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To cite this article: Yong-jie Wang *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **233** 032027

IOP Conf. Series: Earth and Environmental Science 233 (2019) 032027 doi:10.1088/1755-1315/233/3/032027

Cause Analysis of Groundwater Level Changes in a Seismic Monitoring Hole: A Case Study of Well Yu-11 in Kaifeng

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Abstract. Changes in groundwater levels provide important information for seismic monitoring and prediction, but groundwater-level changes can be caused by multiple factors that need to be analyzed carefully. In particular, the effects of changes in precipitation have masked information on activities internal to the Earth. It is therefore of great importance to effectively eliminate the influences of precipitation change on groundwater levels. Kaifeng Well Yu-11, whose water level has dropped remarkably in recent years, lies in a national earthquake key defense area. Based on daily well-water-level and precipitation data from Well Yu-11, this paper analyzes its water-level dynamics and precipitation variation characteristics using Pearson correlation and regression analysis methods. The results show that change in precipitation is not the cause of the abnormal drop in the water level of Well Yu-11.

1. Introduction

Groundwater is highlighted by its wide distribution, fluidity, and incompressibility, among other factors. When an aquifer lies in a well-sealed and confined system, groundwater functions as a "sensitive pressure gauge". In 1970, Bodvarsson [1] pointed out that a confined aquifer is akin to a body strain meter. Previous studies have shown that the pore pressure of a confined aquifer is related to the stress and strain of the aquifer, and variations in the water level of a monitored well is directly related to variations in the aquifer pore pressure [2,3]. Johnson et al. [4] studied variations in the pore pressure in the San Andreas Fault (United States) and argued that monitoring changes in the water level of a well near the active area of a fault is a possible method for measuring variations in the elastic stress deep inside the Earth. In 1979, Li [5] researched variations in groundwater levels caused by tectonic stress and derived an equation that relates variations in the aquifer water level to variations in vertical stress. Based on this equation, Wang et al. [6] used the data from a spouting-type water-level anomaly to invert the rapid variations of some local stress fields prior to an earthquake. Based on dynamic water-level data from more than 40 deep wells in North China, Huang and coworkers [7] investigated the current state of tectonic stress fields in North China using the relationship between earthquake occurrence and water-level dynamics. In addition, deep stress variations can be calculated from variations in the groundwater levels, which provides important information for earthquake monitoring and forecasting [8]. Clearly, water-level-monitoring data from seismic wells are of great value; therefore it is essential to establish a network to monitor seismic well-water levels.

There are many factors that affect groundwater levels. Natural phenomena, such as solid tides in the Earth, deep pressure variations, and fault creep, may interfere with the water pressure of an aquifer, resulting in variations in groundwater levels. Other factors, such as precipitation, artificial groundwater exploitation, and artificial water injection, can disturb the water-level dynamics of a well by changing the water volume in the aquifer. In addition, the water level of a monitored well is closely related to surface water; hence it is also affected by surface water levels [9]. Clearly, groundwater level dynamics are the result of many interacting factors [10,11]. This paper mainly focuses on precipitation as a factor and analyzes whether or not it affects the water-level dynamics of Well Yu-11.

Located at the boundary of Henan and Shandong, Well Yu-11 is in a national key earthquake defense zone. In recent years, there has been seismic activity in this area, which has become the key monitoring area of the Henan Earthquake Agency. Therefore, it is necessary to pay close attention to the development of earthquakes in this area, and to track earthquake trends in a timely manner. Well Yu-11 has been monitored for over 30 years. Previous monitoring data have revealed that external interference has little influence on Well Yu-11; however, this well is highly sensitive to crustal stress and strain, which enables the investigation and tracking of possible precursory information and to correlate it with significant water-level-decline anomalies in Well Yu-11. In addition, this method also provides a possible way to more accurately judge future seismic-activity trends in the area.

2. Research-area data

Well Yu-11 is located in Ruizhuang Village, Fuyang Town, in Lankao County of Henan Province, China, and its geographical coordinates are: 114°58′ E, 34°56′ N (figure 1). Located on the alluvial plain of the Yellow River, the Lankao areal landform includes two parts, namely the old path area of the Yellow River and the flood plain. The altitude distribution reveals that the northwest region is higher and the southeast region is lower in altitude by 50–70 m. The Yellow River, which flows through the research area in a northeasterly direction is the largest river in the research area.

