# Postprint of a Study on the Extent of Phreatic Evaporation Influence Based on Stable Hydrogen and Oxygen Isotope Characteristics

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## Abstract

Arid oasis areas in Xinjiang play important roles in ecological protection and water conservation. Groundwater within these areas not only provides valuable freshwater resources but also serves as the primary water source for plants. Conducting research on the influence degree of phreatic evaporation is of great significance for analyzing soil water movement, the transformation relationship between soil water and groundwater, and plant water utilization in arid oasis areas. This study investigated the soil profile characteristics of typical vegetation growth areas, including Populus euphratica and Tamarix ramosissima, in the arid oasis area of the lower Tarim River in Xinjiang using environmental isotopes and soil physical and chemical analysis methods.

Results show that the arid oasis area in the lower Tarim River has intense phreatic evaporation and capillary action, which significantly affect the fractionation of hydrogen and oxygen stable isotopes in soil water as well as the distribution of soil water content and soil salinity; from the phreatic water table upward, as height increases, the hydrogen and oxygen stable isotope values of soil water gradually decrease, reaching a minimum at 1~1.5 m and then gradually increase; soil water content gradually decreases, with the rate of decrease slowing down at 1~1.5 m; soil salinity remains generally stable near the phreatic water table and begins to gradually increase at 1~1.5 m; integrating soil profile data from different vegetation growth areas reveals that the depth of phreatic evaporation influence in this area during autumn is 1~1.5 m. Utilizing the fractionation characteristics of hydrogen and oxygen stable isotopes to study phreatic capillary rise height and evaporation depth in arid oasis areas can provide information unattainable through traditional hydrogeology and phreatic evaporation experiments.

## Full Text

# Study on the Influence Degree of Phreatic Evaporation Based on Hydrogen and Oxygen Stable Isotope Characteristics

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## Abstract

Arid oasis areas in Xinjiang play a crucial role in ecological protection and water conservation. Groundwater in these regions not only provides valuable freshwater resources but also serves as the primary water source for vegetation. Investigating the influence of phreatic evaporation is essential for understanding soil water transport, the transformation relationship between soil water and groundwater, and plant water utilization in arid oasis zones. This study employed environmental isotope, soil physical, and chemical analysis methods to examine soil profile characteristics in typical vegetation growth areas, including *Populus euphratica* and *Tamarix ramosissima*, in the arid oasis region of the lower Tarim River basin, Xinjiang. The results demonstrate that the lower Tarim River region experiences intense phreatic evaporation and capillary action, significantly affecting the fractionation of hydrogen and oxygen stable isotopes in soil water, as well as the distribution of soil moisture content and salinity. Moving upward from the water table, hydrogen and oxygen stable isotope values in soil water gradually decrease, reaching a minimum at 1-1.5 m above the water table before increasing again. Soil moisture content decreases progressively, with the rate of decline slowing at 1-1.5 m. Soil salinity remains relatively stable near the water table but begins to increase gradually at 1-1.5 m. Integration of soil profile data from different vegetation zones indicates that the influence depth of phreatic evaporation in this region during autumn is 1-1.5 m. Utilizing the fractionation characteristics of hydrogen and oxygen stable isotopes to study phreatic capillary height and evaporation depth in arid oasis areas can provide information unattainable through traditional hydrogeological methods and phreatic evaporation experiments.

**Keywords:** capillary height; phreatic evaporation depth; hydrogen and oxygen stable isotopes; arid oasis area; Xinjiang

## Introduction

The arid oasis area in the lower reaches of the Tarim River, Xinjiang, is located at the southern foothills of the Tianshan Mountains and the northeastern edge of the Tarim Basin, deep in the hinterland of the Eurasian continent, far from the ocean. It belongs to a typical continental arid climate zone with strong evaporation, scarce rainfall, and ecologically fragile oases. Water resources are the most critical constraint factor for economic development and ecological environment construction in the region [citation]. Strong atmospheric evaporation is the main driving force for upward soil water movement [citation], and for phreatic water, dissipation is mainly supplied to soil evaporation through capillary action upward [citation]. Currently, there are few reports on the comparison and patterns of parameters such as hydrogen and oxygen stable isotopes, soil moisture content, and salinity in the vertical depth of the vadose zone in Xinjiang' s arid oasis areas. Therefore, studying the mechanisms of soil capillary water rise, especially phreatic capillary action and evaporation, and determining their influence range is of great significance for analyzing soil water transport, the transformation relationship between soil water and groundwater, and plant water utilization.

