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# Evolution Characteristics of Heilongtan Spring Discharge and Its Response Law to Precipitation in Lijiang City, China

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**Abstract:** The contradiction between water supply and spring preservation issues is becoming increasingly apparent as Lijiang City develops. An investigation into the dynamic variations in the discharge rate of Heilongtan Spring in Lijiang City and the response law between the water level of the spring and precipitation is crucial for safeguarding the landscape water of Heilongtan Spring. This study employed linear regression analysis, Mann–Kendall (MK) mutation test, wavelet analysis, and vector autoregression (VAR) to examine the fluctuating pattern of the Heilongtan Spring discharge and the response of the Heilongtan Spring water level to precipitation in Lijiang City. Furthermore, the study discussed the influence of human activities on the alteration of Heilongtan Spring. The results indicate that the mean discharge rate of Heilongtan Spring is 0.94 $m^3/s$, with an annual variation of 0.05 $m^3/s$. The time series analysis reveals that the variation pattern of Heilongtan Spring discharge aligns with the precipitation trend in Lijiang City. Nevertheless, there is a distinction between the timing of the Heilongtan Spring discharge station point and the precipitation mutation point in Lijiang City. The significant primary cycle of spring discharge change occurs every 18 months, with a cycle length of 12 months. The vector autoregression (VAR) model demonstrates a lagged relationship between the water level of Heilongtan Spring and the precipitation in Lijiang City. Specifically, the water level of Heilongtan Spring has a four-month lag response to precipitation variability in Lijiang City. The results can provide a beneficial reference for preserving spring water and managing regional water resources.

**Keywords:** spring discharge; wavelet analysis; vector autoregression; response law; spring protection

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## 1. Introduction

Groundwater resources are vital to China's water resources [1], serving as the primary source for industry, agriculture, and domestic use [2–4]. They also play a critical role in maintaining ecological and geological stability and coordinating the supply of water resources within the regional water cycle [5]. The relationship between the recharge and discharge of water resources in the region has been disrupted due to climate change [6], human activities, and other factors in recent decades. This disruption has posed significant challenges to the groundwater environment [7]. As a result, the evolution pattern of the groundwater environment has become increasingly intricate, often resulting in various environmental and geological issues such as water quality deterioration, a significant reduction in spring discharge, and even the springs that have dried up [8–10].

Karst formations are extensively found in Southwest China, covering a vast area of approximately 78 × $10^4$ $km^2$ [11]. These formations exhibit unique geological structures, such as karst holes and sinkholes, which facilitate the infiltration of precipitation into the ground [12]. The karst geological conditions largely influence the availability of water resources in this region [13]. When there is a relatively concentrated outlet, karst springs are formed, which play a crucial role in water supply [14]. To achieve the rational development of karst springs and ensure the scientific management of regional water resources, it is essential to investigate the dynamic characteristics of karst spring discharge. Numerous nations have set up hydrological observatories for karst springs to gather up-to-date and dynamic water quality, discharge rate, and water level data [15–17]. During the application phase, it is essential to integrate the current state of the spring with mathematical statistics and conduct simulation studies using the collected monitoring data [18–20].

The Lijiang Basin in Yunnan Province is characterized by a continuous distribution of karst formations, which have created a unique landscape of karst springs due to particular hydrogeological circumstances [21]. Karst springs, a unique type of groundwater resource, serve as a crucial water supply and have various cultural and tourism properties [22–24]. They hold significant hydrological importance and have potential for development. Heilongtan Spring, located in the Lijiang Basin, is the most incredible collection of springs in the area. It is renowned for its historical and cultural significance and distinctive natural scenery, making it a valuable tourist attraction [25]. In the 21st century, the drying phenomenon has become increasingly frequent, with drought years susceptible to seasonal or even inter-annual drying. This significantly impacts the water landscape and the lives of the people in Lijiang City. Relevant researchers have conducted valuable investigations of the Heilongtan Spring in response to the issues. Cen et al. [26]. proposed that groundwater runoff in the Lijiang Basin primarily flows from north to south based on isotopes, hydrochemistry, and field tracer experiments. They also identified the areas where water is replenished and discharged in the Lijiang dam region. Zeng et al. [27] focused on Changes in Heilongtan Spring discharge. They examined the variations in discharge and water level of the spring and the connection between precipitation and the spring's recharge. Their findings indicate that precipitation is the primary factor influencing the discharge of the Heilongtan Spring. Additionally, they observed a delay in the response of the spring's discharge to changes in precipitation. Han et al. [28] discovered a strong correlation between the water level of hydrological observation wells near Heilongtan Spring and the discharge rate of the Heilongtan Spring. This correlation can be utilized by adjusting the water level of the observation wells to regulate the water level of Heilongtan Spring, thereby achieving the desired outflow. Generally, the research is centered around studying the developmental pattern of the spring area of Heilongtan Spring, the variations in discharge and water level, and the relationship between discharge and precipitation. Nevertheless, the cyclic fluctuations in spring discharge and the response law between the water level of Heilongtan Spring and precipitation remain unclear.

This study focuses on the Heilongtan Spring in Lijiang as the research object. It employs linear regression and wavelet analysis to examine the patterns of change in the spring discharge over the past forty years. Additionally, it uses the vector autoregressive (VAR) model to investigate the response law between changes in precipitation and the spring water level. The findings of this research will inform the development of local spring protection measures and guide future water resources protection planning and management in the Lijiang dam area.

## 2. Study Area and Data

### *2.1. Site Description*

The Heilongtan Spring area is situated on the outskirts of the Hengduan Mountains in the western region of Yunnan Province (Figure 1). The Yulong Snow Mountain borders it to the north and the Jinsha River valley to the south. The area's topography is higher in the north and lower in the south. The Heilongtan Spring area mainly encompasses the Gucheng District of Lijiang City and the Yulong Naxi Autonomous County. Mountainous basins and tectonic terrains characterize the geomorphology of the spring area. The Heilongtan Sprin is located in the Lijiang Dam District at the base of Xiangshan Mountain, north of Gucheng. It consists of five spring outcrops with an elevation of approximately 2400 m.