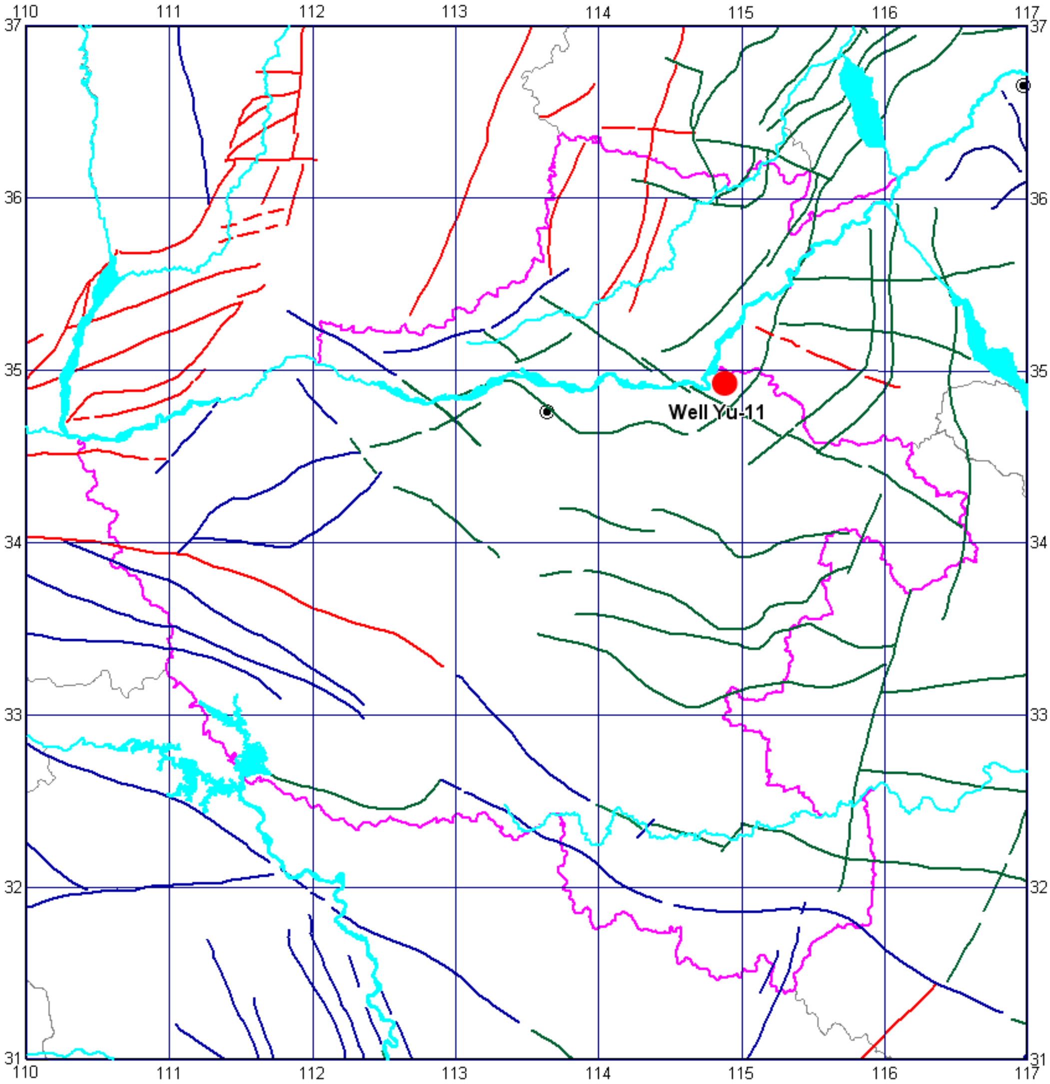

Figure 1. Location of Well Yu-11.

The structure of the Lankao area is complex [12], with uplifts and depressions distributed crosswise; these include the Dongpu Depression and the Luxi Uplift in the north-east direction, and the Zhongmu Depression, the Minquan Depression, and the Taikang Uplift. The directions of the main faults lie NNE-NE, NWW, and near EW. Among them, the NNE-NE Liaolan fault zone plays a dominant role because it is the main seismogenic and seismic structure in the area. There has been a series of moderately strong earthquakes near the fault over the years [13].

Well Yu-11 has a ground elevation of 69.9 m and is 3138.37 m deep. The cement sealing is positioned at 2908 m. The strata exposed by the wellbore, from the top to the bottom, are Cenozoic Quaternary and Tertiary, Paleozoic Carboniferous, Permian, and Cambrian (the Mesozoic Strata Lacuna, the Paleozoic Lacuna Devonian, Silurian, and Ordovician strata) [14]. The monitored aquifer is between 2908 and 3138 m deep, is 130 m thick, with a lithology of Cambrian braided limestone and argillaceous limestone of the Cambrian system. The well was completed on August 13, 1987. The type of groundwater is karst fissure-confined water, with a water depth following completion of 28 m. The groundwater level became officially monitored in 1989. An SWY-2 type automatic water-level recorder monitors the water level, and air pressure, water temperature, temperature, and precipitation, among others, are also recorded.

