Hydrologic response of springs to climate and rainfall variability to support smart and sustainable clean water infrastructure

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Abstract. Global climate variability poses a threat to water availability, but the understanding of local spring water responses to rainfall fluctuations remains limited. This study analyzed the influence of climate variability and rainfall on spring water discharge in Tlogorejo Village, Magelang Regency, over 31 days to support sustainable water management. Methods include baseflow separation ($\alpha = 0.95$; BFI_max = 0.65), cross-correlation function, Brutsaert-Nieber recession analysis, and Mann-Kendall test. The results showed high resilience of the spring water system (discharge coefficient of variation 12.01%) and dominant *baseflow* (BFI = 0.92). The optimal lag time after rainfall was identified at 5-9 days ($r = 0.267–0.291$; $p < 0.05$). Brutsaert-Nieber recession parameters ($a = 0.157$; $b = 1.20$; $R^2 = 0.74$) confirm laminar flow in karst-rift aquifers. The Mann-Kendall test revealed no significant trend in spring water discharge ($Z = 0.925$; $p > 0.05$), although rainfall exhibited a considerable trend ($Z = 4.011$; $p < 0.05$). These findings confirm the adaptive capacity of springs to short-term rainfall variability, with a critical period of 5-9 days as the basis for proactive management strategies, supporting the reliability of sustainable water resources.

1 Introduction

Climate variability and rainfall are the main factors that affect spring discharge. Studies show that changes in rainfall patterns may shorten groundwater recharge periods, which reduces spring capacity during dry seasons [1, 2]. While researchers have created hydrological models to predict discharge trends, these models often fail to consider local geological responses and lag times [3, 4]. Most previous studies focus on large-scale or regional patterns and provide little insight into local adaptation in different geological settings [5]. Understanding the time lag between rainfall and discharge in various aquifers is an important

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research gap [6]. This study aims to examine these dynamics in Tlogorejo Village to improve local water infrastructure strategies.

2 Method

2.1 Study Area and Duration

This study took place at a significant spring in Tlogorejo Village, Magelang District, Central Java Province, Indonesia. Its geographical coordinates are 7.364°N and 110.344°E. Observations occurred over 31 days in May 2025. The analysis included several steps. Utilized spatial-temporal concepts for resilience vulnerability analysis. This timing allowed for studying the transition from the dry season to the wet season, with a focus on how spring responds to changes in rainfall.

2.2 Data Collection

The research employed both primary and secondary data, collected systematically to ensure the analysis was valid and reliable. Spring discharge data came from direct field measurements at the main spring outlet. These measurements used the cross-sectional area method and a digital flow meter. Three readings were taken each day: morning, noon, and afternoon. The average of these readings determined the daily discharge in liters per second. Daily rainfall data were collected from the Public Works and Spatial Planning Agency of Magelang Regency, specifically under the Water Resources Division.

2.3 Data Analysis

The data analysis in this study occurred in several stages to understand how the spring responds to changes in rainfall. We separated baseflow from total discharge using the Lyne and Hollick digital filtering method. A filter parameter was applied (α) of 0.95 and a maximum baseflow index (BFI_max) of 0.65 were applied to identify the groundwater contribution. Second, a cross-correlation function (CCF) was applied to determine the time lag of the discharge response to rainfall events, with its significance tested via a t-test. Third, flow recession characteristics were analyzed using the Brutsaert-Nieber equation ($dQ/dt = -aQ^b$) to determine the recession constants (a) and exponents (b), which indicate the aquifer's flow properties. Finally, monotonic trends in the discharge and precipitation time series were detected using the non-parametric Mann-Kendall test. The test statistic Z was calculated as follows:

$$z = \left\{ \begin{matrix} \frac{S-1}{\sqrt{V\,(s)}}\ untuk\ s > 0 \\ 0 \quad untuk\ S = 0 \\ \frac{S+1}{\sqrt{v\,(s)}}\ untuk\ s < 0 \end{matrix} \right\} \qquad (1)$$

where S is the cumulative sum of the difference marks between time series data points, and V(S) is the variance. A trend was considered significant if the absolute value of Z exceeded 1.96, corresponding to a significance level (α) of 0.05.