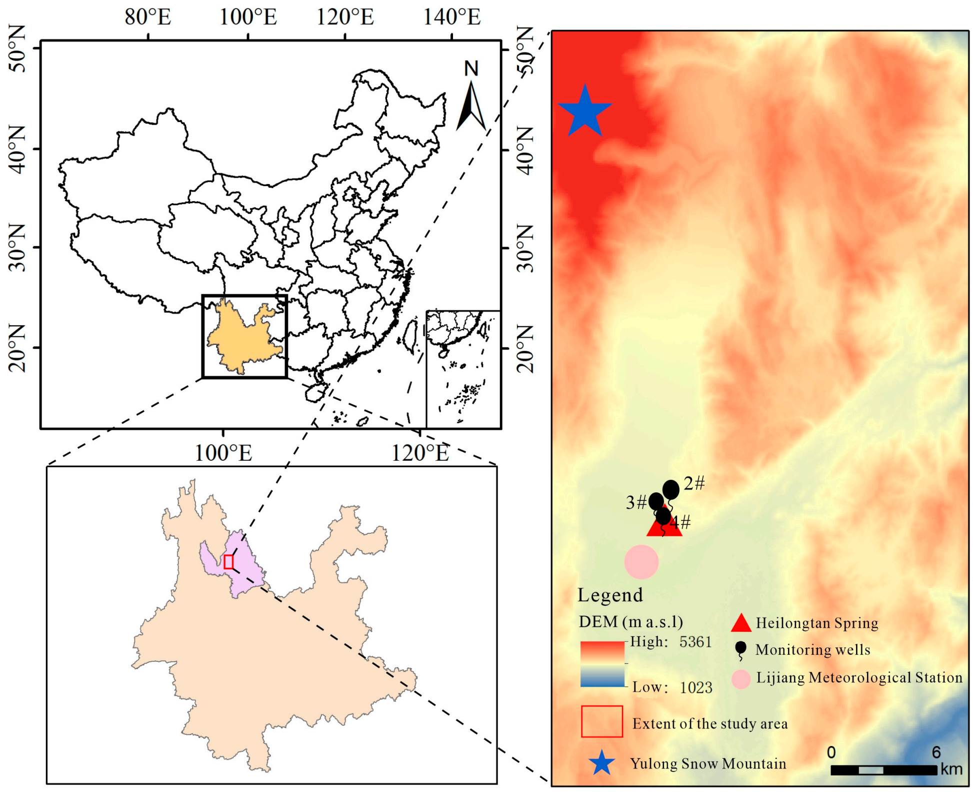


**Figure 1.** The extent of the study area (# represents the monitoring well number).

The region is abundant in water resources, with a surface water system that includes significant rivers such as the Heibaishui River, Culture River and Yanggong River, all of which are part of the Jinsha River water system. Additionally, several exposed springs are in the area, including Qingxi Spring, Heilongtan Spring, Shuhe Spring, and Shuangbao Spring. The spring area is in the warm-temperate plateau mountain monsoon climate zone, characterized by a combination of dry and wet conditions throughout the year. The mean annual precipitation over several years is 954.2 mm, with the most excellent inter-annual temperature recorded at 15.8 °C and the lowest at 12.1 °C. The mean temperature across the years is 13.0 °C, while the mean relative humidity is 63.3%, as depicted in Figure 2. The distribution of precipitation throughout the year is unequal, with the majority occurring from June to September. During this period, there is a significant amount of rainfall, which makes up about 85% of the total annual precipitation. The predominant groundwater in the Heilongtan Spring Area is Triassic limestone fissure karst water, which is also the type of groundwater in the Heilongtan Spring area. This spring exhibits typical characteristics of the rain-source type. In its natural state, the primary recharge region of Heilongtan Spring is predominantly the karst depression located to the north of Heilongtan Spring. This area is distributed throughout Jiuzihai, Lariguang, Hongshuitang, and other locations. The Lijiang Dam District is a well-developed karst region, where characterized by numerous sinkholes, caves and karst holes. The karst groundwater is mainly recharged by atmospheric precipitation, rapidly replenishing the karst aquifers by dissolving karst holes and sinkholes. The karst water is replenished by atmospheric precipitation in the karst highlands and then flows southward through the karst aquifer. Due to the pressure generated by the hydraulic head difference, the karst water converges and flows outward.

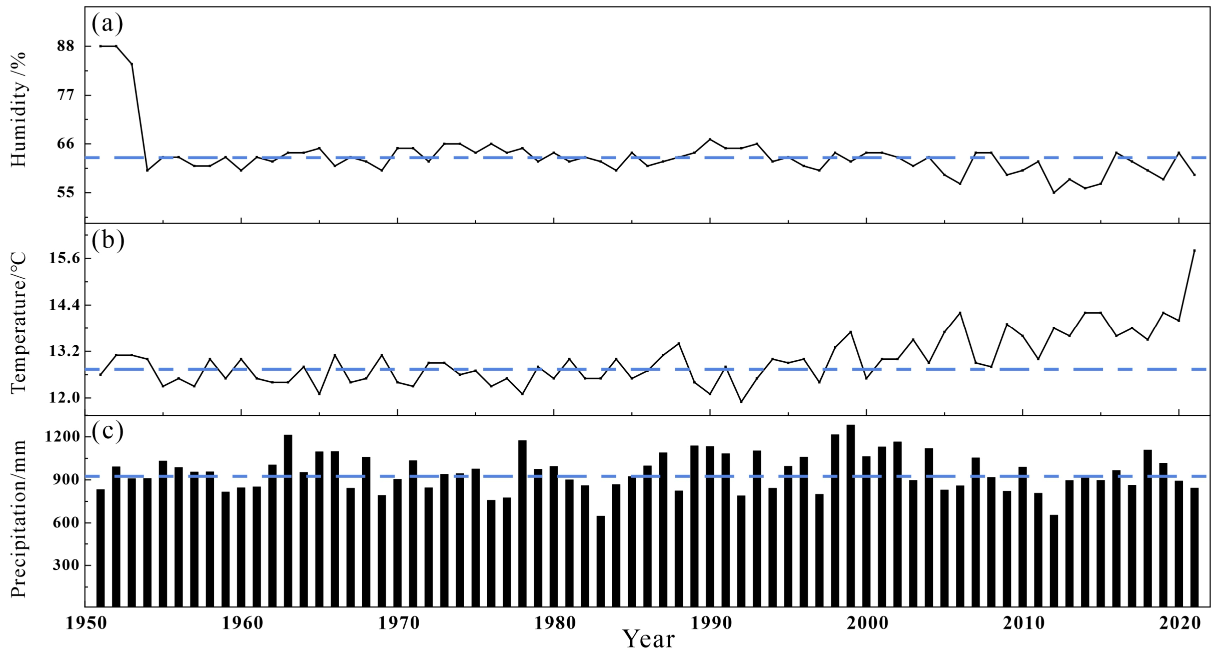


**Figure 2.** The extent of the study area. Changes in climate factors in the Lijiang area from 1951 to 2021 (in Figures (**a**–**c**), the blue dotted line represents the data mean): (**a**) annual-mean relative humidity; (**b**) annual-mean temperature; (**c**) annual precipitation.

## *2.2. Data Sources*

The primary data employed in this study encompass water discharge data (daily scale) from Heilongtan Spring between the years 1988 and 2021, water level data (daily scale) from monitoring wells No. 2, No. 3, and No. 4 of Heilongtan Spring between the years 2013 and 2021, and precipitation data (monthly scale) from the Lijiang station between the years 1988 and 2021. The precipitation data were obtained from the meteorological observation station of the Lijiang Meteorological Bureau, Lijiang City, China (26°52′ N, 100°13′ E; 2400 m.a.s.l). The annual-scale precipitation data were obtained by accumulating and processing the monthly-scale data. The data pertaining to the flow of Heilongtan Spring and the levels of water in the three monitoring wells were provided by the Lijiang Branch of the Lijiang Hydrology and Water Resources Bureau of Lijiang City, Yunnan Province. This organisation has been monitoring the flow and water level of the Heilongtan Spring in Lijiang City for a considerable period of time. The flow data were obtained through manual measurements, with the flow data on a monthly and annual scale being derived from the daily scale data through averaging. The groundwater levels in the three monitoring wells were calibrated using a ZKGD200-D groundwater level observer (Beijing Zhongkeguangda Automation Technology Co., Ltd., Beijing, China) in combination with manual measurements, with an accuracy of ±0.2 cm. This did not affect the analysis of the results. The aforementioned dataset was measured continuously without any missing data over the specified time period, and the data were subjected to rigorous quality control and inspection procedures. Following the acquisition of the datasets, the distribution characteristics were initially analysed using the Kolmogorov-Smirnov (K–S) test, which revealed that none of the datasets exhibited a normal distribution. Linear regression and Spearman's correlation analyses were subsequently employed to investigate the trend of the discharge of the Heilongtan Spring and the response pattern between the water level of the Heilongtan Spring and precipitation.

