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Influence of Spring Water Residence Time on the Irrigation Water Stability in the Hani Rice Terraces

Kun Wei [1], Yuanmei Jiao [1,*], Guilin Zhang [2], Ying Wang [1] and Hua Zhang [3]

1 Provincial Key Laboratory of Plateau Geographic Processes and Environmental Change, Faculty of Geography, Yunnan Normal University, Kunming 650500, China; wwwweikun95@163.com (K.W.)
2 School of Metallurgy and Materials, Wenshan University, Wenshan 663099, China
3 Key Laboratory of Geohazard Forecast and Geoecological Restoration in Plateau Mountainous Area Plateau mountains, Ministry of Natural Resources of the People′s Republic of China, Yunnan Institute of Geo-Environment Monitoring, Kunming 650216, China
* Correspondence: ymjiao@sina.com

Abstract: The stability of irrigation water is critical for the sustainability of alpine agriculture. Based on monthly precipitation and terraced field water and spring water samples obtained between 2015 and 2016, the study used the mean residence time and isotope mixing model to analyze the influence of spring water residence time on irrigation water stability in the Hani Rice Terraces. The results indicate that: (1) The mean residence time of precipitation and terraced field water in spring water was 2.46 years and 1.55 years, respectively, implying that the terraced field's irrigation water source could be refilled by spring water recharged 1.5–2.5 years ago. (2) The mean residence time of precipitation in ascending and descending springs was 2.73 years and 1.95 years, respectively. The mean residence time of terraced field water in ascending and descending springs was 1.54 years and 1.04 years, respectively. The ascending spring's recharge water residence time is 0.5–0.8 years longer than that of the descending spring, indicating that the spring water exhibits intra-seasonal and inter-seasonal staggered peak recharging. At the same time, the total recharge period of the ascending–descending spring is extended to 1–3 years, which means the terraced fields have a drought resistance of three years. (3) The mean residence time of precipitation and terraced field water at higher altitudes in the ascending spring is 2.52 times and 3.73 times, respectively, while in the descending spring, it is 3.36 times and 6.49 times to the lower altitude region. This means that the mean residence time of the recharge water source in the lower terraced fields was shorter, and the elevation difference between ascending and descending springs was smaller, thereby regulating the spatial homogeneous distribution of recharge water sources in the terraced fields.

Keywords: Hani Rice Terraces; hydrogen and oxygen isotopes; mean residence time; spring recharge-discharge ratio; the stability of irrigation water sources

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1. Introduction

Groundwater is an important freshwater resource for ecosystems and human survival [1], but it is at risk of being depleted and is difficult to regenerate as a result of the effects of global climate change, over-abstraction by humans, and pollution, especially in mountainous and irrigated agricultural areas where water resources are scarce [2–4]. Therefore, in order to achieve effective management and sustainable utilization of groundwater resources, a comprehensive scientific understanding of the sources of groundwater recharge, the transportation and transformation process of groundwater flow, and understanding the transit time of groundwater and its renewal capacity are critical to solving the above problems.

The stable isotope of hydrogen and oxygen, as a natural tracer, can be efficiently applied in the study of the water cycle [5–7]. Mean residence time (MRT) is the average time water spends in a subsurface system before it emerges as surface flow [8]. Because biogeochemical reactions are time-dependent, MRT can provide valuable insights into the hydro-chemical systems within a watershed and the effects of the catchment recharge-discharge of water on human activities. MRT can also serve as an effective indicator of water storage, flow path, and sources [9,10]. Currently, studies on the residence time of groundwater based on stable isotopes of hydrogen and oxygen are currently being conducted to examine the interactions between various water bodies, such as surface water to groundwater, precipitation to groundwater, and soil water to groundwater. The factors influencing these interactions, including watershed area, slopes, soil depth, and physicochemical properties of the soils, have also been analyzed [8,11–16]. Generally speaking, the smaller the watershed area, the steeper the slope, and the thinner the soil layer, the shorter the water residence time and the longer the time [17].

The Honghe Hani Rice Terraces are the only rice terraces in southern China that were inscribed on the UNESCO World Heritage of Cultural Landscapes in 2013. It is mainly located in the Quanfuzhuang watershed on the leeward slopes of the southern portion of the Ailao Mountain in the southwestern region of China [18–22]. The basin has abundant precipitation with two main east–west tributaries, and the groundwater is mainly exposed by crevice springs formed by rock fissures, which is of high socio-ecological value. The rice farming system has been around for over 1300 years, and water is a key factor in sustaining the longevity of the entire farming system. The Hani terrace irrigation process is not a single rain-fed agricultural irrigation, but a composite agricultural irrigation consisting of precipitation, ditch diversion, upstream terrace water, and spring water [23–28]. However, with the globalization of society and the economy, the transformation and upgrading of the terrace industry, and the rapid development of tourism in the Hani Rice Terraces, the contradiction between people and land has become more and more obvious [19,20]. Due to the influence of global warming, precipitation in the Hani Rice Terraces decreases during the rainy season, and the terraces' primary source of water replenishment during the dry season is groundwater recharge. Local residents indiscriminately cut down the upstream forests and plant understorey cash crops under the forest's water source or economic forests such as cedar trees for the sake of economic benefits, resulting in a decline in the ability of the forest to conserve water [26–28]. However, upstream forested areas can effectively store groundwater, which will have a significant impact on groundwater recharge to terraces in midstream terrace areas [23–25]. The primary issue facing the locals is figuring out how to divide and manage water resources sensibly in order to provide water to terraced agriculture and sustain the steady growth of terraced rice growing.

