher species richness

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. The sandy soil and alluvial-fan hydrogeological background of the study area lead to easy loss of shallow water and relatively stable deep water, providing a physical basis for the vertical differentiation in water use described above.

In addition, sampling in this study was conducted at the end of the growing season (October). At this time, precipitation was scarce, and shallow soil water had nearly dried up after intense summer evaporation and transpiration. The shallow water sources available to herbaceous plants were extremely limited, whereas shrubs, by virtue of their deep root systems and higher water-use efficiency, could still effectively use deep water storage, thereby further highlighting the ecological niche difference between the two life forms along the temporal dimension. This corresponds to the drought-environment adaptation strategy of *Caragana* in the Inner Mongolian Plateau desert, namely "low transpiration and high water-use efficiency"

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. However, *Caragana* places greater emphasis on physiological regulation of osmotic adjustment and free-radical scavenging, whereas the advantage of shrubs in this study is more reflected in the dual adaptation of "root-system spatial expansion + physiological regulation." It should be added that some studies have shown that selective water uptake by halophyte root membranes may lead to preferential absorption of light isotopes. However, because the study area is dominated by drought-tolerant plants and the fractionation effect of their roots may be relatively weak, the model assumptions remain reasonable

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3.2 Regional ecohydrological mechanisms and sustainability prospects for GDEs

Isotopic evidence for plant water sources revealed a clear water-use differentiation mechanism between herbaceous plants and shrubs in the study area. The δ^2H and δ^{18}O values of shrubs were more positive than those of herbaceous plants at the numerical level, indicating that the water sources on which they relied had longer residence times and more stable isotopic compositions. Their total utilization rate of middle–deep soil water (0.5–3 m) and groundwater was as high as 79.6%, consistent with the water-use characteristics of deep-rooted plants. This finding mutually corroborates classical theory and previous studies. Dawson et al.

[27]

pointed out that the evaporative fractionation effect in dry-region deep-rooted plants is weak, and the isotopic values of their xylem water are closer to those of the water sources they use; Xu

[28]

also confirmed that the isotopic composition of deep-rooted plants tends to be biased toward more enriched deep soil water, whereas the isotopic values of shallow-rooted plants are more strongly affected by surface soil water, further confirming the stability-oriented strategy of shrub ecology and its dependence on deeper layers. The enrichment of shrub isotopic values may be related to the sampling time (autumn); deep soil water, enriched in heavy isotopes due to residual summer evaporation, meant that the study failed to capture the effects of early-growing-season snowmelt or summer precipitation on plant water sources. For example, studies on the Qinghai–Tibet Plateau have shown that alpine meadow plants rely significantly on shallow meltwater during the snowmelt period

[29]

. Using changes in soil-water δ^{18}O with depth to estimate contributions to plant xylem water use has already been widely applied

[30]

. As depth increases, soil-water δ^{18}O values become more negative; this more negative value may result from preferential recharge by precipitation in colder seasons or at higher elevations

[31–32]

. Therefore, multi-season continuous monitoring is urgently needed in the future to clarify the seasonal elasticity and transition thresholds of different plants' dependence on groundwater. This is a prerequisite for assessing the vulnerability of GDEs and is crucial for refined management and ecological water-demand assessment of GDEs.

Against the background of global climate change, the Urumqi River Basin is facing the dual pressures of rising temperatures and changes in precipitation patterns, which may fundamentally alter the existing ecohydrological balance. On the one hand, intensified soil evaporation caused by warming may reduce shallow soil-water availability, forcing herbaceous plants to expand toward deeper layers and directly compete with shrubs for water; on the other hand, groundwater over-extraction or reduced precipitation will directly threaten deep-water …

stability of sources, thereby affecting regional community structure; similar ecological degradation has already appeared in desert ecosystems in the southwestern United States

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. Therefore, to ensure the long-term sustainability of GDEs, the above ecohydrological mechanisms must be incorporated into the core of management practice. First, ecological groundwater-level thresholds should be delineated according to the water-use strategies of different plants—especially key shrub species—and incorporated into basin water-resource early-warning and allocation systems, so as to guarantee their ecological water demand at the end of the growing season (September–October). Second, future ecohydrological models need to integrate feedback mechanisms between plant water-use strategies and groundwater dynamics, and simulate the evolutionary trajectories of GDEs under different climatic conditions, thereby providing quantitative support for adaptive management strategies such as vegetation restoration, groundwater-abstraction permitting, and ecological water replenishment. Only by achieving the transition from "phenomenon analysis"to "mechanism prediction"and then to "management intervention" can the function and stability of ecological barriers in arid regions be effectively maintained.