## 3. Methods

### *3.1. Mann–Kendall Mutation Test*

The Mann-Kendall (MK) mutation test is a non-parametric method for analyzing hydrological and meteorological time series data. It is widely recognized in this field [29]. Mutation in this context refers to transitioning from one stable state of data series to another. The MK mutation test is advantageous compared to other methods as it can eliminate the influence of outliers on the analysis results. Additionally, it does not require assumptions about the data distribution [30]. An ordered series can be established for analysis for a time series with n samples:

$$S_k = \sum_{i=1}^{k} r_i, k = 2, 3, \ldots, n \tag{1}$$

Within Equation (1):

$$r_i = \begin{cases} +1, & x_i > x_j \\ 0, & x_i < x_j \end{cases} \tag{2}$$

In Equation (2), $x_i$ and $x_j$ are the time series values at moments $i$ and $j$, respectively; $S_k$ represents the cumulative value. MK mutation test of constructed statistics:

$$\mathrm{UF}_k = \frac{S_k - E(S_k)}{\sqrt{\mathrm{var}(S_k)}} \tag{3}$$

where $\mathrm{UF}_k$ is the standard regular distribution series; $E(S_k)$, $\mathrm{var}(S_k)$ represent the mean and variance of $S_k$, respectively. When two curves intersect in the confidence interval, the moment corresponding to the intersection point may be the time of mutation; if the two curves have only a unique intersection point in the confidence interval, the intersection point is the time of the study of the time series data mutation, if the two curves have more than one intersection point within the confidence interval, it means that there is an ambiguous point, which the moving *t*-test can further verify to determine the actual time series mutation point [31].

### *3.2. Wavelet Analysis*

Currently, wavelet analysis is extensively employed in hydrology [32]. This method effectively handles information in the localized transformation signals of time-frequency. Consequently, wavelet analysis is commonly utilized to investigate the periodic patterns of temperature, precipitation, runoff, and their corresponding dynamics across various time scales [33]. Wavelet analysis encompasses both Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). Continuous Wavelet Transform (CWT) denotes a signal processing method wherein both time and time-shift parameters are continuous. This method is frequently employed in applications that necessitate continuous scale analysis. The Discrete Wavelet Transform (DWT) is a signal processing method that employs discrete time and time-shift parameters. It is frequently utilized in applications that necessitate multi-resolution analysis. In comparison to the discrete transform, the continuous transform is more conducive to the extraction of time-series features. Consequently, the continuous wavelet transform is frequently selected for use in time-series analysis [34]. CWT is defined as:

$$\mathrm{W}_f(a, b) = |a|^{-1/2} \int_{-\infty}^{+\infty} f(t)\overline{\psi}(\frac{t-b}{a})\mathrm{d}t \tag{4}$$

where $a$ is the scale expansion factor, $b$ is the time translation factor, $t$ represents time, $\mathrm{W}_f(a, b)$ is the wavelet transform coefficients, $f(t)$ is a variable time series, $\overline{\psi}(\frac{t-b}{a})$ is the complex conjugate function of the wavelet $\psi(\frac{t-b}{a})$, From the aforementioned equation, it can be observed that the scale parameter, a, has the capacity to alter not only the spectral structure of the wavelet, but also the dimensions and configuration of its window.

The selection of an appropriate wavelet basis function is of paramount importance when studying a given period through wavelet analysis, as it directly impacts the precision and reliability of the resulting wavelet transform, with the most commonly utilized ones including the Haar, Daubechies, and Morlet wavelets, among others. In the context of hydro-meteorological sequence time series analysis, the objective is to obtain a smooth and continuous wavelet amplitude. In such cases, a non-orthogonal wavelet function is a more suitable option [35]. The Morlet wavelet is employed in this study due to its superior time-frequency localisation properties and capacity to effectively capture the details of the signal in the frequency domain. A substantial body of research employs Morlet wavelets to analyse hydrometeorological sequence data. In practical applications of wavelet analysis, the presence of boundary effects can lead to significant alterations in the results of wavelet variation at the boundaries of the analysis, resulting in inaccurate outcomes. To address this issue, the symmetric extension of the sequence data is processed using the wavelet tool in MATLAB 2021b software, aiming to mitigate the impact of boundary effects. Meanwhile, in order to more accurately reflect the fluctuations in the wavelet coefficients, the data employed for this wavelet analysis are the monthly anomaly data of Heilongtan Spring and the monthly precipitation anomaly data of Lijiang station from 1988 to 2021. These data are combined with the Morlet wavelet as the base wavelet function for the analysis. The expression of the Morlet wavelet is as follows:

$$\psi(t) = e^{i\omega_0 t} e^{-\frac{t^2}{2}} \tag{5}$$

where $t$ represents time, $i$ is an imaginary number, and $\omega_0$ is the center frequency. The frequency variations in the real part portion of the Morlet wavelet coefficients can be used to observe the periodic oscillations of the sequence data, defining the wavelet power spectrum as $\left|W_f(a,b)\right|^2$ and the overall wavelet power spectrum as:

$$E(a) = \frac{1}{N}\sum_{b=1}^{N}\left|W_f(a,b)\right|^2 \tag{6}$$

The formula for the wavelet variance is:

$$Var(a) = \int_{-\infty}^{+\infty}\left|W_f(a,b)\right|^2 \mathrm{d}b \tag{7}$$

The magnitude and peak of the wavelet variance correspond to periods of different time scales. The significance of the periodic components of the resulting signal is analyzed, and whether the wavelet power spectrum is significant or not is tested with red or white noise standard spectra. Since most of the precipitation series data and discharge series are characterized by red noise, the results are tested using a red noise background spectrum [36]. The red noise process can be modelled by a 1st order autoregressive process whose power spectrum can be defined as:

$$P_a = \frac{1-\alpha^2}{1+\alpha^2 - 2\alpha\cos(\frac{2\pi\delta t}{a})} \tag{8}$$

where $P_a$ is the red noise spectrum, $\alpha$ is the autocorrelation coefficient of the original series lagged to order 1, and $\delta t$ is the sequence time interval. The theoretical power spectrum is:

$$P = \frac{\sigma^2 P_a \chi_\nu^2}{\nu} \tag{9}$$

where $\sigma^2$ is the variance of the original sequence, $\chi_\nu^2$ is the value of $\chi^2$ with degree of freedom $\nu$. When the overall wavelet power spectrum is larger than the theoretical spectrum it indicates that the corresponding period is significant.

### *3.3. Vector Autoregression*

The vector autoregressive (VAR) model is extensively employed in econometrics and has gained popularity in the domains of environment and geography [37]. The VAR model is able to consider multiple time-series variables simultaneously and analyse the dynamics between them, which can better capture the possible influencing relationships and feedback mechanisms between spring flow and precipitation [38]. The VAR (vector autoregressive) model with a lag order of can be represented as:

$$Y_t = c + \sum_{i=1}^{p} A_i Y_{t-i} + e_t \tag{10}$$

where $Y_t$ is a $k$-dimensional column vector of endogenous variables, $c$ is a constant, $p$ is the lag order, $A_i$ is the regression coefficient, $Y_{t-i}$ is a $i$-order lagged variable, and $e_t$ represents the disturbance term. Prior to establishing the model, it is essential to conduct the ADF unit root test on the serial data to ascertain its smoothness. Additionally, it is imperative to pass the Johansen test to evaluate the research serial cointegration relationship (long-term stable proportionality) to guarantee the model's stability and efficacy. The causal relationship between the two variable series is investigated through the application of the Granger causality test. A bivariate vector autoregressive (VAR) model was constructed to examine the relationship between precipitation in Lijiang City and the water level in Heilongtan Spring. The autoregressive (AR) characteristic root test was employed to assess the stability of the established model. When all the root modes were less than 1, the model was deemed stable. The impulse response analysis was then conducted on the basis of the established VAR model to investigate the dynamic relationship between the two variables.