3. Research methods

Based on the mean well-water level and precipitation data from 2008–2017 at the Yu-11 earthquake monitoring well in Henan province, this study used graphical methods, namely Pearson correlation analysis together with regression analysis [15-17] to analyze the groundwater level dynamics and precipitation variations at Well Yu-11 so as to determine whether or not precipitation is the reason for abnormal variations in the water level of the Well Yu-11.

The amplitude of the well-water level (ΔW) is the difference between the maximum value W_{max} and the minimum value W_{min} of the well-water level over a period of time; i.e., $\Delta W = W_{max} - W_{min}$. In order to analyze the relationship between precipitation and variations in well-water level, this study selected these two variables and conducted correlation and regression analyses on the two variables to determine whether or not they are relevant in a given period of time.

3.1 Pearson correlation analysis

The Pearson correlation coefficient is used to measure whether or not two sets of data, x and y, are linearly related between the interval variables, with the correlation coefficient r calculated by [18]:

$$r=\frac{N\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{N(\sum x_i)^2}\sqrt{N\sum y_i^2 - (\sum y_i)^2}} \quad (1),$$

where a larger |r| is associated with a stronger correlation; the closer r is to 1 or -1, the stronger the correlation. Conversely, the closer the correlation coefficient is to 0, the weaker the correlation.

3.2 Regression analysis

For several sets of data, such as x_i, y_i (i = 0, 1, 2, 3..., n), if a functional relationship exists between x_i and y_i, then a polynomial can be used to fit the functional relationship [19]:

$$y = f(x) \approx a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n \quad (2).$$

The approximate polynomial expression that describes the functional relationship between the variables can be determined by locating the coefficients a_i (i = 0, 1, 2, 3..., n) of this polynomial. The correlation coefficient R can be obtained by the least squares method to determine the polynomial fit; the closer R is to 1 or -1, the better the fit and the closer the correlation coefficient is to 0, the poorer the fit.

4. Results and discussion

4.1 Water level and precipitation characteristics

4.1.1 Variations in well-water level. Groundwater level data for Well Yu-11 over the 2008–2017 period were selected, and a plot of the daily water level of this well was constructed, as shown in figure 2.

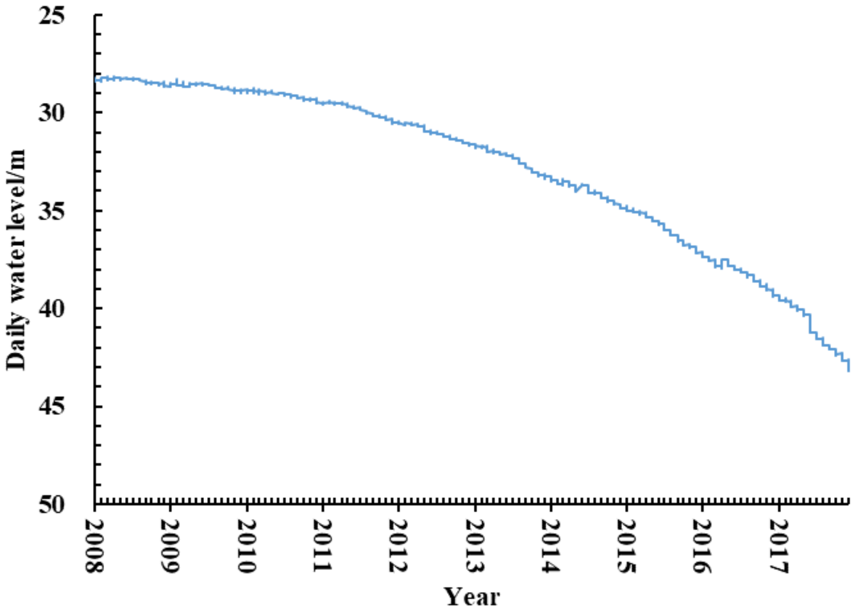

Figure 2. Daily water level (depth) of Well Yu-11 between 2008 and 2017.

Table 1. The average annual water level (depth) of Well Yu-11 between 2008 and 2017.

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Water level /m	28.350	28.648	29.085	29.848	30.997	31.906	31.764	35.754	38.010	41.030

Figure 2 and table 1 reveal that the well-water level has been decreasing from 2008 to 2017. The water level was 28.35 m deep in 2008; this depth increased to 41.03 m in 2017, at an average decline rate of 1.41 m/y. The average annual well-water decline rate was relatively small, at 0.57 m/y between 2008 and 2014, after which the average decline rate increased to 3.09 m/y in the 2014–2017 period. In addition, the water level exhibited small fluctuations during a single year, with the daily mean value changing slightly as a consequence. Overall, the water level of Well Yu-11 decreased year by year.