Currently, research on the stability of irrigation water sources in the Hani terrace agricultural system has been carried out. Liu et al. [19], in conjunction with the local cycle of agricultural activities, indicated that high-intensity rice farming activities in the Hani Rice Terraces would increase the supply of terraced water to groundwater, thus ensuring the sustainability of rice cultivation in the terraces during the dry season. Wang et al. [24] analyzed Hani terrace structure, soil water holding capacity, and topsoil productivity, revealing that drainage of paddy terraces along with associated changes in crop and field management led to an increase in soil productivity, but degradation of terrace structures and a decrease in water holding capacity will inhibit restoration to paddy terraces. In fact, analyzed from the perspective of the water cycle, there is a time-lag effect in the process of irrigation water recharge in the Hani terraces [8–10], especially in the process of groundwater recharge-discharge. In other words, a major component affecting groundwater circulation is the periodic time or residence time of groundwater recharge sources. There are not many studies on the MRT of different water bodies in the Hani terraces. Ma et al. [25] analyzed the soil moisture residence time in the forested area of the Hani terraces and concluded that the primary determinants of the water residence time in the Hani terraces are soil depth and non-capillary porosity (macropores). However, analyzing all sources of groundwater recharge, including precipitation, surface water, and soil water, and then recharging local farmland through spring outcrops to ensure the stability of farmland water sources and the impact of the discharge time of different spring types on the recharge of agricultural water sources has not yet been reported.

In this study, the influence of spring water residence time on irrigation water stability in the Hani Rice Terraces was the objective of the study, which was analyzed by using MRT and the isotope mixing model. The main concerns include (1) characteristics of stable hydrogen and oxygen isotopes in the various water bodies of the Hani Rice Terraces, (2) how the stability of irrigation water sources in the Hani Rice Terraces is affected by the MRT of spring recharge water sources, and (3) how the MRT of spring recharge water sources in the Hani Rice Terraces is affected by the ratio of recharge to discharge of spring water. This will offer insightful concepts for the development and use of regional water resources as well as a deeper understanding of how the water cycle process affects terraced agriculture irrigation.

2. Materials and Methods

2.1. Study Area

The Quanfuzhuang River Basin is located in the upper reaches of the Malizhai River basin in Yuanyang County, Yunnan Province [18–24], with a latitude and longitude range of 23°05′20″–23°13′18″ N, 102°43′16″–102°50′39″ E (Figure 1a), which receives abundant precipitation and has developed two main east–west tributaries. The terraces are mainly located in the Quanfuzhuang watershed between 1475 and 1737 m above sea level. The aquifers in the basin can be divided into two categories: pore aquifers and bedrock weathering fissure aquifers. The pore aquifer is dominated by clayey soil, with pore diving and weak water enrichment, and is the relative water barrier in the area. The bedrock weathering fissure aquifer, with joints and fissures developed in the rock body and loose structure, is endowed with network fissure diving and is the main aquifer in the area. Fissure water is widely exposed in the area and there are several springs [25–28].

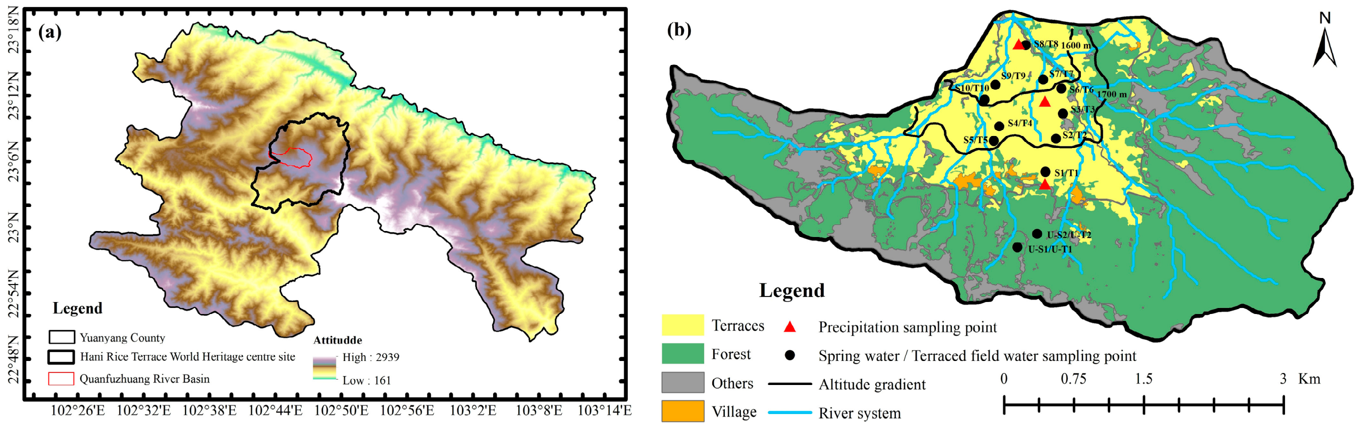

Figure 1. (**a**) Location and altitude of the study area; (**b**) Study area and distribution of sampling points.