## 4. Results

### *4.1. Analysis of the Discharge Dynamics of the Heilongtan Spring*

Figure 3 displays the yearly and seasonal variations in the discharge of Heilongtan Spring based on the data collected from 1988 to 2021. Regarding the inter-annual discharge fluctuations of the Heilongtan Spring, According to Figure 3a analysis, the Heilongtan Spring discharge has shown an overall declining trend; the annual change in discharge rate during this period was 0.05 $m^3/s$. The average discharge rate over many years is 0.94 $m^3/s$, with the maximum discharge rate reaching up to 2.44 $m^3/s$ in 2000. From 2012 to 2017, the Heilongtan Spring discharge was at its lowest, with intermittent discharge occurring. The inter-month data from 1988 to 2021 indicate that the maximum spring discharge of 3.86 $m^3/s$ was recorded in October 2000, after which the spring discharge exhibited a variable degradation pattern. The discharge of Heilongtan Spring varies throughout the year due to the influence of atmospheric precipitation. From year to year, the discharge of Heilongtan Spring shows a declining trend in January-June and November-December, while it shows an increasing trend in July-October. This is because the precipitation in Lijiang City is mainly concentrated from June to September. With the increase in precipitation during this period, Heilongtan Spring receives a significant recharge, causing the water table in the area to rise. As a result, the springs in the region increased in both numbers and the rate from June to September. Due to reduced precipitation, the groundwater level in the Heilongtan Spring area has decreased, resulting in a fall from June to September of the spring. There is a delay between the largest from June to September of Heilongtan Spring and the precipitation peak. The smallest from June to September occurs in June and July, while the maximum from June to September is observed in October and November, as shown in Figure 3b.

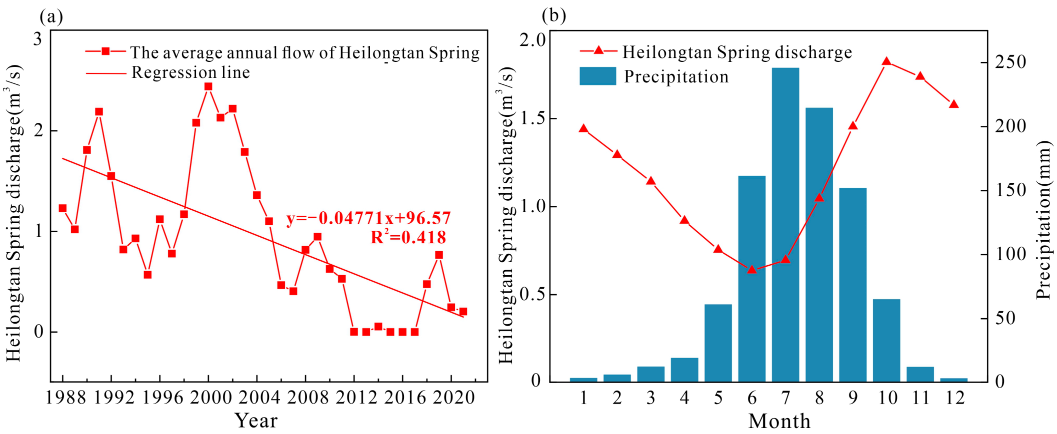


**Figure 3.** Characteristics of the discharge variation of Heilongtan Spring from 1988 to 2021: (**a**) interannual discharge variation; (**b**) intra-annual discharge variation.

### *4.2. Outflow Conditions of Heilongtan Spring*

An analysis was conducted on the yearly fluctuations of groundwater levels in Heilongtan Spring from 2013 to 2021. The study focused on three specific monitoring sites, namely Heilongtan Spring No. 2, No. 3 and No. 4, as seen in Figure 4. Using statistical methods, an analysis was conducted on the water level (monthly scale) fluctuations of monitoring wells No. 2–3 at Heilongtan Spring from 2013 to 2021. The study revealed a consistent trend in the water level changes of these monitoring wells. During low peak groundwater levels, the water level in monitoring well No. 4 of Heilongtan Spring is higher than the other two wells. However, during high peak groundwater levels, the water level in monitoring well No. 4 is lower than that of monitoring wells No. 2 and No. 3. This difference is because the three monitoring wells are positioned based on surface elevation, with monitoring wells No. 2 and No. 3 being the highest and lowest, respectively, at Heilongtan Spring. The three monitoring wells are arranged in order of decreasing surface elevation. The No. 2 well of Heilongtan Spring has an elevation of 2446.24 m and a depth of 100.65 m. The No. 3 well has an elevation of 2412.96 m and a depth of 52.83 m. The No. 4 monitoring well has an elevation of 2408.84 m and a depth of 50.70 m.

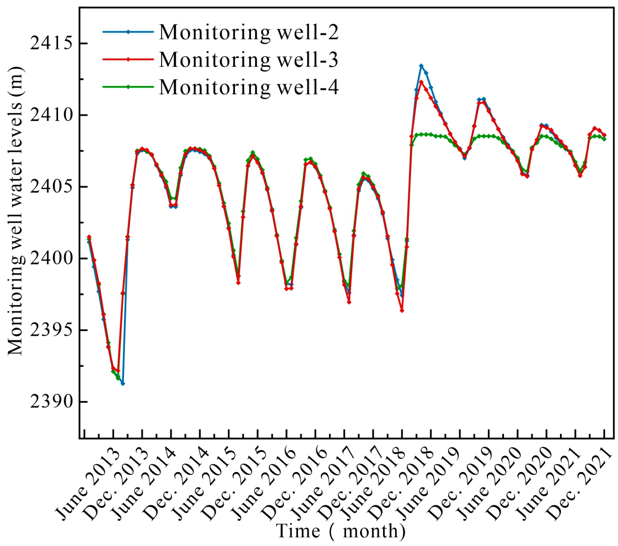


**Figure 4.** Dynamic changes in water level in the Heilongtan Spring monitoring well from 2013 to 2021.

Through field research, it was discovered that when the Heilongtan Spring dried up, water availability in the landscape was maintained by importing water from the adjacent river. There is a phenomenon of river water backflow at the spring point of No.4 monitoring well of Heilongtan Spring. During the drying-up period, the recorded water level in the No.4 monitoring well of Heilongtan Spring is inaccurate and should be considered a false water level. When the groundwater level rises from the Heilongtan Spring, monitoring well No. 4 at the spring will experience a minor overflow, causing the water level to be slightly higher than the surface elevation. The other two wells do not exhibit this phenomenon. Therefore, when the groundwater level at the Heilongtan Spring is high, the water level behavior differs slightly between monitoring well No. 4 and the other two wells at its peak value. To accurately represent the total fluctuation of groundwater level in the Heilongtan Spring area, we utilized the average values of water levels from monitoring wells No. 2–4 in the Heilongtan Spring for further study. Research has shown that the water level and discharge rate of the Heilongtan Spring follow a consistent pattern of change throughout the year, resembling a "V" shape. The lowest values occur in June and July, while the highest are observed in October and November. Its water level determines the outflow conditions of Heilongtan Spring. Analysis of the daily water level data from the past ten years shows that when the water level of Heilongtan Spring falls below 2407.7 m, the discharge may dry up. This is indicated by the water level breaking the warning line, as shown in Figure 5.