The application of hydrogen and oxygen stable isotopes in phreatic evaporation research began in the [decade] years, mainly experiencing studies on steady-state evaporation in saturated soils, constant and non-constant temperature steady-state evaporation in unsaturated soils, and hydrogen and oxygen stable isotope movement under non-steady-state evaporation conditions in unsaturated soils [citation]. Research suggests that phreatic water and soil water movement are closely related to groundwater depth, and are also affected by factors such as atmospheric evaporation, surface coverage, vadose zone structure, and microgeomorphology [citation]. When soil moisture content is greater than the water-holding capacity of oasis soils, soil water will continuously supply soil evaporation through capillary action; conversely, soil evaporation will decrease as soil moisture content decreases. When soil moisture content drops to the capillary rupture moisture content, water movement can only proceed through molecular diffusion [citation]. The influence depth is mainly determined through field experiments, laboratory tests, or calculated using the Haisen formula, and fruitful results have been achieved [citation]. Since water in the capillary zone can be considered saturated or near-saturated, the capillary zone can also be regarded as an extension of the saturated zone.

This study employed fine vertical soil profile excavation to investigate the vadose zone structure and plant root distribution in typical vegetation growth areas such as *Populus euphratica* and *Tamarix ramosissima* in arid oasis regions. We conducted tests on soil moisture content, soil salinity, and hydrogen and oxygen stable isotopes of groundwater, soil water, and plant water in the profiles, and analyzed the vertical distribution curve data to reveal the influence depth of phreatic evaporation and soil water movement patterns in the area during autumn, providing a scientific basis for rational water resource development and ecological environment protection and restoration in the lower Tarim River arid oasis area.

## 1. Study Area Overview

The arid oasis area in the lower reaches of the Tarim River, Xinjiang, is located in the northeastern part of the Tarim Basin [Figure 1: see original paper], between the Taklamakan Desert and the Kumtag Desert (86°34 ~88°00 E, 40°30 ~41°05 N). It borders the Kongque River to the north and the Tarim River to the south. The terrain is flat, with most elevations below 855 m, sloping from west to east and from south to north. The area consists mainly of alluvial plains and large desert and wind-eroded lands. The region has a typical desert arid climate with abundant sunshine, an average annual temperature of 10.8°C, average annual precipitation of 34.7 mm, and average annual evaporation reaching 2408.6 mm. Except for a few areas with irrigation conditions where natural vegetation has been replaced by artificially cultivated vegetation, most of the region remains uncultivated saline wasteland, maintaining natural vegetation growth [citation]. This area is an important population gathering place for the Xinjiang Production and Construction Corps in southern Xinjiang and a major production area for high-quality cotton in China, playing an important role in ecological protection and water conservation, with significant geographical location [citation]. Since water resources, especially groundwater, in this region not only provide precious freshwater resources but are also the main source of water for plants, they affect local ecology, production, and living conditions.

This study selected moderately growing *Tamarix ramosissima* and *Populus euphratica* areas as research objects, with total coverage of 25.38% and 35.79% respectively. The sampling point distribution is shown in [Figure 1: see original paper]. Due to the distribution of many ancient river channels and oxbow lakes in the study area, the differentiation of sedimentary environments results in vadose zone lithology mainly consisting of fine sand, medium-fine sand, and silty clay, which facilitates the evaporation of soil water and phreatic water.

## 2. Research Methods

In early October, artificial soil drilling and vertical profile excavation were primarily used to reveal vadose zone structure and plant root distribution. To avoid errors from long-term exposure to air, profile excavation was conducted in the early morning until the water table was exposed, obtaining a complete unsaturated zone soil profile. The profile specifications were 2.2 m × 1.8 m, and soil samples were collected every 20 cm on the profile for analysis of soil moisture content and salinity; soil water isotope samples were collected as much as possible while considering soil texture, and plant xylem water isotope samples were collected during the period.