2.2. Sample Collection and Testing

Based on the results of our field investigations and taking into account the water isotope sampling criteria and precautions, we laid out sampling points in the terraced area at altitudes ranging from 1475 m to 1720 m above sea level. Sampling sites were selected based on the principle of selecting areas with springs and corresponding water terraces on different elevation gradient bands, while precipitation collection buckets were installed at 1508 m, 1698 m, and 1872 m near the spring sampling sites. Samples of precipitation, terrace water, and springs were collected at the end of each month from May 2015 to April 2016 (Figure 1b). Water samples were collected using 100 mL plastic bottles. The spring/terrace water samples were collected by firstly washing the sampling bottles three times with spring/terrace water, placing the sampling bottles 3–5 cm underwater, filling them quickly, making sure that there were no air bubbles in the bottles, sealing them with sealant, labelling them, and recording the location and time of collection. Precipitation samples were collected, firstly, from reformed rain gauges (using a 15 L plastic bucket with the top converted into a plastic funnel with ping pong balls), and secondly, at the end of each month from the reformed rain gauges, in the same way that the spring/terrace water samples were collected. The hydrogen and oxygen isotope tests were conducted in the Key Laboratory of Plateau Lake Ecology and Global Change, Yunnan Normal University. Using a Picarro L2130-i ultra-high precision liquid water and moisture isotope analyzer, the measurement accuracy of $\delta^{18}O$ and $\delta^{2}H$ was ±0.1‰ and ±0.5‰, respectively [19,23]. In this study, according to the hydrodynamic nature of the springs in the terraced area when they were exposed [29,30], the exposed springs were classified into ascending springs (S3, S9, S10), which showed an upward movement under hydrostatic pressure, and descending springs (S1, S2, S4, S5, S6, S7, S8), which were overflowed and formed under the action of gravity.

2.3. Mean Residence Time (MRT)

With a watershed area of roughly 13.92 km^2 and a slope ranging from 17° to 58°, the Hani Rice Terraces are primarily composed of rice soils with thick soil layers and brief residence times for various water bodies. Therefore, sine-wave curves are used in this study, which favor the estimation of the MRT of younger water bodies. The MRT in the local water circulation system was estimated from the amplitude and phase lag difference of seasonal changes in $\delta^{18}O$ in different water bodies [17,31]. The time series of its distribution can then be described as:

$$\delta^{18}O = X + A{*}\cos(ct - \theta) \quad (1)$$

where $\delta^{18}O$ denotes the projected oxygen isotope values of precipitation, terraced field water, and spring water; X represents the interannual mean values of measured oxygen isotopes of precipitation, terraced field water, and spring water; A is the yearly amplitude of precipitation, terraced field water, and spring water of $\delta^{18}O$ (‰); c is the annual fluctuation radial frequency (0.017214 rad·d^{-1}); t is the actual sample sampling time (d); and θ is the phase lag.

$$MRT = c^{-1}[(A_{z1}/A_{z2})^{-2} - 1]^{0.5} \quad (2)$$

where MRT represents the mean residence time of water in the water circulation system; A_{z1} represents the amplitude of the input signal (the amplitude of $\delta^{18}O_{spring\ water}$); and A_{z2} represents the amplitude of the output signal (the amplitude of $\delta^{18}O_{precipitation}$/the amplitude of $\delta^{18}O_{terraced\ field\ water}$).

2.4. End Member Mixing Analysis

A spring is a natural outcrop of groundwater, a phenomenon that occurs when groundwater gushes from an aquifer or a water-bearing channel outcropping the surface of the ground. Ascending springs are subjected to hydrostatic pressure so that the water in the confined aquifer is in an upward movement, while descending springs are subjected to a downward movement under the influence of the shallow aquifer [32,33]. Therefore, we constructed a formula for the recharge sources of ascending and descending springs in the terraced area, and the formula is as follows:

$$\delta^{18}O_{A\text{-}S} = f_{P}\delta^{18}O_{P} + f_{T}\delta^{18}O_{T} + f_{L}\delta^{18}O_{L} \quad (3)$$

$$\delta^{2}H_{A\text{-}S} = f_{P}\delta^{2}H_{P} + f_{T}\delta^{2}H_{T} + f_{L}\delta^{2}H_{L} \quad (4)$$

$$1 = f_{P} + f_{T} + f_{L} \quad (5)$$

where f_P, f_T, and f_L, respectively, denote the percentage of precipitation, terraced field water, and lateral groundwater recharge; $\delta^{18}O_{A\text{-}S}$, $\delta^{18}O_P$, $\delta^{18}O_T$, and $\delta^{18}O_L$ denote oxygen isotope values of ascending spring water, precipitation, terraced field water, and lateral groundwater, respectively; and $\delta^2H_{A\text{-}S}$, δ^2H_P, δ^2H_T, and δ^2H_L denote hydrogen isotope values of ascending spring water, precipitation, terraced field water, and lateral groundwater, respectively.

$$\delta^{18}O_{D\text{-}S} = f_P \delta^{18}O_P + f_T \delta^{18}O_T \tag{6}$$

$$\delta^2H_{D\text{-}S} = f_P \delta^2H_P + f_T \delta^2H_T \tag{7}$$

$$1 = f_p + f_T \tag{8}$$

where f_p and f_T, respectively, denote the percentage of precipitation and terraced field water recharge; $\delta^{18}O_{D\text{-}S}$, $\delta^{18}O_P$, and $\delta^{18}O_T$ denote oxygen isotope values of descending spring water, precipitation, and terraced field water, respectively; and $\delta^2H_{D\text{-}S}$, δ^2H_P, and δ^2H_T denote hydrogen isotope values of descending spring water, precipitation, and terraced field water, respectively.

