# Soil Water Infiltration Patterns in the Southern and Northern Mountains of Lanzhou Based on Stable Isotopes (Post-print)

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## Abstract

Based on precipitation and soil water isotope data at different altitudes on the north and south mountains of Lanzhou City from April to October 2018, this study quantitatively analyzed the soil water infiltration process in these areas using the lc-excess method and lc-excess balance equation. The results show that soil water lc-excess indicates the coexistence of piston flow and preferential flow modes during the soil water infiltration recharge process in the study area. During July–August, preferential flow signals appeared at all sampling sites. The lc-excess balance equation demonstrates that the contribution rate of piston flow mode to deep soil water is approximately 70%, while that of preferential flow is about 30%. Soil water content is positively correlated with soil water lc-excess. No significant differences in soil water lc-excess were observed between the north and south mountains at the monthly scale or in depth, indicating that the deep soil water infiltration recharge patterns are consistent in both mountains, originating from piston flow of upper soil water percolation. However, preferential flow mode occurred more frequently on the South Mountain with higher vegetation coverage, especially during July–August when precipitation was concentrated. The findings of this study provide a theoretical reference for understanding the hydrological processes in the loess hilly region of Lanzhou's north and south mountains.

## Full Text

### Soil Water Infiltration Process in North and South Mountains of Lanzhou City Based on Stable Isotope

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## Abstract

Based on precipitation and soil water isotope data at different elevations in the north and south mountains of Lanzhou from April to October 2018, this study employed the lc-excess method and lc-excess equilibrium equation to qualitatively and quantitatively analyze the soil water infiltration process in the study area. The soil water lc-excess values revealed that both piston flow and preferential flow modes coexist during soil water infiltration and recharge. Priority flow signals appeared at all sampling sites from July to August. The lc-excess equilibrium equation indicated that the piston flow mode contributed approximately 70% to deep soil water, while the preferential flow mode contributed approximately 30%. Soil water content showed a positive correlation with soil water lc-excess. No significant differences in soil water lc-excess were observed between the north and south mountains across monthly scales and depths, indicating consistent deep soil water recharge patterns in both areas, primarily from piston flow infiltration of upper soil water. However, preferential flow signals appeared more frequently in the south mountains with higher vegetation coverage, especially during the precipitation-concentrated months of July-August. These results provide theoretical reference for understanding hydrological processes in the loess hilly region of Lanzhou's north and south mountains.

**Keywords:** stable isotope; lc-excess method; piston flow; preferential flow; north and south mountains of Lanzhou

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## 1. Introduction

Water is an indispensable resource for life, and soil water constitutes a vital component of water resources that plays a crucial role in ecosystems. Infiltration represents an important form of soil water movement and serves as a bridge connecting surface water and groundwater. Early soil water research primarily focused on ideal conditions of homogeneous soils, where water percolates layer by layer downward and the soil matrix acts as a filter. Since the 1980s, the discovery of pesticides and other contaminants in groundwater that should have been filtered by the soil matrix has made preferential flow a hot research topic, marking a shift from homogeneous to heterogeneous soil studies. Over the past 40 years, water conflicts have made the study of soil water infiltration mechanisms for groundwater recharge a focal issue. Quantifying the contribution rates of different infiltration modes to groundwater recharge is essential for assessing both the quantity and quality of groundwater resources, particularly in arid and semi-arid regions with deep groundwater tables where different infiltration patterns critically affect deep soil water recharge processes.

In infiltration studies, isotopic technology offers unique advantages for tracing water movement paths compared to traditional techniques. However, due to the complexity of soil water infiltration processes, quantifying recharge amounts remains challenging. Recent studies have combined soil water and precipitation isotopic compositions with Bayesian mixing models (MixSIAR) to quantify the relative contributions of piston flow and preferential flow modes to groundwater. However, compared to Bayesian mixing models, the lc-excess balance equation offers simpler operation while yielding consistent results.