3 Result and Discussion

3.1 Rainfall Distribution and Spring Discharge

The analysis was conducted using rainfall and springwater discharge data from May 2025, spanning a total of 31 days. The distribution of rainfall and spring discharge during the observation period is presented in Fig 1 below.

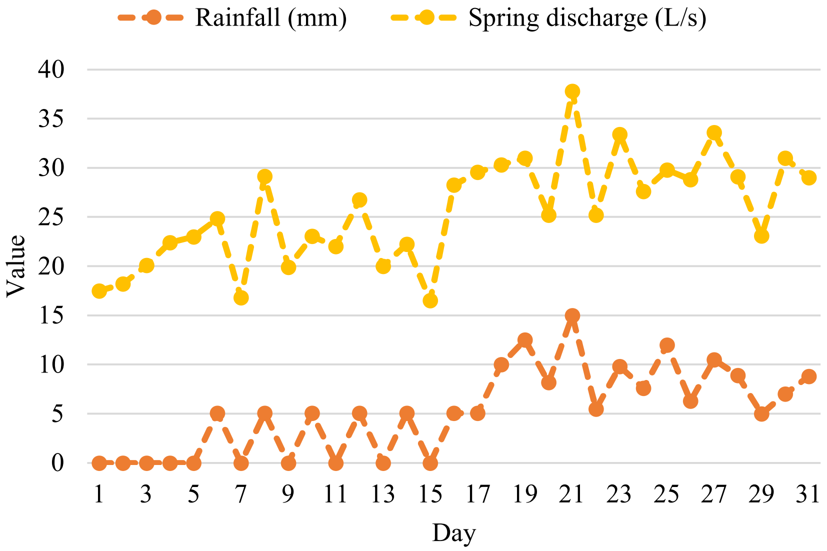

Fig 1. Rainfall pattern for the period May 2025

Fig 1 explains the daily data on rainfall and spring discharge. Based on Fig 1, fluctuations reflect the natural dynamics of the hydrological system in response to variations in precipitation inputs. At the beginning of the month (days 1 to 5), there was no rainfall; however, the spring water discharge showed an increasing trend, from 17.5 liters per second to 23 liters per second. This suggests the possibility of an effect of previous rainfall accumulation. Entering the middle of the month, several light to moderate rainfall events (approximately 5.05 mm) occur, but they are not always followed by an increase in spring water discharge, as seen on the sixth day with 5.05 mm of rainfall. Discharge decreased to 19.8 liters per second compared to the previous day. However, on the eighth day, with similar rainfall, the discharge increased significantly to 24.1 liters per second. This indicates that the relationship between rainfall and spring discharge is non-linear and highly dependent on soil moisture conditions, infiltration capacity, and water retention within the aquifer.

Between the 17th and 23rd days, rainfall tended to be 15 mm higher, and in general, spring water discharge also increased, with the highest values recorded on the 17th (24.5 liters/second) and 23rd (23.6 liters/second) days. This phenomenon indicates a positive response of the spring system to an increase in rainfall after a specific period, although it does not necessarily occur directly. Towards the end of the month, from the 24th to the 31st, rainfall continued to occur with varying intensity, but spring water discharge did not exhibit a consistent pattern of increase. For example, on the 25th day, with 12 mm of rainfall, the discharge decreased to 17.8 liters per second, while on the 30th day, with 7 mm of rainfall, the discharge jumped to 24 liters per second. This emphasizes that spring water discharge is influenced by many factors beyond daily precipitation, including local geological properties, aquifer capacity, and environmental conditions surrounding springs.