**2.1 Soil Moisture Content Testing** Undisturbed soil samples greater than 100 g were collected using cutting rings, placed in aluminum boxes, and weighed on an electronic balance with 0.01 g precision to obtain wet soil weight. They were then taken back to the laboratory and dried in a soil drying oven at 110°C, and weighed again to obtain dry soil weight. Soil moisture content (W) was calculated using the following formula:

$$W = \frac{\text{wet soil weight} - \text{dry soil weight}}{\text{dry soil weight}} \times 100\%$$

**2.2 Extraction of Soil Water and Plant Water** Layered soil samples and plant samples collected in the field were quickly placed in sealed bags and then put into a constant temperature box with ice packs and taken back to the laboratory. Plant water isotope samples were extracted using low-temperature vacuum distillation, and soil water extraction used an automatic vacuum condensation extraction system.

**2.3 Testing of Hydrogen and Oxygen Stable Isotopes in Soil Water, Plant Water, and Groundwater** The determination of hydrogen and oxygen stable isotopes in soil water, plant water, and groundwater samples was completed by the Key Laboratory of Groundwater and Ecology in Arid and Semi-arid Areas, Xi' an Center of China Geological Survey. The measurement instrument was a liquid water isotope laser analyzer (analysis precision for $\delta^2$H and $\delta^{18}$O values could reach $±$0.5‰ and $±$0.1‰ respectively). The hydrogen and oxygen stable isotope content in all water samples was expressed as per mil deviation from VSMOW.

**2.4 Soil Soluble Salt Testing** Layered soil soluble salt samples were collected on-site using canvas bags, sealed in fresh-keeping bags, and placed in a constant temperature box with ice packs. During testing, 100 g of soil sample was placed in a polyethylene plastic bottle with 100 mL deionized water, shaken vigorously for 20 min, and the supernatant was taken to directly determine pH and EC values. The remaining supernatant was centrifuged at 10000 $\mathrm{r \cdot min^{-1}}$ for 30 min to obtain a clear solution, which was then used for anion and cation determination. $K^+$ and $Na^+$ contents were determined by inductively coupled plasma spectrometry (ICP), $Ca^{2+}$ and $Mg^{2+}$ contents were determined by ion chromatography, and $HCO_3^-$ content was determined by titration.

## 3. Results

**3.1 Vadose Zone Structure and Plant Root Distribution in Soil Profiles** As shown in [Figure 2: see original paper], the vadose zone structure in the *Tamarix ramosissima* profile from top to bottom consists of medium-fine sand, fine sand, silt, fine sand, silty clay, and fine sand. The *Tamarix* roots in the profile exhibit a fish-tail shape, mainly composed of fine roots ($d \leq 2$ mm), medium roots (2 mm $< d \leq$ 5 mm), and coarse roots ($d > 5$ mm). The roots extend relatively long, indicating that the hydrotropic nature of *Tamarix* roots promotes expansion to more distant areas, and root biomass decreases with increasing profile depth, suggesting that *Tamarix* mainly absorbs and utilizes shallow soil water and nutrients.

The *Populus euphratica* profile ([Figure 3: see original paper]) vadose zone structure from top to bottom consists of fine sand, silt, and interbedded clayey silt. The *Populus* root distribution in the profile is asymmetric, mainly composed of fine roots (d $\leq$ 2 mm), coarse roots (10 mm $<$ d $\leq$ 50 mm), and large roots (d $>$ 50 mm), with well-developed lateral roots and strong spatial extension capability, indicating that *Populus* roots seek required nutrients and water through horizontal extension. Some dead roots are concentrated mainly within 30 cm of the surface, indicating that dead root distribution is closely related to water distribution, and most dead roots are fine roots, suggesting that fine roots have the most active metabolism.