This study was based on the research background of the influence of spring water residence time on the irrigation water stability in the Hani Rice Terraces. The MRT of spring water in the Hani terraces was considered the dependent variable in this study, with precipitation, terrace water, and groundwater recharge serving as the independent variables. On the independent and dependent variables, correlation analysis, linear regression analyses, and significance tests were carried out using SPSS 13.0 statistical software.

3. Results

3.1. Spatial and Temporal Characteristics of Hydrogen and Oxygen Stable Isotopes in Springs and Their Recharge Water Sources

During the observation period, the stable isotope data of the precipitation yield the local meteoric water line (LMWL) equation: $\delta D = 8.36\delta^{18}O + 22.01$ ($R^2 = 0.98$, $n = 36$) (Figure 2a). The slope and intercept are larger than those of the global meteoric water line (GMWL) equation $\delta D = 8\ \delta^{18}O + 10$ ($R^2 = 0.98$). The results indicate that the study area is subject to the subtropical monsoon climate and precipitation in the region consists mainly of humid oceanic air masses. Nevertheless, the local terraced field water line (LTWL) is: $\delta D = 6.10\ \delta^{18}O - 3.90$ ($R^2 = 0.86$, $n = 120$), indicating that there is evaporative fractionation during the process of precipitation and groundwater recharge to the terraced field water. The local spring water line (LSWL) is: $\delta D = 4.95\ \delta^{18}O - 15.22$ ($R^2 = 0.92$, $n = 120$), and its slope and intercept are significantly smaller than LMWL and LTWL, indicating a stronger evaporative fractionation process during the process of recharging groundwater and then outgrowth from springs by precipitation and terraced field water.

We chose $\delta^{18}O$ for our systematic analyses because of the correlation between hydrogen and oxygen isotopes [5–7]. Figure 2b,c illustrates seasonal fluctuations in the monthly mean $\delta^{18}O$ of springs. The $\delta^{18}O$ of spring water varied from −9.65‰ to −3.01‰, with a mean value of −7.29‰. Spring water's $\delta^{18}O$ varies seasonally, forming a soft "S" shape with an upward trend from May to August, a slow fall from August to January, and a slow upward trend from January to April. In terms of different spring types, ascending springs have higher temperatures and faster $\delta^{18}O$ fractionation than descending springs due to hydrostatic pressure, resulting in more positive isotopic values. The isotopic anti-elevation effect of spring water was observed in November and January in the ascending springs and from December to February in the descending springs, which was related to the local farming cycle. With the harvesting of terraced rice at the end of October, local farmers ploughed and rebuilt the terraces, artificially destroying the impermeable/weakly permeable layer in the terraced fields and allowing terraced field water to enter the subsurface more rapidly. This caused a rapid enrichment of groundwater $\delta^{18}O$, and the response to this phenomenon was more sensitive in the ascending springs than in the descending springs.