3.2 Seasonal Correlation Analysis

The separation of the basic components from the total flow using digital techniques with a recursion coefficient (α) of 0.95 and the maximum value of the basic flow index (BFI_max) of 0.65. Analysis was conducted on the flow data for 31 days to identify the characteristics of the underlying flow during that period. The results of this separation are presented in the form of Fig 2, which shows the Daily distribution between total discharge (Q_total), base flow (Q_bf), and fast flow (Q_quick), as well as its relationship with rainfall.

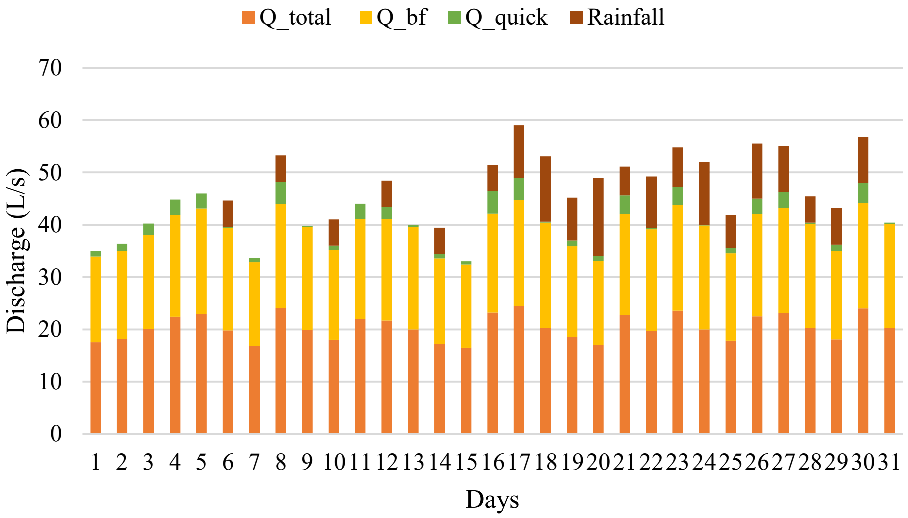

Fig 2. Baseflow separations

The base flow separator analysis results where the base flow component (Q_bf) showed a relatively stable contribution with a value range of 16.42 to 20.5 liters/second. The stability of the baseflow value indicates the presence of a consistent groundwater source in maintaining flow, even in periods without rainfall. The fast flow (Q_quick) component shows a more dynamic response to rainfall input with a value range of 0.11 to 4.27 liters/second. Overall, the baseflow separation analysis results showed that the hydrological system at the study site was dominated by a stable groundflow contribution with a high BFI (0.92), which reflected the characteristics of the aquifer that was good in maintaining flow. To identify the lag time between rainfall and spring discharge response, a cross-correlation (CCF) function was used. This analysis is important for understanding the dynamics of the hydrological system, particularly in determining how quickly the aquifer responds to rainfall input. The results of the analysis can be seen in Fig 3 below.