Since the 1990s, stable isotope technology has been widely applied due to its safety and non-polluting characteristics. With continuous advancements in soil water extraction technology, stable isotopes have further demonstrated unique advantages in tracing soil water infiltration processes and recharge sources. Studies have shown that under different precipitation events, isotopic compositions of soil water at different depths exhibit significant differences, leading to the proposal of two soil water infiltration modes: piston flow and preferential flow. In piston flow mode, new water in soil slowly pushes old water deeper, whereas in preferential flow mode, new water can reach deep soil layers rapidly through preferential pathways. Research indicates that both modes can occur simultaneously, though external environmental factors such as rainfall intensity, land use type, and surface conditions may cause shifts in infiltration patterns.

Lanzhou City, located on the western edge of the Loess Plateau, features a fragile ecological environment due to its natural conditions and geographical location. Since the 1990s, the north and south mountains greening project has restored the ecological environment to some extent, but has also highlighted water use conflicts in these areas. Therefore, studying soil water infiltration processes in Lanzhou's north and south mountains holds significant importance. Previous studies in this region have primarily used traditional methods, while isotopic technology can reveal water movement processes in soil. Based on the current water use situation in Lanzhou's north and south mountains, this study selected precipitation and soil water isotope data from different elevations to investigate soil water infiltration patterns and the contribution rates of different modes to deep soil water, providing theoretical basis for understanding hydrological processes in Lanzhou's loess hilly region.

### 1.1 Study Area Overview

Lanzhou's north and south mountains (35°34 ~37°07 N, 102°35 ~104°34 E) are located in the western Loess Plateau of China. The terrain is higher in the southwest and lower in the northeast, with an average urban elevation of approximately 1500 m. The study area features a temperate semi-arid continental monsoon climate with no severe summer heat or winter cold. Precipitation is scarce and concentrated in summer, with distinct seasons, an annual average temperature of 7.4°C, and annual average precipitation of 312.9 mm. Soils are primarily sierozem developed on loess parent material, with dark sierozem and typical sierozem in the south mountains and light sierozem and red sandy soil in the north mountains. Vegetation coverage is low with single species composition, dominated by xerophytic and halophytic plants.

### 1.2 Methods

**1.2.1 Sample Collection** Samples were collected from April to October 2018. Soil samples were collected monthly at sampling sites with uniform surface conditions (bare land). At each site, soil profiles were excavated to 120 cm depth, and samples were collected at 20 cm intervals. Two parallel samples were collected at each depth: two were placed in aluminum boxes for soil water content measurement, and two were sealed in 10 mL glass bottles for hydrogen and oxygen stable isotope analysis.

Precipitation samples were collected using standard rain gauges placed at each sampling site. After each precipitation event, samples were immediately transferred to 50 mL plastic bottles and sealed with Parafilm to prevent evaporation-induced isotopic fractionation.

Meteorological data including temperature, precipitation, and relative humidity were obtained from the China Meteorological Data Network (http://data.cma.cn) for Yongdeng (west of the airport) and Gaolan (Baoling Lingxiushan) stations. Data from Lanlian Zaolinchang and Renjiazhuang were provided by the Lanzhou Meteorological Bureau.

**1.2.2 Sample Measurement** All samples were analyzed at the Stable Isotope Laboratory of the College of Geography and Environmental Science, Northwest Normal University. Soil water was extracted using a LI-2100 fully automatic low-temperature vacuum extraction system (Beijing LICA United Technology Limited) with vacuum pressure controlled below -1 Pa • s, heating temperature at 105°C, and extraction time of 120 minutes. Random samples were weighed after extraction to ensure efficiency.

Isotopic compositions were measured using a Los Gatos Research DLT-100 liquid water isotope analyzer. Each sample was injected six times, with the first two injections discarded due to memory effects and the remaining four averaged. Measurement precision was $±$0.5‰ for $\delta^{2}$H and $±$0.1‰ for $\delta^{18}$O.

**1.3 lc-excess Method** The lc-excess (line-conditioned excess) method mathematically expresses the relationship between hydrogen and oxygen stable isotope ratios. When water undergoes equilibrium processes such as condensation, lc-excess values are typically positive; when experiencing non-equilibrium processes like evaporation, values become negative. Based on this principle, local atmospheric precipitation generally shows lc-excess values around 0‰, while evaporated water exhibits negative values. The calculation formula is:

$$lc\text{-}excess = \delta^{2H} - \alpha\delta^{18}O - b$$

where $\alpha$ is the slope and b is the intercept of the local meteoric water line (LMWL), fitted from local precipitation isotope data: $\delta^2$H = 6.82 ± 0.38$\delta^{18}$O + 2.59 ± 2.54.