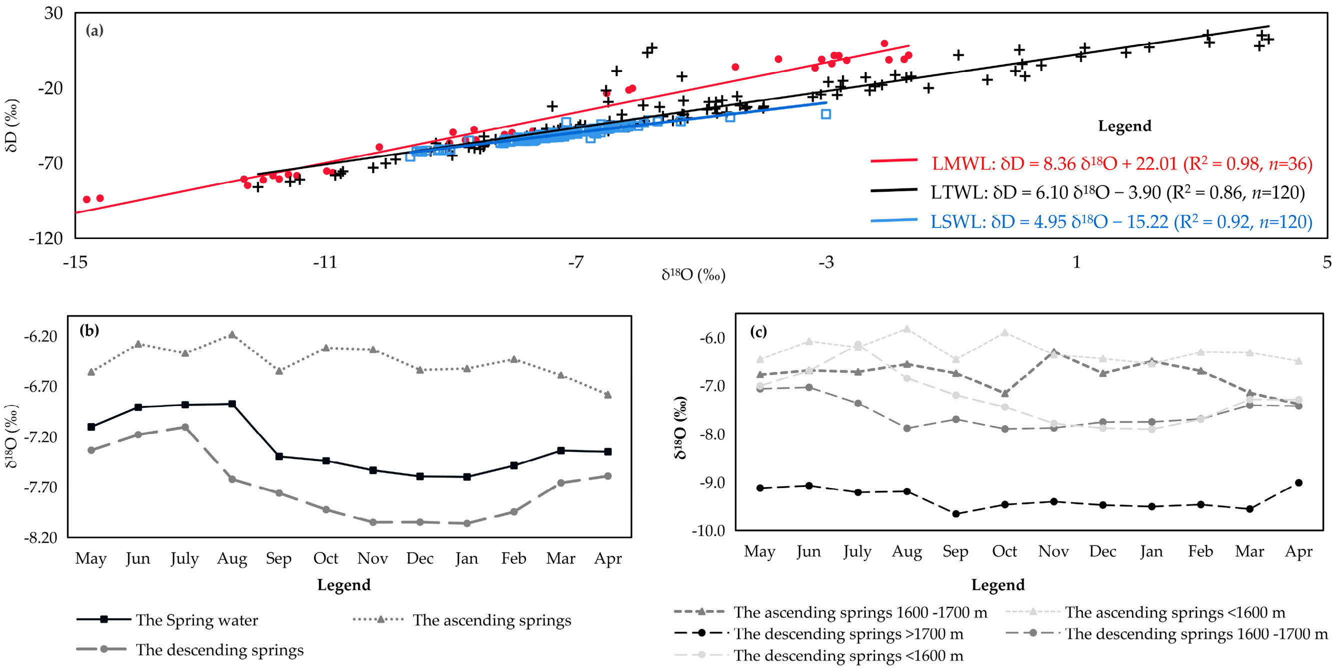

Figure 2. (**a**) Local meteoric water line (LMWL), Local terraced field water line (LTWL) and Local spring water line (LSWL) for the study area; (**b**) the temporal distributions of $\delta^{18}O$ in ascending and descending springs; (**c**) the spatial distributions of $\delta^{18}O$ in ascending and descending springs.

3.2. Effect of MRT of Spring Recharge Water Sources on the Stability of Irrigation Water Sources in the Hani Rice Terraces

Based on Equation (2), the mean multi-year residence time of spring recharge sources in the Hani terrace area was calculated (Table 1 and Figure 3). As shown in the table, the inter-annual residence time of precipitation and terraced field water in springs was 2.46 years and 1.54 years, respectively, indicating that the springs in May 2015–April 2016 were influenced by 2.46 years of former precipitation and 1.54 years of former terraced field water. In other words, both the precipitation from 2.46 years ago and the terraced field water from 1.54 years ago were able to effectively recharge the water used for agriculture in the terraces in that year. This explains the drought event that occurred in the whole province of Yunnan Province in 2015 under the influence of the El Niño event, but the drought event did not affect the sustainable development of rice agriculture in the Hani Rice Terraces that year.

We discovered that different types of springs had distinct emergence timings, allowing for staggered refilling of terraced water sources. The time it took for precipitation and terraced field water to be transited and exposed as ascending/descending springs in the terraced area was 2.73 years and 1.95 years, and 1.55 years and 1.04 years, respectively. The MRT of ascending springs was about half a year longer than that of descending springs, implying that ascending and descending springs can be staggered to recharge the terraced field water.

At higher elevations, precipitation and terraced field water residence in ascending and descending springs took 2.52 and 3.73 times longer to emerge from terraces, and 3.36 and 6.49 times longer than at lower levels. This means that the lower the altitude, the shorter the MRT of the recharge water source, and the elevation gradient of the ascending spring is smaller than that of the descending spring. It further illustrates that the ascending springs regulate the temporal distribution of the terrace recharge water sources, while the descending springs regulate the spatial distribution of the terrace recharge water sources, demonstrating that the Hani Rice Terraces are a relatively stable agroecosystem.