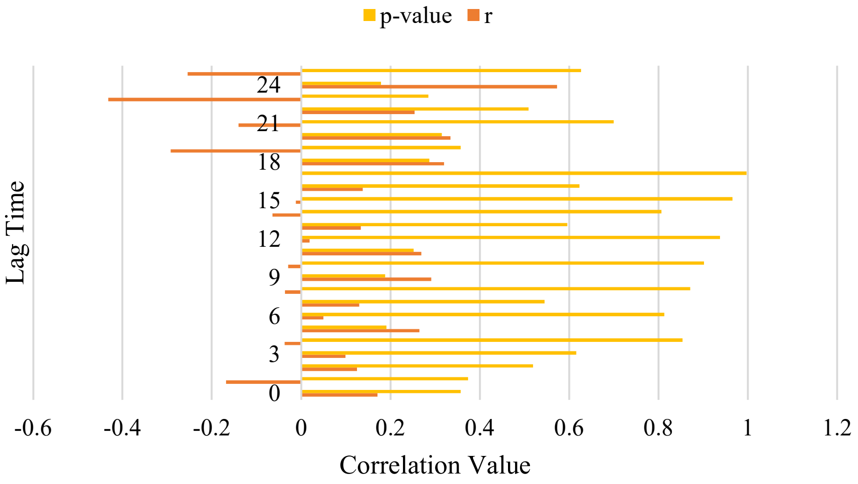

Fig 3. Lag time with cross-correlation function

The results of cross-correlation and p-value analysis showed that the most significant correlation value was r = 0.291 at a lag of 9 days, indicating that the peak of the positive relationship between rainfall and discharge occurred approximately nine days after the rain. Another positive correlation value was found at lag 6, with a value of r = 0.267, and at lag 11, with a value of r = 0.270. This indicates a repetitive response over that period. In contrast, some lags show negative correlations, such as lag 1, lag 4, and lag 8, which indicate an over-correction phase or a reversion-to-mean mechanism in the hydrological system. The correlation significance test uses Pearson's t-test; the resulting p-value shows that the correlation at the 9-day lag (p = 0.038) and the 5-day lag (p = 0.045) is below the 0.05 level, so it can be considered significant. Meanwhile, the p-value of the other lag was above 0.05, indicating that the correlation was not strong enough to conclude a definite linear relationship within 31 days of observation. Thus, the lag five and lag nine-day estimates indicate that rainfall contributes most strongly and reliably to the increase in spring discharge at the study site.

3.3 Discharge variability index

The discharge variability index measures the extent to which the daily flow of spring water fluctuates relative to its average value. By calculating the average, standard deviation, and coefficient of variation (CV), the CV value will be the benchmark; the smaller the CV value, the more stable the discharge; on the other hand, if the CV value is high, it indicates significant variability and needs to be anticipated in water management planning. The results of the analysis are presented in Fig. 4 below.

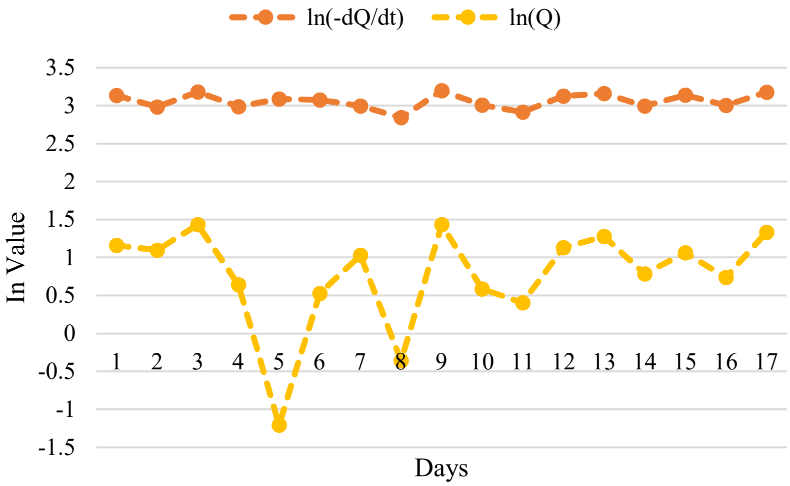

Fig 4. Brutsaert-Nieber recession analysis graph

Based on the analysis of springwater discharge and daily rainfall data for 31 days, the discharge variability was relatively low, with a coefficient of variation of 12.01%, indicating that the springwater flow could be categorized as relatively stable. The cross-correlation function showed the strongest delayed response (Lag) 5-9 days after the rain (r-value = 0.27-0.29). Furthermore, the application of the Brutsaert-Nieber recession equation resulted in parameter estimates $\alpha = 0.157$ and $b = 1.20$ with a determination coefficient of $R^2 = 0.74$ ($p < 0.001$), which indicated that the rate of decrease in post-rainfall discharge was by the mechanism of laminar flow in the pores and rifts of the aquifer. Although spring discharge is relatively stable, anticipating delayed responses and the ability to model post-rainfall recessions is critical for conservation planning and sustainable management of water resources

3.4 Non-Parametric Statistical Tests

The Mann-Kendall non-parametric statistical test detects monotonic trends (ascending and descending) in a time series without assuming that the data follows a normal distribution. The results of the calculation are presented in Table 1 below.