**1.4 lc-excess Equilibrium Equation** During soil water infiltration, piston flow and preferential flow modes exhibit distinct isotopic compositions. Therefore, a two-component isotopic mass balance can calculate their relative contributions:

$$f_{\text{piston flow}} = \frac{lc_{\text{deep soil water}} - lc_{\text{preferential flow}}}{lc_{\text{piston flow}} - lc_{\text{preferential flow}}}$$

where $f_{\text{piston flow}}$ represents the relative contribution rate of piston flow mode, and the preferential flow contribution rate can be calculated as $1 - f_{\text{piston flow}}$. The $lc_{\text{deep soil water}}$ values were selected from the 100-120 cm soil layer, $lc_{\text{piston flow}}$ from soil water showing piston flow signals, and $lc_{\text{preferential flow}}$ from monthly precipitation showing clear preferential flow signals.

**1.5 Data Processing** Origin software was used to analyze soil water content, lc-excess values, and stable isotopes. Single-factor ANOVA was applied to test differences, with significance level at $p < 0.05$.

## 2. Results and Analysis

**2.1 Soil Water Content Variation** In the soil vertical profile (0-120 cm), soil water content at different sampling sites varied across monthly scales and depths [Figure 1: see original paper]. Due to external factors, soil water data for May were missing. Overall, soil water content in the north mountains was higher than in the south mountains (north: 5.61%, south: 3.98%). At different elevations, high-altitude sites showed greater soil water content than low-altitude sites (N1 > S1, N2 > S2).

Soil water content showed significant changes at 0-40 cm depth, with greater variation in the north mountains (3.66%-12.60%) than in the south mountains (2.82%-10.77%). The 60-100 cm layer showed the opposite pattern, with more variation in the south mountains (4.27%-16.53%) than in the north mountains (4.75%-9.25%). Soil water content at 40-60 cm depth was notably higher in July (north: 8.70%, south: 16.37%) and August (north: 5.16%) compared to other months.

Precipitation in the study area was concentrated from June to September, accounting for 85.60% of annual precipitation, with maximum precipitation in July (84.90 mm). Soil water content responded to precipitation with a time lag: high monthly cumulative precipitation occurred in July-August, while high monthly average soil water content appeared in August-September. Precipitation stable isotopes were most enriched in April ($\delta^2$H: -29.63‰, $\delta^{18}$O: -5.37‰) and most depleted in July ($\delta^2$H: -94.78‰, $\delta^{18}$O: -13.22‰). Monthly average temperature peaked in July (23.60°C), and relative humidity reached its maximum in September (66.70%) [Figure 2: see original paper].

**2.2 Soil Water Stable Isotope Characteristics** Temporally, soil water $\delta^{18}$O and $\delta^2$H at different sampling sites showed consistent trends [Figure 3: see original paper]. While the timing of maximum isotopic values varied among sites, minimum values consistently appeared in August-September, influenced by depleted precipitation isotopes. North mountain soil water isotopic composition ($\delta^2$H: -57.33‰ to -7.33‰, $\delta^{18}$O: -8.11‰ to -0.59‰) was slightly more enriched than south mountain values ($\delta^2$H: -61.05‰ to -6.11‰, $\delta^{18}$O: -8.78‰ to 1.16‰).

In July, soil water isotopes at 60-80 cm depth in the north mountains were most depleted and distinct from other months. In August, south mountain soil water isotopes at 40-100 cm depth were most depleted. In September, north mountain soil water isotopes at 80-100 cm depth were most depleted.

Spatially, with increasing soil depth, $\delta^2$H and $\delta^{18}$O gradually became depleted and more stable. Conversely, values were more enriched near the surface. The 0-40 cm layer showed large isotopic variations, while the 40-100 cm layer exhibited more stable isotopic compositions. In the 0-40 cm range, north mountains showed smaller variations than south mountains. In the 60-100 cm range, differences between north and south mountains were less pronounced.