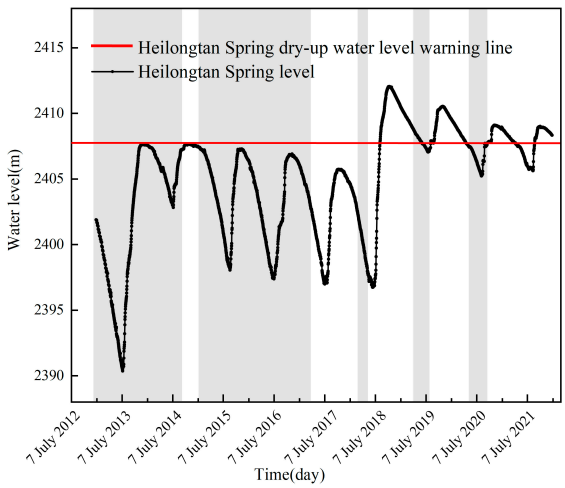


**Figure 5.** Dynamic changes in the water level of Heilongtan Spring from 2013 to 2021 (the shaded area represents the dry period).

### *4.3. Mutation Test Analysis*

The MK mutation test analysis was carried out to obtain the MK mutation test plot of annual precipitation at Lijiang station, see Figure 6a and ±1.96 and ±1.645 were taken as the MK test values for the critical curves also i.e., confidence test intervals at 0.05 and 0.1 significance levels. It was found that the precipitation in Lijiang City has a general decreasing trend and fluctuates with no significant trend from 1988 to 2005 and a decreasing trend after 2005 and this decreasing trend exceeds the critical line of significance level of 0.1 from 2013–2018. The observed forward and reverse series analyses showed multiple intersections within the confidence intervals.

The moving *t*-test is employed to conduct a secondary test on the intersection of the UB and UF series to clarify the mutation point and its position further. Based on the data in Figure 6b, the sliding statistic surpasses the significance level of 0.05 throughout 2014–2015. When paired with the findings of the MK mutation test, it can be concluded that there is a mutation point in precipitation around the year 2005.

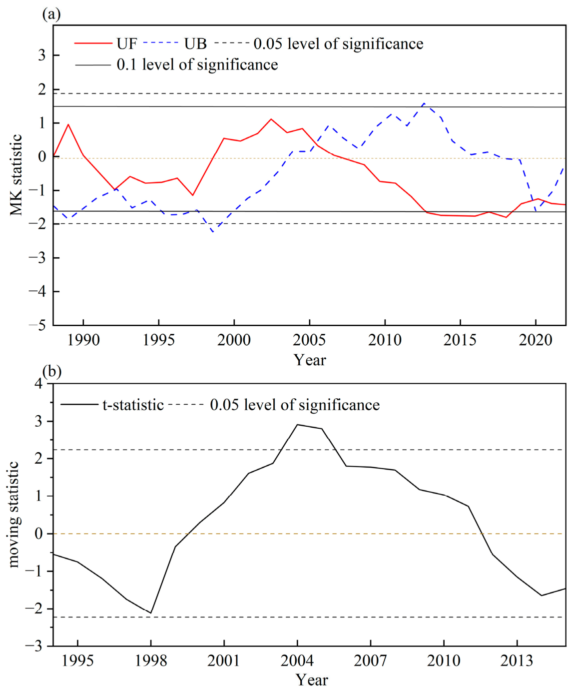


**Figure 6.** Mutation test analysis of annual precipitation in Lijiang City: (**a**) MK mutation test; (**b**) moving *t*-test.

Based on the analysis of the annual discharge data of Heilongtan Spring from 1988 to 2021 (Figure 7), it can be observed that there was no clear trend of increase or decrease in the discharge from 1988 to 2006. However, since then, there has been a consistent decrease in the discharge. In 2012, the discharge of Heilongtan Spring dropped below the −1.645 threshold (0.1 significance level), and passed the test of significance at the confidence level of 0.05, indicating a significant reduction in the average annual discharge. It was markedly reduced. Simultaneously, the sole crossing point between the two curves representing the forward series UF and inverse series UB occurred inside the confidence interval. Therefore, it can be concluded that the average annual discharge of Heilongtan Spring saw a severe decline starting from 2007. The mutation point in the average yearly discharge at Heilongtan Spring occurred around 2007.

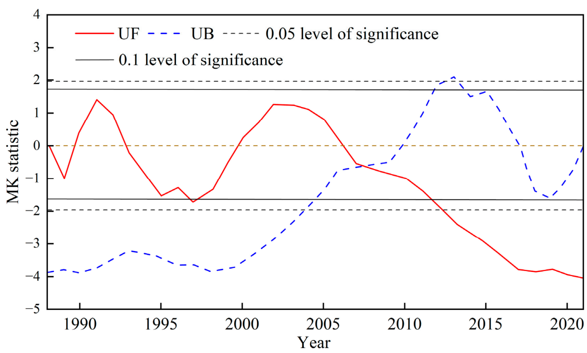


**Figure 7.** MK mutation test of annual discharge in Heilongtan Spring.

### *4.4. Characteristics of Cyclical Changes*

#### 4.4.1. Precipitation Wavelet Transform Analysis

Based on the annual precipitation data in Lijiang City from 1988–2021, there is no discernible pattern of increasing or decreasing precipitation in the Lijiang Dam area. Additionally, the intra-annual variations in different years indicate no significant shift in the timing of the maximum precipitation. It is worth noting that the highest precipitation levels consistently occur in July and August. The minimum precipitation was observed in January and December, while most rainfall in Lijiang City was concentrated between June and September. Figure 8 displays the wavelet analysis of monthly precipitation in Lijiang City. The mode-square value exhibits the highest and most intense energy in the time scale of 18–21 months, encompassing the entire time domain of the study. This indicates the most prominent variation in the first main cycle period of precipitation change in Lijiang City. Changes in cycle time to 12 months.

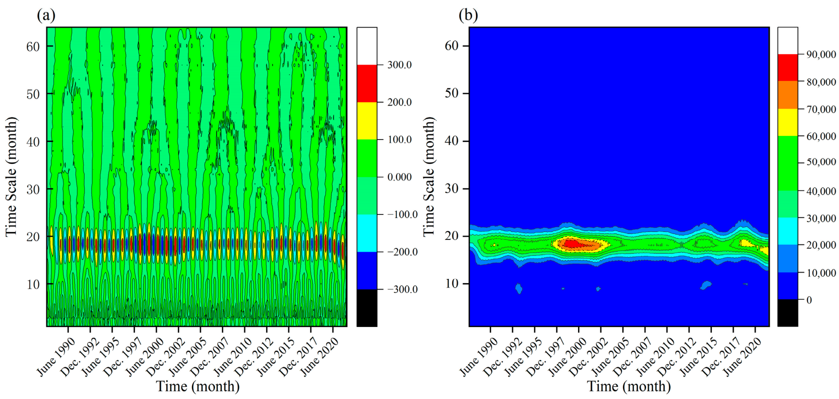


**Figure 8.** Wavelet analysis of monthly precipitation in Lijiang City: (**a**) accurate part contour map of Morlet wavelet coefficient; (**b**) modulus square contour map of Morlet wavelet coefficient.

### 4.4.2. Discharge Wavelet Transform Analysis

Figure 9 displays the wavelet analysis of the monthly discharge of Heilongtan Spring in Lijiang City. The study reveals that the main prominent cyclic change in the discharge of Heilongtan Spring occurs at a scale of 18–21 months, representing the first main cycle. Additionally, the mode square value, which indicates the cycle's strength, is highest at approximately 12 months and covers most of the study period. Another noticeable cycle change occurs at a scale of 50–60 months, representing the secondary cycle with a duration of about 36 months. However, this cycle exhibits localized characteristics, as it is not consistently evident throughout the entire period from April 2011 to December 2017. From 1988 to 2011 and from 2018 to 2021, the spring discharge was always high. However, from 2012 to 2017, the spring discharge was consistently low.