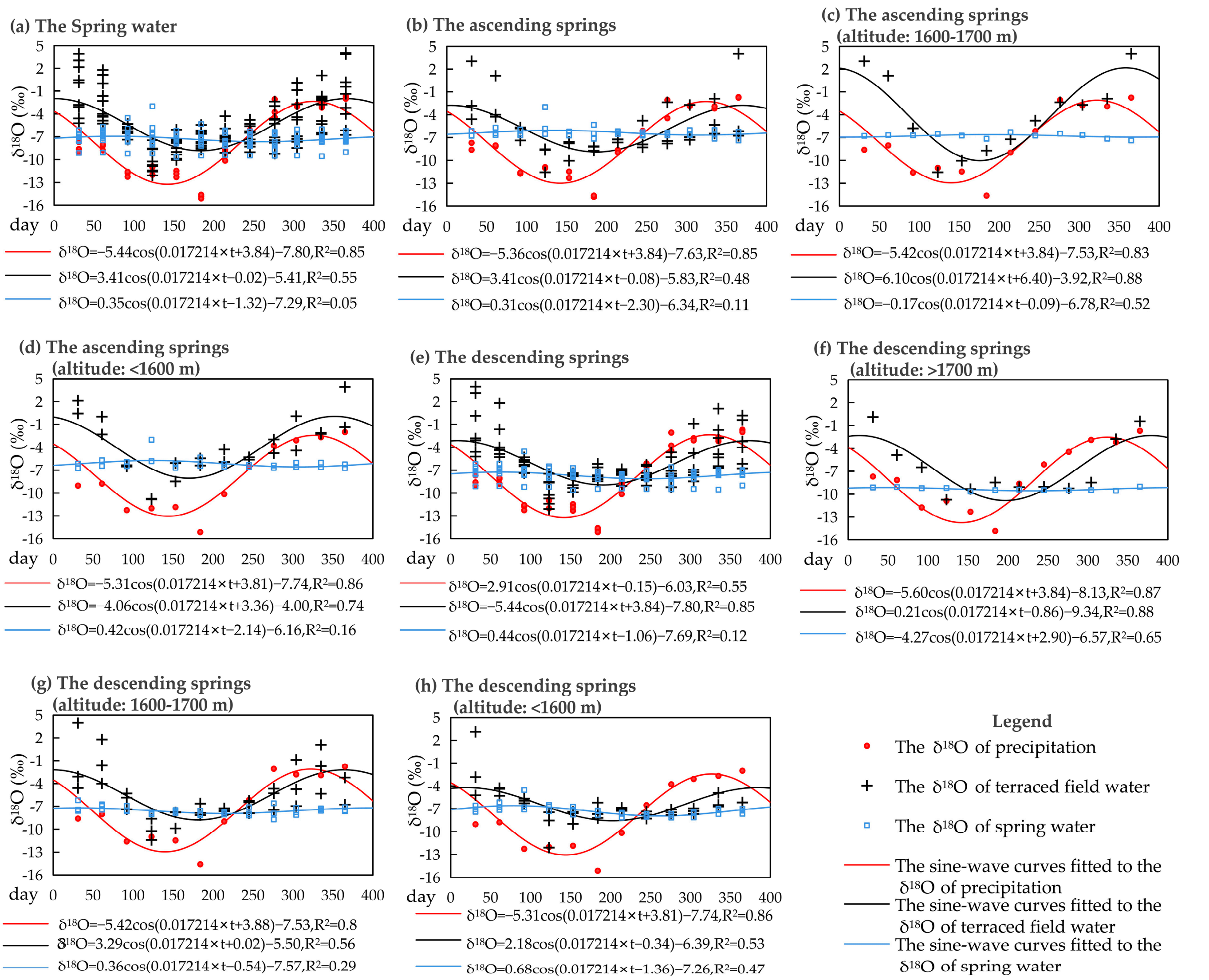

Figure 3. Seasonal oxygen-18 variations in Precipitation, Terraced field water, and Spring water at the Hani terraced fields; raw data and sine-wave curves fitted to data.

Table 1. The MRT of spring recharge water sources in the Hani Rice Terraces.

Type of Springs	Altitude	Intersubstance Transport Processes	MRT (a)
The Spring water		Precipitation → Spring water	2.46
		Terraced field water → Spring water	1.54
The ascending springs		Precipitation → Spring water	2.73
		Terraced field water → Spring water	1.55
	1600–1700 m	Precipitation → Spring water	5.03
		Terraced field water → Spring water	5.67
	<1600 m	Precipitation → Spring water	2.00
		Terraced field water → Spring water	1.52
The descending springs		Precipitation → Spring water	1.95
		Terraced field water → Spring water	1.04
	>1700 m	Precipitation → Spring water	4.17
		Terraced field water → Spring water	3.18
	1600–1700 m	Precipitation → Spring water	2.37
		Terraced field water → Spring water	1.43
	<1600 m	Precipitation → Spring water	1.24
		Terraced field water → Spring water	0.49

4. Discussion

4.1. Effects of the Spring Recharge-Discharge Ratio on the Stability of Irrigation Water Sources in the Hani Terraced Fields

According to Equations (3)–(8), the recharge-discharge ratios of ascending and descending springs in the Hani terrace area were obtained (Figure 4). As a whole, groundwater in the terraced area is distinguished by short recharge routes, in situ recharge, and in situ discharge, and its quantity is directly tied to topography [34]. The ascending spring percolates upward in a confined aquifer, thus lateral groundwater supplies more than half of its recharge; the descending spring's primary recharge source is shallow groundwater, which is influenced by precipitation and terraced field water. The ascending springs in the terraced area follow the rule that the lower the elevation, the greater the proportion of lateral groundwater recharge; the descending springs obey the rule that the lower the elevation, the greater the ratio of terraced field water recharge. This suggests that the upstream–downstream recharge relationship of groundwater in the terraced area is critical to ensuring the stability of the terraced water source.

To effectively explain the effect of the spring water recharge ratio on the periodicity of Hani terrace irrigation water sources, this study used linear regression to explore the relationship between precipitation, the terraced field water recharge ratio, and the MRT of spring water in different water bodies (Table 2). It has been discovered that there is a significant correlation between the ratio of field water recharge to springs in the Hani terraces and the MRT of field water in springs. Among these, there is a substantial negative connection for descending springs, indicating that the ratio of terraced field water recharge will influence the MRT of spring water on the Hani terraces. This suggests that local agricultural activities on the terraces will effectively interfere with shallow groundwater, thus affecting the MRT of groundwater and ensuring the ongoing recharge of descending springs to the terraced water. The ratio of precipitation recharging the springs, on the other hand, has a correlation with the MRT of springs but is not significant. It demonstrates that the process of direct recharging of precipitation to springs is reduced, and the ratio of precipitation recharge to springs is not a key factor determining the MRT of springs by precipitation.