**2.3 Soil Water lc-excess Indicating Infiltration Process** During piston flow, soil water moves slowly in layers with extensive mixing between new and old water. During preferential flow, water rapidly reaches deep layers through macropores with minimal mixing. When soil water isotopic composition is closer to precipitation, it indicates less mixing between new and old water.

Temporally [Figure 4: see original paper], soil water lc-excess values showed alternating infiltration recharge and evaporation fractionation. From April to June, lc-excess was negative, indicating dominant evaporation fractionation. July values approached positive, showing infiltration recharge effects. August lc-excess was negative (except at N2), while September values were closest to precipitation, indicating south mountain soil water received precipitation recharge with minimal mixing.

From July to August, all sites showed clear preferential flow signals, with stronger signals in July. South mountains exhibited more preferential flow signals than north mountains. Spatially, lc-excess variation decreased with depth and approached positive values. The 0-40 cm layer showed greater lc-excess variation than the 40-100 cm layer, with more pronounced differences in south mountains [Figure 5: see original paper].

The soil profile was divided into 0-40 cm and 40-100 cm layers based on water content and isotopic characteristics. The 0-40 cm layer experienced both evaporation fractionation and infiltration recharge with large variations, while the 40-100 cm layer remained more stable. Analysis showed that preferential flow signals in the 0-40 cm layer preceded those in the 40-100 cm layer by one month.

Using lc-excess signals, qualitative analysis revealed that piston flow dominated in both north and south mountains, though south mountains showed more preferential flow signals. Quantitative analysis using the lc-excess equilibrium equation showed piston flow contributed approximately 70% to deep soil water, while preferential flow contributed about 30%. Preferential flow contribution rates were higher at low-altitude sites than high-altitude sites, indicating altitude affects infiltration processes.

## 3. Discussion

Soil water content and lc-excess showed positive correlation [Figure 6: see original paper], indicating infiltration recharge increases soil water content. Correlations were stronger in the 40-100 cm layer than in the 0-40 cm layer, suggesting deep soil water is primarily recharged by upper soil water through piston flow with less evaporation influence.

Single-factor ANOVA showed no significant differences in soil water lc-excess between north and south mountains across depths, indicating both areas are dominated by single precipitation-recharged piston flow infiltration with similar isotopic compositions. This aligns with previous studies showing precipitation as the sole recharge source for shallow groundwater in the Loess Plateau, where piston flow dominates though dual infiltration mechanisms coexist.

South mountains showed more preferential flow signals than north mountains. Previous research indicates preferential flow dominates infiltration in some Loess Plateau landscapes, and intense rainfall events ($>$50 mm day$^{-1}$) generate runoff that facilitates preferential flow at topographic lows. Soil macropores, cracks, and fissures also promote preferential flow. South mountains, located on sunny slopes with better light and heat conditions, support more trees and shrubs, creating root channels that enhance preferential flow.

## 4. Conclusion

1) Soil water content in the study area was generally higher in north mountains than south mountains, with variations across monthly scales and depths. Soil water loss dominated from April to June, while accumulation dominated from July to September. High-altitude sites showed greater wa-

ter content than low-altitude sites. Precipitation was concentrated from June to September, with isotopes most enriched in April and most depleted in July.

2) Soil water stable isotopes $\delta^{18}$O and $\delta^{2}$H showed consistent trends across sites, with minimum values in August-September. North mountain isotopic values were slightly more enriched than south mountains. With increasing depth, soil water isotopes became depleted and stabilized, with greater variation in the 0-40 cm layer.

3) Soil water lc-excess revealed dual infiltration modes coexisting in the study area, with piston flow dominating. Preferential flow signals appeared frequently from July to August, more so in south mountains than north mountains. Low-altitude sites showed higher preferential flow contributions than high-altitude sites. Soil water content correlated positively with lc-excess.

These findings provide theoretical reference for understanding hydrological processes in Lanzhou's loess hilly region and suggest that vegetation restoration should consider these infiltration characteristics for sustainable water resource management.

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**Table 1** Sampling point information
**Table 2** The relative contribution rate of piston flow and preferential flow model to deep soil water

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

*Source: ChinaXiv — Machine translation. Verify with original.*