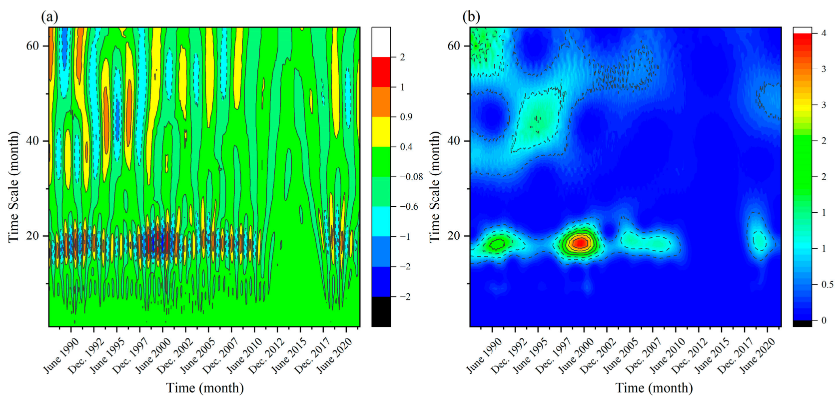


**Figure 9.** Wavelet analysis of monthly discharge of Heilongtan Spring in Lijiang City: (**a**) real part contour map of Morlet wavelet coefficient; (**b**) modulus square contour map of Morlet wavelet coefficient.

### 4.4.3. Wavelet Variance Test and Significance Test

To validate the accuracy of the wavelet transformation analysis results for the discharge rate of Heilongtan Spring and the precipitation in Lijiang City, a wavelet variance test was conducted on the monthly average discharge rate of Heilongtan Spring and the monthly precipitation in Lijiang City. The results are presented in Figure 10. The main cycle of precipitation in Lijiang City occurs every 18 months. Additionally, there is a secondary cycle with a peak around October. However, it is less noticeable com-pared to the primary cycle. Based on the analysis of Figure 10, it can be observed that the discharge of the Heilongtan Spring exhibits characteristics of multiple time scales. Four distinct peaks correspond to 10, 18, 40 and 55 months of oscillation cycles. The 18 month cycle is the most prominent and primary cycle among these cycles. This cycle aligns with the Heilongtan Spring discharge and the precipitation in Lijiang City, as indicated by the wavelet's natural part, mode square, and other linear plots.

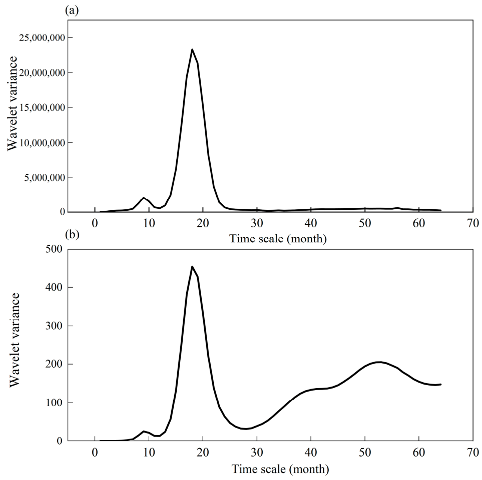


**Figure 10.** Wavelet analysis of monthly discharge of Heilongtan Spring in Lijiang City: (**a**) accurate part contour map of Morlet wavelet coefficient; (**b**) modulus square contour map of Morlet wavelet coefficient.

The overall wavelet power spectrum, defined as the cumulative average of the wavelet power spectrum at all times, is illustrated in Figure 11. The solid red line represents the 95% confidence test curve. When the red dashed line is situated below the wavelet power spectrum curve, this indicates that the corresponding periodicity feature of the zone passes the 95% confidence test. The two change cycles (10 m, 18 m) of precipitation in Lijiang City are significant cycles, and the four change cycles (10 m, 18 m, 40 m, 55 m) of spring discharge in Heilongtan, with only 18 m being a significant change cycle, and the remainder of the cycles being insignificant. These findings provide evidence for the cycle features in monthly precipitation and spring discharge in the study area.

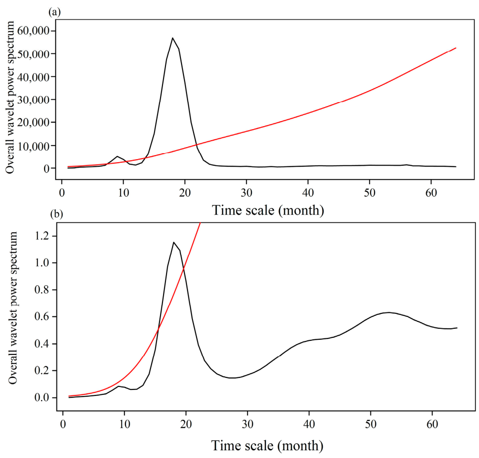


**Figure 11.** Overall wavelet power spectrum: (**a**) Lijiang Precipitation; (**b**) Heilongtan Spring discharge.

### 4.5. Analysis of the Response of Spring Level to Precipitation

Wavelet analysis reveals that the periodic fluctuations in precipitation over time align with the Heilongtan Spring discharge trend. Since 2012, there have been frequent interruptions in the Heilongtan Spring discharge, leading to its continued drying up. We used water level data from Heilongtan Spring from 2013 to 2021 to supplement the results of our analyses. To ensure the data's stationary, logarithmic processing and Augmented Dickey-Fuller (ADF) unit root test are employed simultaneously. The result is listed in Table 1.

**Table 1.** Result of ADF test.

| Sequence | *t*-Statistic | Critical Value at 1% Significance Level | *p*-Value | Conclusion |
|---|---|---|---|---|
| water level | −4.4487 | −4.0478 | 0.0029 | stationary |
| precipitation | −8.6628 | −4.0543 | 0.0000 | stationary |

The time series of each variable is stationary and can be modeled. The Granger causality test can test the causal relationship between the two variables, and the results show that the precipitation in Lijiang City significantly affects the groundwater level of Heilongtan Spring, which is also consistent with the actual situation. Then, the Johansen cointegration test is carried out on the two variables series to ensure that the model is stable and effective, and the results are shown in Table 2.

**Table 2.** Result of Johansen cointegration test.

| Trace Test | | | | | Maximum Eigenvalue Test | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Null Hypothesis | Eigenvalue | Trace Statistic | 0.05 Critical Value | *p*-Value | Null Hypothesis | Eigenvalue | Max-Eigen Statistic | 0.05 Critical Value | *p*-Value |
| r = 0 * | 0.312 | 48.105 | 15.494 | 0.000 | r = 0 * | 0.312 | 38.465 | 14.265 | 0.000 |
| r ≤ 1 * | 0.089 | 9.6398 | 3.842 | 0.002 | r ≤ 1 * | 0.089 | 9.639 | 3.841 | 0.002 |

Note: * Denotes rejection of the original hypothesis at the 5 percent significance level.

The results of the two tests indicate the existence of a stable long-term equilibrium relationship between the groundwater level of Heilongtan Spring and the precipitation time series of Lijiang City, with a significance level of 5%. Following the aforementioned data analysis, a bivariate VAR model was constructed, and the lag order of the established model was determined by the principle of taking the smallest value of the Akaike Information Criterion (AIC), the Schwartz Information Criterion (SC) and the log-likelihood value (logL). The results are presented in Table 3.