**3.2 Soil Moisture Content and Salinity in Profiles** From the vertical distribution perspective, soil profile moisture content generally shows an increasing trend from the surface to the phreatic surface. However, due to constraints from vadose zone lithology structure and surface coverage, the patterns of salinity change vary at different depths. In the *Tamarix* profile ([Figure 2: see original paper]), soil moisture content gradually increases with depth. Due to the influence of silt interlayers, moisture content is relatively high at 30–50 cm depth, and subsequently the rate of increase slows down, with moisture content gradually increasing to the phreatic surface. The *Populus* profile ([Figure 3: see original paper]) also shows that soil moisture content gradually increases with depth. Due to clay layer influence, moisture content is relatively high at 50 cm depth, after which the rate of change decreases, and moisture content gradually increases to the phreatic surface.

The overall trend of soil salinity in the profile shows a decrease with increasing depth. However, due to different topographic and hydrogeological conditions, the patterns of salinity change in the vadose zone vary. Salinity in the shallow vadose zone changes significantly with depth, reaching a certain depth after which salinity tends to stabilize at a certain value. The *Tamarix* profile ([Figure 2: see original paper]) shows that soil salinity first gradually increases with depth, with the highest salinity near the surface at 100 cm depth. Subsequently, salinity decreases with an increasing rate of change, stabilizing at 150 cm depth. The *Populus* profile ([Figure 3: see original paper]) shows that soil salinity gradually decreases with depth, with the highest surface soil salinity. After 100 cm depth, the rate of salinity change slows down, stabilizing at 150 cm depth.

**3.3 Vertical Distribution of Hydrogen and Oxygen Stable Isotopes in Soil Water** As shown in [Figure 4: see original paper], the hydrogen and oxygen stable isotopes in the *Tamarix* profile soil water exhibit the following patterns: isotope values gradually decrease with increasing vadose zone depth and tend to stabilize, approaching phreatic water values when stable. Phreatic water isotope values are generally lower than soil water, and both are lower than rainwater. Relative to soil water, groundwater has a higher renewal rate, which dilutes phreatic water isotopes. From the phreatic surface upward, soil water isotope values first decrease to a minimum at approximately 1.0 m depth, then gradually increase to a maximum at approximately 50 cm depth, reaching extremely low values at the profile surface.

The *Populus euphratica* profile ([Figure 5: see original paper]) soil water hydrogen and oxygen stable isotopes show similar patterns: isotope values gradually decrease with increasing vadose zone depth and approach phreatic water values. Phreatic water isotope values are generally lower than soil water, and both are lower than rainwater. From the phreatic surface upward, soil water isotope values first decrease to a minimum at approximately 1.5 m depth, then gradually increase to a maximum at approximately 50 cm depth, reaching extremely low values at the profile surface.

## 4. Discussion

**4.1 Sources of Soil Water Recharge** Hydrogen and oxygen stable isotopes are called the "fingerprint" of water because, as components of water molecules, they differ from general solutes [citation]. As a new research method, they can trace water movement at point and watershed scales. Due to scarce precipitation and absence of stable surface runoff in the lower Tarim River arid oasis area, soil water sources include atmospheric precipitation and groundwater, except for artificial irrigation. From the vertical distribution of soil water hydrogen and oxygen stable isotopes in different vegetation profiles, soil water values are lower than both phreatic water and rainwater, indicating that soil water does not originate from atmospheric precipitation but is supplied by phreatic water. After replenishment, it moves upward in the vadose zone under strong capillary action and evaporation, gradually mixing with vadose zone water, and undergoes continuous fractionation and enrichment in the shallow surface layer. The extremely low values in the surface layer may be due to the large temperature difference between day and night in arid oasis areas. During morning sampling, some atmospheric condensation water may have caused depletion of hydrogen and oxygen stable isotopes in shallow soil water [citation], resulting in extremely low isotope values.