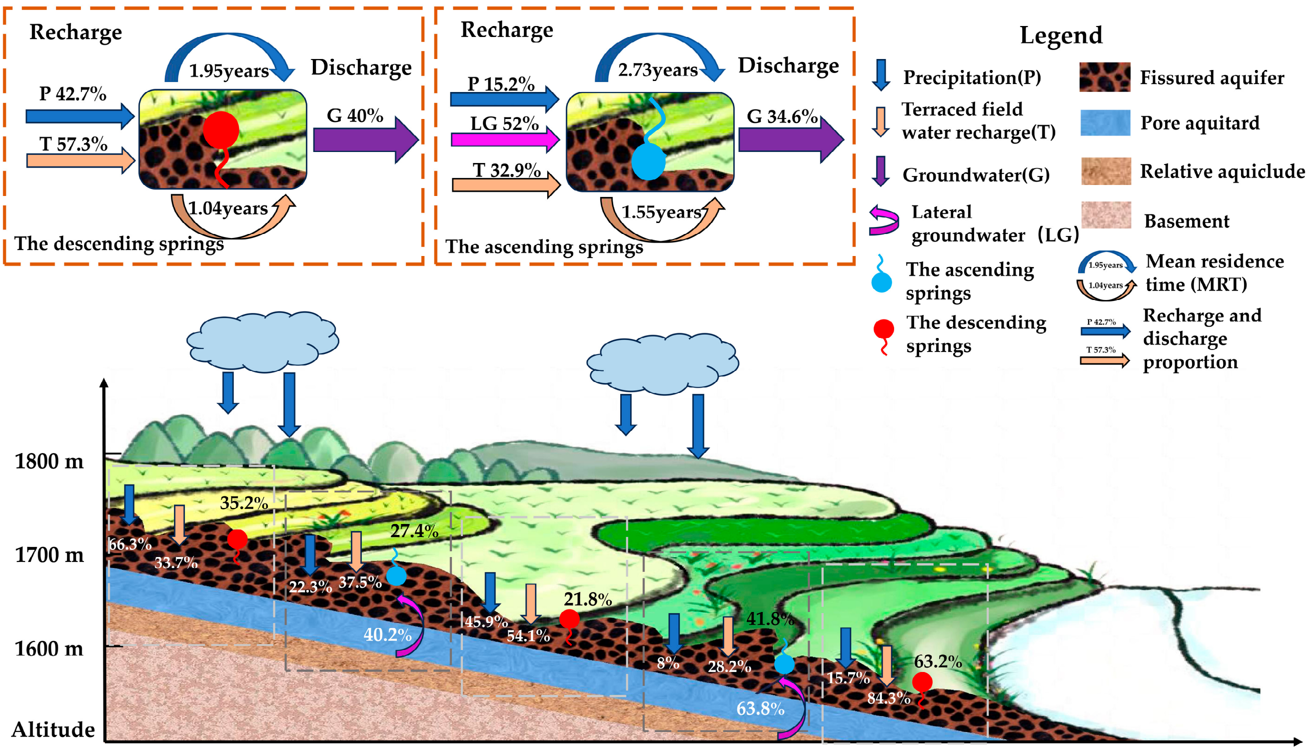

Figure 4. Ratio of recharge/discharge from ascending/descending springs at different altitudes in the Hani Rice Terraces.

Table 2. The relationship between precipitation, the terraced field water recharge ratio, and the MRT of spring water in different water bodies.

Type of Springs	Intersubstance Transport Processes	Pearson Correlation	Linear Regression Equation	R^2
The Spring water	Precipitation → Spring water	0.21	-	-
	Terraced field water → Spring water	−0.70 *	MRT = 10.18 T − 13.90 T^2	0.77 **
The ascending springs	Precipitation → Spring water	−0.92	-	-
	Terraced field water → Spring water	0.96	-	-
The descending springs	Precipitation → Spring water	0.56	-	-
	Terraced field water → Spring water	−0.92 **	MRT = −7.56 T + 2.33 T^2 + 4.79	0.85 *

Notes: * indicate the *p*-value is less than 0.05 (5%); ** indicate the *p*-value is less than 0.01 (1%).

4.2. Effect of MRT of Spring Water and Its Influencing Factors on the Stability of Irrigation Water Sources

Table 3 summarizes the residence times of various types of water bodies in different regions of the globe, with precipitation residence in surface water ranging from 0.5 to 1.5 years, precipitation residence in groundwater from 1.1 to 1.3 years, surface water residence in groundwater from 0.41 to 3.15 years, precipitation residence in 0.15 to 0.55 years for soil water, and soil water residence in rock water from 0.06 to 1.15 years. Globally, water residence time is not only related to the hydraulic gradient of the watershed, but also closely related to the catchment area, soil depth, and land use type [11–18,26]. Generally speaking, the smaller the watershed area, the steeper the slope, and the thinner the soil layer, the shorter the water residence time, and the longer the time. Despite the small watershed area (13.92 km^2) and steep slope (17°−58°) of the Hani terrace area, its water residence time is longer than that of other watersheds around the globe due to its thick soil layer, which is dominated by rice soil, and the plow pan is effective in isolating the water [35,36], implying that the terraces function as a source of water conservation.

From a global perspective, different locations maintain water resource stability in terraced agricultural systems in different ways, with different transmission cycles and their influencing factors [37–41]. For irrigated terraced agriculture in semi-arid areas, the construction of terraces can effectively improve the soil erosion phenomenon of sloping arable land, increase the residence time of rainwater on the ground, and improve the infiltration of soil moisture, guaranteeing the stability of water sources in the region [37]. Rice terrace agriculture in the humid zone is distinguished by flooded fields throughout the year, and springs are essential for preserving the stability of water sources in the terraces [19–23,38–41]. Previously, some scholars have found that the recharge of terrace irrigation water sources has the characteristics of alternating seasons and spatial staggered distribution of spring and rainwater, and that the terrace irrigation water source is most stable when recharged by spring water [19]. However, we found that precipitation and terraced field water are transited for about half a year longer in the ascending springs than in the descending springs, implying that different spring types have different discharge times in the same area and that different types of springs can be staggered to recharge the terraced field water to maintain the stability of the terraced rice agriculture. This suggests that the Hani terraces' spring irrigation water source is not only multi-temporal but also spatially heterogeneous. This also explains why the Hani terraces can maintain the stability of water resources in the rice farming system even during drought years.