4 Conclusions

Through quantitative analysis using stable hydrogen and oxygen isotope tracing and the stable-isotope Bayesian mixing model framework (MixSIAR), this study constructed an analytical framework of "water source–vegetation strategy–GDEs health."It systematically revealed the water-source utilization strategies of herbaceous and shrub plants in the Urumqi River Basin and clarified the mechanisms by which these strategies affect the stability of GDEs. Shrubs exhibited typical "deep-layer dependence,"with their utilization proportion of 2–3 m soil water and groundwater reaching as high as 48.4%; by contrast, herbaceous plants mainly used mid-layer soil water at 0.5–2 m (53.6% in total), and their dependence on deep water sources (37.6%) was significantly lower. This phenomenon of vertical ecological-niche differentiation clearly indicates that maintaining the dynamic stability of deep soil water and groundwater is a key prerequisite for ensuring the structural and functional health of groundwater-dependent ecosystems in this region, such as deep-rooted shrub communities. Future research can improve understanding of "water source–vegetation strategy" at a dynamic level through continuous multi-season monitoring; in combination with environmental covariates such as soil texture and groundwater depth, it can further clarify the causal mechanisms of "environment-plant-water source." In summary, by integrating plant water-use strategies with GDEs health assessment, this study deepens understanding of the mechanisms underlying plant-water relationships in arid regions and provides an operable decision-making basis for the coordinated management of water resources and ecosystems at the basin scale.

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Analysis of plant water sources in the Urumqi River Basin and its implications for identifying groundwater-dependent ecosystems in arid regions

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Abstract: Water resources are a critical factor influencing ecosystem stability and vegetation growth in arid regions. Analyzing plant water sources within river basins is essential for elucidating ecological hydrological processes in these areas. This study focuses on the Urumqi River Basin, a typical groundwater-dependent ecosystem (GDE), as its research area. Using hydrogen and oxygen isotope tracing techniques, direct comparison methods, and two mixing models (IsoSource and MixSIAR: mixing stable isotope analysis in R), we investigated the water sources utilized by vegetation. We quantitatively assessed the relative contributions of atmospheric precipitation, surface water, soil water, and groundwater to plant xylem water and evaluated their impacts on GDEs. Results show that the local meteoric water line is $\delta^2\text{H} = 6.96\delta^{18}\text{O} + 4.44$ ($R^2 = 0.95$). Xylem water isotope values fell entirely within the range of soil water and groundwater. Direct comparison revealed ecological niche differentiation in water source use between herbaceous plants and shrubs. Evaluation of model performance at the category level using bias and mean absolute error demonstrated that the MixSIAR model was more stable than the IsoSource model, with the latter exhibiting a significant systematic negative bias of −8.481‰ in δ^2H predictions for shrubby plants. Model results indicate that shrubs derive

48.4% of their water from deep soil water (2.5–3 m) and groundwater, reflecting their dependence on deep water sources. Significant fluctuations in deep soil water and groundwater could therefore directly threaten shrub survival and potentially trigger GDEs degradation or collapse. Consequently, shrub water use patterns serve as a sensitive indicator for assessing GDEs health. This study integrates plant water source analysis within the broader framework of GDEs conservation, establishing a research pathway linking water sources, vegetation strategy, and GDEs health. It provides a scientific basis for vegetation restoration, water resource management, ecological groundwater level delineation, and GDEs conservation in the Urumqi River Basin, contributing to the sustainable protection of ecological barrier functions in arid regions.

Keywords: analysis of plant water sources; groundwater-dependent ecosystems (GDEs); hydrogen and oxygen isotopes; direct comparison method; MixSIAR model; the Urumqi River Basin

Note: Figure translations are in progress. See original paper for figures.