**4.2 Sources of Plant Water** By comparing the hydrogen and oxygen stable isotope composition of plant xylem water with potential water sources, we can preliminarily determine the water source for plants at different sample sites. If an intersection point exists, the corresponding water source at that point is the main water source for the plant [citation]. This method can only qualitatively determine plant water sources but cannot quantify plant water utilization rates. From the distribution of hydrogen and oxygen stable isotopes in *Tamarix*, $\delta^2$H values range from ‰, which is smaller than both phreatic water and rainwater $\delta^2$H values, intersecting with soil water near 1.0 m depth. $\delta^{18}$O values show similar patterns, being smaller than both phreatic water and rainwater values, intersecting with soil water near 1.0 m depth. Since $\delta^{18}$O is more stable and less prone to fractionation during plant absorption, this indicates that *Tamarix* may mainly absorb soil water from the vadose zone near 1.0 m depth.

From the distribution of hydrogen and oxygen stable isotopes in *Populus*, $\delta^2$H values range from ‰, and $\delta^{18}$O values range from ‰. These values are greater than phreatic water $\delta^2$H values but smaller than rainwater $\delta^2$H values, intersecting with soil water near 0.8–2.5 m depth, indicating that *Populus* may mainly absorb soil water from the vadose zone at 0.8–2.5 m depth.

**4.3 Influence Degree of Phreatic Evaporation** According to physical fractionation principles, moving upward from the phreatic surface, as capillary action decreases, hydrogen and oxygen stable isotopes are gradually diluted and reach a certain height, i.e., the capillary height. In molecular diffusion processes caused by adsorption and desorption, diffusion velocity is inversely proportional to the square root of molecular mass. Therefore, light isotopes are enriched at the front of diffusion, while heavy isotopes remain behind. From the surface downward, as evaporation increases, hydrogen and oxygen stable isotopes are gradually diluted and reach a certain depth, i.e., the evaporation depth. In molecular diffusion processes caused by evaporation and condensation, diffusion velocity is inversely proportional to the square root of molecular mass. Thus, light isotopes are enriched in the shallow part of the evaporation surface, while heavy isotopes remain in the deeper part [citation].

Therefore, based on the distribution of soil water hydrogen and oxygen stable isotopes in [Figure 4: see original paper], the capillary height at this point can indirectly reach above 1.5 m depth. Based on the distribution in [Figure 5: see original paper], the capillary height can indirectly reach 1.5 m depth, and evaporation occurs above 1.5 m depth. This is basically consistent with the distribution curves of soil moisture content and salinity in the profiles. [Figure 2: see original paper] shows that from the phreatic surface upward, soil profile moisture content gradually decreases to the 100 cm position, after which the rate of decrease slows down, reaching the lowest value at the surface. Soil profile salinity remains relatively stable near the phreatic surface, but begins to increase gradually at 150 cm depth, reaching the highest value near the surface. [Figure 3: see original paper] similarly shows that from the phreatic surface upward, soil profile moisture content gradually decreases to the 150 cm position, after which the rate of decrease slows down, reaching the lowest value at the surface. Soil profile salinity remains relatively stable near the phreatic surface, but begins to increase gradually at 150 cm depth, reaching the highest value at the surface. Overall, this reflects strong phreatic evaporation and capillary action in the region.

## 5. Conclusions

1) In Xinjiang’ s arid oasis areas, strong atmospheric evaporation and soil capillary action are the main driving forces for upward soil water movement in the vadose zone. Phreatic water in the region not only provides abundant soil water but is also the main source of water for plants.
2) Moving upward from the phreatic surface, the vertical distribution of hy-

drogen and oxygen stable isotopes in soil water shows that values gradually decrease with increasing height, reaching a minimum at 1-1.5 m and then gradually increasing. Soil moisture content in the profile gradually decreases, with the rate of decrease slowing at 1-1.5 m. Soil salinity in the profile remains relatively stable near the phreatic surface, but begins to increase gradually at 1-1.5 m.

3) Integrating the distribution of hydrogen and oxygen stable isotopes, soil moisture content, and soil salinity in the soil profile reflects strong phreatic evaporation and capillary action in the arid oasis area of the lower Tarim River. Due to the significant influence of water movement on the physical fractionation of hydrogen and oxygen stable isotopes, this indirectly indicates that the influence depth of phreatic evaporation in this region during autumn may be 1-1.5 m.

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