The current study examines the time scale of the spring water cycle, concentrating on the impact of spring water residence time on irrigation water stability in the Hani Rice Terraces. However, we did not account for the effect of soil water on spring water residence time. In the future, we need to focus on quantitative research on the effect of soil factors in the Hani terraces based on the soil's physicochemical properties, so as to systematically and comprehensively reveal the mechanism of irrigation, recharge, and discharge transformation of the Hani terraced irrigation water source, as well as its impact on the sustainability of terraced agriculture, and to provide effective scientific basis for the protection of the Hani terraces.

Table 3. The residence times of various types of water bodies in different regions of the globe.

Region	The Intersubstance Transport Processes	MRT (a)	The Influence Factor	Sampling Time Period
Tuojiang river [16]	Precipitation → Surface water	0.95–1.35 year	Topography; Catchment area; Soil type; Land use type	2018.5–2019.4
The Abay/Upper Blue Nile [14]	Precipitation → Surface water	0.34 year, 0.5 year		2008.8–2011.8
Upper Indus River Basin [11]	Precipitation → Surface water	0.5–1.03 year	The steep gradient of stream profile; Flowpath length; Landscape physiography	2007.11–2009.1
Redondo Peak, located in the Valles Caldera, New Mexico, United States [13]	Precipitation → Surface water	0.34 year	Topographical features (such as flow path length, slope gradient, aspect and elevation)	2007.3–2007.8
Two forested basins in West Virginia and one in Pennsylvania [17]	Precipitation → Spring water; Precipitation → Stream water	The Fernow watersheds: 1.1–1.3 year; The Benner Run: 1.4–1.6 year	Catchment area; Slope; Soil depth	1989.3–1990.3
The Tianguer River and Duowang Rive, in Yilan, Taiwan [9]	Surface water → Groundwater	0.41 year, 3.15 year		2018.10–2020.4
The Honghe Hani Terraces [25]	Precipitation → Soil water	The forest land: 0.15–0.26 year; The shrubland: 0.21–0.39 year	Land use type; non-capillary porosity	2015.7–2015.12
Jeju Island [15]	Precipitation → Soil water	30 cm depth: 0.14 year, 60 cm depth: 0.44 year, 80 cm depth: 0.55 year	Soil depth; The boundary between the upper fine-grained soil and the lower coarse-grained soil	2002.11–2003.11
Huanjiang County of northwest Guangxi, southwest China [8]	Soil water → Spring water	0.06–1.15 year, 0.98 year	Soil thickness; Epikarst	2011.4–2013.4

5. Conclusions

In this study, the influence of spring water residence time on the irrigation water stability in the Hani Rice Terraces was assessed using MRT and the isotope mixing model based on monthly samples of precipitation, terrace water, and spring water collected between 2015 and 2016. The results show that:

(1) All inter-water body transformations between precipitation recharge to terraced field water, recharge to the subsurface, and spring water outcropping to the surface have undergone varying degrees of evaporative fractionation. The $\delta^{18}O$ of the springs in

the terraced area showed a gentle "S" shape, with ascending springs having more positive isotopic values than descending springs. The isotopic anti-elevation effect of spring water was observed in the ascending springs from November to January and in the descending springs from December to February, which was related to the local farming cycle, and the ascending springs were more sensitive to the response to the farming cycle than the descending springs.

(2) The residence time of precipitation and terraced field water in springs was 2.46 years and 1.54 years, respectively, indicating that the springs were affected by 2.46 years of previous precipitation and 1.54 years of previous terraced field water. When analyzed in terms of different spring types, the time for precipitation and terraced field water to be transited and exposed as ascending/descending springs in the terraced area was 2.73 years and 1.95 years, and 1.55 years and 1.04 years, respectively, where the residence time of ascending springs was about half a year longer than that of descending springs, indicating that the ascending springs and the descending springs can be staggered to recharge the terraced field water. From different elevations, the lower the elevation, the shorter the MRT of the recharge water source, and the elevation difference of the MRT of the ascending spring is smaller than that of the descending spring, indicating that the ascending spring regulates the temporal distribution of the recharge water source of the terraces, while the descending spring regulates the spatial distribution.

(3) Groundwater in the terraced area has short recharge routes, in situ recharge, and in situ discharge, and its quantity is strongly tied to topography. The ascending spring percolates upward in a confined aquifer, thus lateral groundwater supplies more than half of its recharge; the descending spring's primary recharge source is shallow groundwater, which is influenced by precipitation and terraced field water. The ascending springs in the terraced area follow the rule that the lower the elevation, the higher the ratio of lateral groundwater recharge; the descending springs obey the rule that the lower the elevation, the higher the ratio of terraced field water recharge.

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