**Table 3.** Testing result of lag order.

| Lag | AIC | SC | logL |
|---|---|---|---|
| 0 | 17.24 | 17.292 | −860.002 |
| 1 | 14.567 | 14.723 | −722.357 |
| 2 | 13.925 | 14.186 | −686.275 |
| 3 | 13.926 | 14.291 | −682.346 |
| 4 | 13.956 | 14.425 | −679.839 |
| 5 | 13.964 | 14.537 | −676.227 |
| 6 | 13.954 | 14.632 | −671.745 |
| 7 | 13.903 | 14.684 | −665.158 |
| 8 | 13.853 | 14.739 | −658.672 |

The results showed that AIC, SC, and logL values were minimized when the lag order was 8th order. Therefore, the model lag order was determined to be 8th order. The stability of the model was assessed using the autoregressive (AR) characteristic root test (Figure 12). The inverse of the roots of the AR characteristic polynomials in Figure 12 are all within the unit circle. It indicates that the established VAR model is stationary, and the VAR impulse response function estimation can be used to assess how the water level of the Heilongtan spring responds to changes in local precipitation.

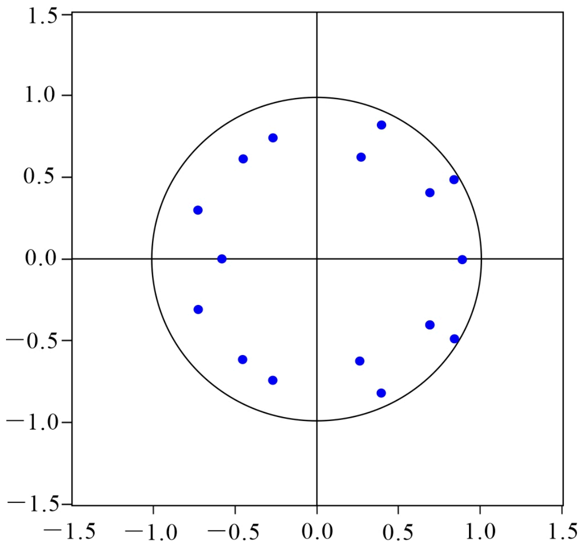


**Figure 12.** Stability test of VAR.

Based on the data presented in Figure 13, it is evident that the water level of Heilongtan Spring exhibited an immediate response to a 1-unit shock from Lijiang City. Subsequently, the water level gradually increased and peaked during the fourth period. Following this peak, the impact of Lijiang City's precipitation on the water level of the spring in Heilongtan diminished, eventually stabilizing at approximately 0. The plot of the impulse response function indicates that the precipitation in Lijiang City has a sustained effect on the water level of Heilongtan Spring. This effect is positive between the 2nd and 9th months but becomes negative after September. Subsequently, the impact stabilizes as the disturbance term continues to influence in a backward manner. The model findings indicate that the groundwater level of Heilongtan experiences its highest impact around the fourth month when it receives precipitation. Additionally, the water level of Heilongtan Spring in Lijiang City shows a noticeable delay in response to precipitation.

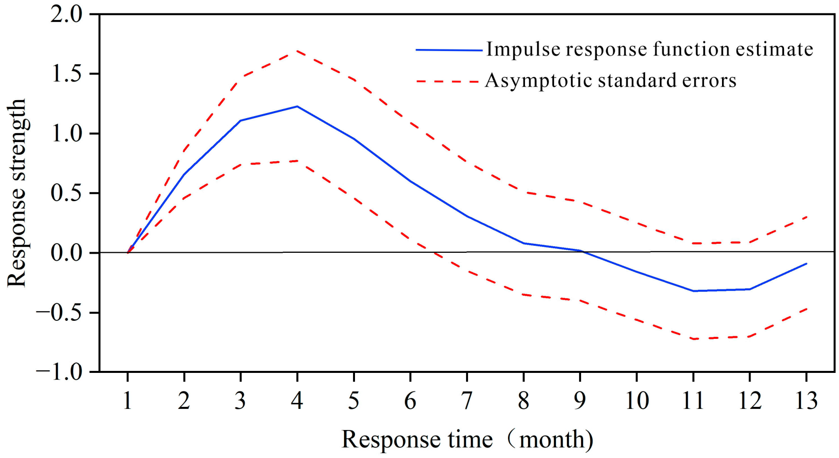


**Figure 13.** Impulse response using vector autoregression (VAR) results (water level of Heilongtan Spring response to precipitation variability (monthly scale), 2013–2021).

Based on the simulation findings of the VAR model, the groundwater level of Heilongtan Spring exhibits the highest magnitude of response to the precipitation impulse of Lijiang City in the third month. To further assess the feasibility of the VAR model simulation, we analyzed monthly precipitation and water level data from 2013 to 2021. The current month's precipitation was selected, along with lagged precipitation values from A1 to A7 (A0 denotes precipitation in Lijiang in the current month, A1 denotes precipitation in Lijiang with a lag of 1 month, A2 denotes precipitation in Lijiang with a lag of 2 months, A3 denotes precipitation in Lijiang with a lag of 3 months, A4 denotes precipitation in Lijiang with a lag of 4 months, A5 denotes precipitation in Lijiang with a lag of 5 months, A6 denotes precipitation in Lijiang with a lag of 6 months, and A7 denotes precipitation in Lijiang with a lag of 7 months). We conducted Spearman correlation analyses between the water levels of Heilangtan spring in the current month and the corresponding lagged precipitation amounts. The results in Table 4 indicate a strong and statistically significant correlation between the current month's Heilongtan Spring water level and precipitation with a 3 to 6 month lag. However, there is no significant correlation between the precipitation and the Heilongtan Spring water level when lagged by 1, 2 and 7 months. Overall, the highest and strongest correlation coefficients were observed at delays of 4 and 5 months. This finding reinforces the outcomes of the model simulation and suggests that the VAR model is suitable for assessing the impact of precipitation on groundwater levels.

**Table 4.** Correlation coefficient matrix between spring water level and precipitation.

| | Water Level | A0 | A1 | A2 | A3 | A4 | A5 | A6 | A7 |
|---|---|---|---|---|---|---|---|---|---|
| water level | 1 | −0.371 ** | −0.125 | 0.146 | 0.345 ** | 0.434 ** | 0.426 ** | 0.318 ** | 0.113 |

Note: ** Statistically significant ($p < 0.01$).

## 5. Discussion

The Heilongtan Spring in Lijiang City has experienced frequent drying up in recent years. To address this issue, the local government has implemented several measures. These include the Heilongtan Spring Protection Project in Lijiang City, Yunnan Province, which began in 2012. The Heibaishui River Diversion Project and the Lashihai Water Transfer Project in Lijiang City have also been implemented to ensure a particular water supply to the Heilongtan Spring. However, despite these efforts, the disconnection of the spring persists in the current climatic conditions, Figure 14. Hence, the primary focus of the forthcoming study should be on effectively restoring the Heilongtan Spring, enhancing the safeguarding of local water sources, and rehabilitating the ecosystem of the Heilongtan Spring.