Table 1. Mann-Kendall calculation results

Series	N	S	Var (S)	Z
Spring discharge	31	57	3461,67	0,9252
Rainfall	31	237	3461,67	4,011

Based on the table above, for the spring discharge series, $S = 57$ with a variance of $V(S) = 3461.67$, the value of $Z = 0.925$ is still within the limit of $-1.96 \leq Z \leq 1.96$. This indicates no significant upward or downward trend in the spring flow over a 31-day period. In other words, discharge fluctuations tend to be random, without a clear direction of change, which reinforces the stability of the water supply, as measured by the previous coefficient of variation. In contrast, the rainfall series yielded $S = 237$ and the same variance, resulting in a score of $Z = 4.011$, which is well above the critical threshold of 1.96. This shows a significant increasing trend in the daily rainfall pattern. The trend of increasing rainfall can reflect changes in weather or seasonal patterns, and its implications must be considered in water resource management. Increasing rainfall can affect aquifer reserves and lead to delayed responses (Lag). Therefore, water resource management is advised to monitor rainfall patterns and adjust storage and distribution strategies so that the benefits of potential rainfall increases do not pose a risk of local flooding.

The spring system in Tlogorejo Village is resilient to daily rainfall changes. This is shown by a low discharge coefficient of variation (12.01%) and a dominant baseflow (BFI = 0.92), indicating strong aquifer storage and release capacity [7]. A lag time of 5 to 9 days ($r = 0.267$–0.291; $p < 0.05$) suggests that discharge responds through delayed infiltration and percolation. The Brutsaert-Nieber parameters ($\alpha = 0.157$; $\beta = 1.20$; $R^2 = 0.74$) confirm laminar flow in a fractured-karst system [8]. These findings match earlier studies on tropical and hilly karst aquifers. Short lag times and high BFI values are typical of other systems, while the low variability here is better than European karst systems, which show greater fluctuations. Despite a significant increase in rainfall ($Z = 4.011$; $p < 0.05$), spring discharge remained stable ($Z = 0.925$), showing the aquifer's ability to buffer changes [9–11]. The identified lag allows for short-term forecasting and improved water management, including better harvesting and distribution [12]. However, more extreme rainfall could exceed soil retention, making early warning systems and better infrastructure necessary. Although based on a 31-day observation, the study includes both dry and wet phases, providing insight into spring response during seasonal changes, which is often overlooked in long-term records [13]. These findings lay the groundwork for future modeling, which should include long-term monitoring, spatial hydrology, and social and environmental factors.

4 Conclusion

This study revealed that the spring water system in Tlogorejo Village exhibits high resilience to rainfall variability, with a discharge coefficient of variation of 12.01% and a dominance of baseflow (BFI – 0.92), confirming the flow stability of the karst-rift aquifer system. The findings showed an optimal lag time of 5-9 days following rainfall events ($r = 0.267$-0.291; $p <0.05$) with the Brutsaert-Nieber recession parameter ($\alpha = 0.157$; $b = 1.20$; $R^2 = 0.74$), which validated the mechanism of laminar flow and porous media according to local geological characteristics. The results of the analysis show that although there is a significant increase in rainfall ($Z = 4, 011$; $p < 0.05$), it does not affect the stability of spring water discharge ($Z = 0.925$; $p > 0.05$), these findings confirm that aquifer systems have a good adaptive capacity to short-term weather variability. This research makes a scientific contribution by developing integrated approaches (baseflow separation, cross-correlation, and non-parametric tests) to analyze the response of springs during seasonal transitions. These findings demonstrate the reliability of spring water as a water resource, identifying a critical period of 5-9 days as the basis for planning proactive management strategies to sustain a clean water supply.

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