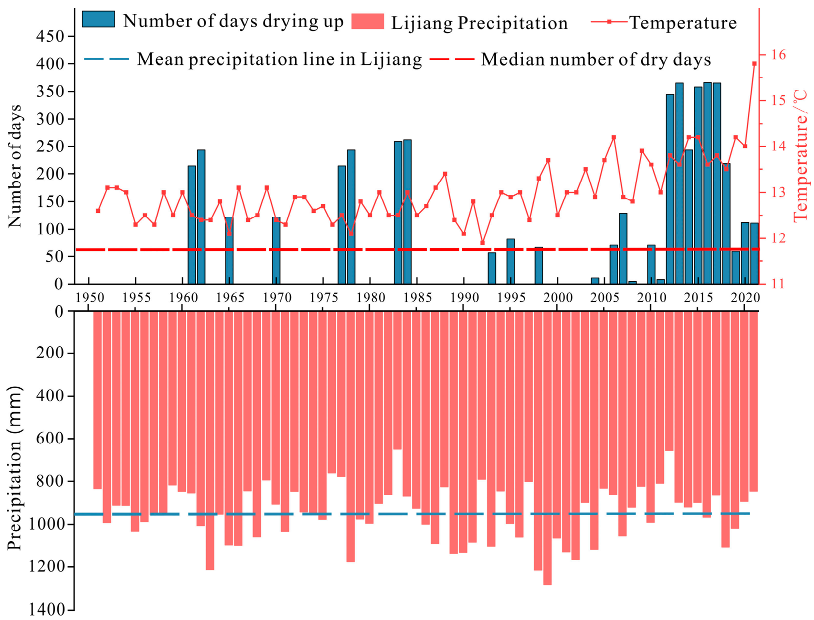


**Figure 14.** The occurrence of Heilongtan Spring has dried up in the past 70 years.

*5.1. Water Resources Conservation*

In conjunction with the aforementioned study, it becomes evident that there are discrepancies between the Heilongtan Spring discharge cycle change law and the precipitation patterns observed in Lijiang City. The precipitation cycle in Lijiang City is more stable, whereas the Heilongtan Spring discharge cycle demonstrates a tendency to fluctuate. The phenomenon above can be attributed to the influence of human activities on the Heilongtan Spring, which has resulted in a gradual reduction in the spring discharge. This leads to the cyclical manifestation of localized features. In recent years, Lijiang City has undergone a significant process of urbanization, with the rapid expansion of the urban area driven by tourism. This has increased groundwater discharge, with the artificial exploitation of groundwater representing a significant contributor to this phenomenon. The surge in groundwater exploitation has also led to a lengthening of the groundwater cycle time and a subsequent decrease in the sustainable utilization rate [39–41]. In the context of rapid urbanization and tourism development, the phenomenon of illegal and disorderly groundwater exploitation by various units and individuals in Lijiang City is particularly prevalent, with private groundwater extraction being a common practice. According to the available evidence, on 3 June 2017, the relevant authorities in Lijiang City Gucheng District and Yulong County initiated the sealing and filling of privately extracted groundwater wells in the central urban areas of Lijiang City, Yulong County City, Baisha, Shuhe, Xintuan, Huangshan and other central city planning areas. As of 24 August In total, 324 groundwater wells were sealed and filled in the area of Lijiang Dam, comprising 114 deep water wells and 210 shallow wells. With the further rebound of the groundwater level, by the beginning of 2018, although precipitation in Lijiang City began to decline year by year, the break in the discharge of the Heilongtan Spring showed a significant improvement. On the other hand, this expansion has increased impervious surfaces, such as asphalt pavements, which hinder the natural connection between the vadose zone, soil, and atmospheric precipitation [42]. As a result, surface infiltration is reduced, and groundwater recharge from atmospheric precipitation is also decreased. In light of the issue of reduced or even interrupted spring water flow, it is imperative to adopt a strategy of reasonable water diversion and recharge in order to guarantee a consistent supply of spring water. In terms of water resource recharge, precipitation is the primary source of recharge for the Heilongtan Spring in Lijiang City. In the Jiuzhihai area, which is the core recharge area for the Heilongtan Spring region, a barrage has been constructed on the Heishui and Baishui rivers. This has facilitated the introduction of the water source into the Jiuzhihai Depression through the use of canals and tunnels, thereby forming a natural reservoir. The water from the reservoir enters the seepage channel of the Heilongtan Springs via natural seepage, thereby increasing the natural recharge of the springs. A comparison of Lijiang City's precipitation and Heilongtan Spring flow cycle, coupled with an examination of the relationship between Heilongtan Spring flow and the lagged response of precipitation, indicates the necessity for the transfer of water from the nearby area. This transfer is required to ensure that the springs can still be adequately recharged during the dry season or in dry years, thus satisfying the local landscape demand.

*5.2. Water Quality Protection*

Urbanization and tourism will lead to excessive exploitation of groundwater resources and degradation of groundwater quality [43]. Tourism in Lijiang City primarily revolves around the ancient city of Lijiang (including the Heilongtan Spring scenic area) and the Jade Dragon Snow Mountain. However, the groundwater water environment in the Lijiang Dam area is facing significant issues due to urban sewage, landfill leakage, daily life water consumption, and pollution caused by tourism activities. In order to address the issue of spring water quality pollution, it is essential to implement rigorous control measures to prevent agricultural surface pollution and wastewater from ancient cities from entering the water source. Moreover, the formulation and enforcement of rigorous discharge standards are vital to guarantee the unpolluted quality of the water. Furthermore, the advancement of clean production technology, the reduction of pollutant emissions, the construction of sewage treatment facilities, the enhancement of the sewage network, and the gradual improvement of the karst water environment of the springs are actively pursued. The objective is to alleviate the scarcity of water resources in the springs and to achieve a more harmonious integration with economic development and social needs. In addition to the pollution caused by tourism and urbanization, the Heilongtan Spring in Lijiang City requires monitoring due to the river water backup phenomenon resulting from the spring-preservation and recharge project. The proximity of the water sources to the residential areas renders them susceptible to contamination and deterioration in water quality. Furthermore, the groundwater resources are situated in a relatively confined environment with limited mobility, which makes it challenging to resolve groundwater pollution. Therefore, it is necessary to regulate the water diversion of Lashihai River through targeted monitoring of the water diversion channels. During the period of enhanced monitoring of water quality and diversion process supervision, the discharge of Heilongtan Spring will be monitored in order to prevent a decline in groundwater quality from the source. This will help to mitigate the adverse effects of human activity on the Heilongtan Spring.

## 6. Conclusions

(1) Between 1988 and 2021, Heilongtan Springs' discharge rate substantially decreased, with an annual variation of 0.05 $m^3/s$. The discharge rate of Heilongtan Springs follows a similar pattern to the water level, forming a "V" shape throughout the year. The average monthly water level and discharge rate are at their lowest in June and July and reach their maximum values in October and November. The water level warning line for the drying up of Heilongtan Spring was set at 2407.7 m

(2) The trend of Heilongtan Spring discharge and Lijiang City precipitation change is similar. However, there are discrepancies in the mutation points of annual precipitation at Lijiang station and Heilongtan Spring discharge, as determined through mutation test analysis. Both the spring discharge of Heilongtan and the precipitation of Lijiang City exhibit a significant principal cycle of 18 months in terms of temporal changes. The temporal variation of the spring discharge cycle in the time series aligns with the trend in precipitation. The periods from 1988 to 2011 and 2018 to 2021 had consistently high spring discharge, while 2012 to 2017 consistently saw low spring discharge.

(3) A long-term, stable relationship exists between the water level of the Heilongtan Spring and precipitation in Lijiang City. This relationship can be modeled using a vector autoregression (VAR) approach. The VAR model demonstrates a clear lagged response of Heilongtan Spring's water level to the precipitation in Lijiang City. The fourth month's precipitation has the most substantial impact on the water level of the Heilongtan Spring. This, along with the correlation analysis, confirms the accuracy of the simulation results from the VAR model. The VAR model is an effective tool for evaluating how groundwater levels respond to precipitation.

**Author Contributions:** W.S. build the framework of the article; W.L., research data and analysis results; J.F., write the article and edited figures; P.Y. edit figures and typeset the article. All authors have read and agreed to the published version of the manuscript.

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