4.1.2 Variation in precipitation. Using the precipitation-monitoring data from the Well Yu-11 meteorological observatory (data between November 29, 2011 and October 31, 2012 were lost), graphs of monthly and annual precipitation at Well Yu-11 were constructed, as shown in figures 3 and 4.

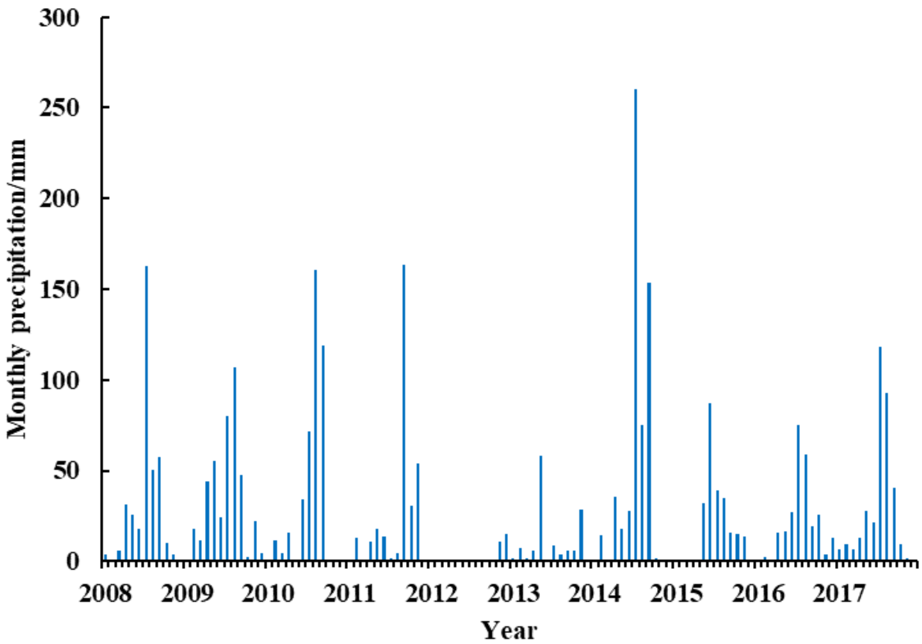

Figure 3. Monthly precipitation at the Well Yu-11 observation station between 2008 and 2017.

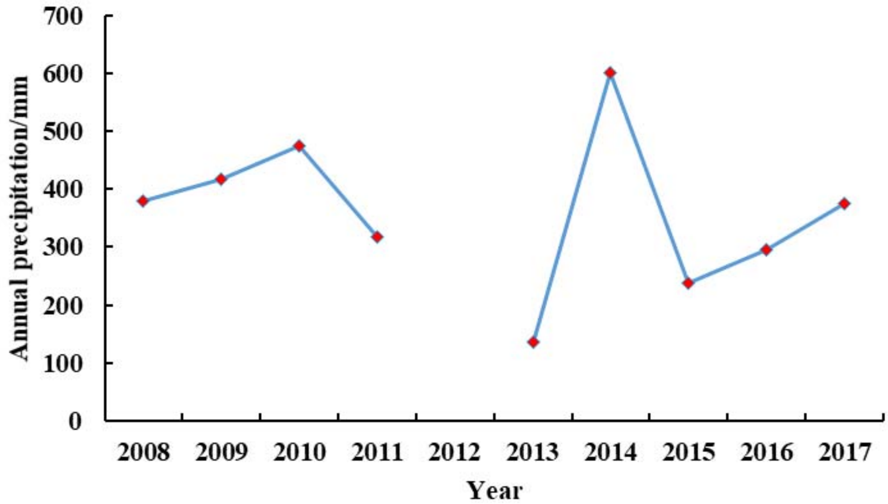

Figure 4. Annual precipitation at the Well Yu-11 observation station between 2008 and 2017.

Figures 3 and 4 clearly reveal that the annual precipitation at Well Yu-11 is 130–610 mm; annual rainfall does not show a significant increasing or decreasing trend. The precipitation during a single year shows a "valley-peak-valley" type trend between 2008 and 2017, with precipitation in each year mainly concentrated between April and September. The precipitation in this period accounts for more than 60% of the annual rainfall, while it accounted for 95% of the annual rainfall in 2014.

4.2 Analyzing the causes of groundwater-level variation

4.2.1 Relationship between precipitation and annual variations in water level. As described above, the annual water-level amplitude is obtain by subtracting the minimum value of the daily water level of Well YU-11 from the maximum value [20].The annual water-level amplitude of Well YU-11 and the annual precipitation at the well are shown in figure 5 as functions of time. Correlation and regression analyses on the annual water-level amplitude and annual precipitation were then carried out, the results of which are summarized in table 2 and shown in figure 6.

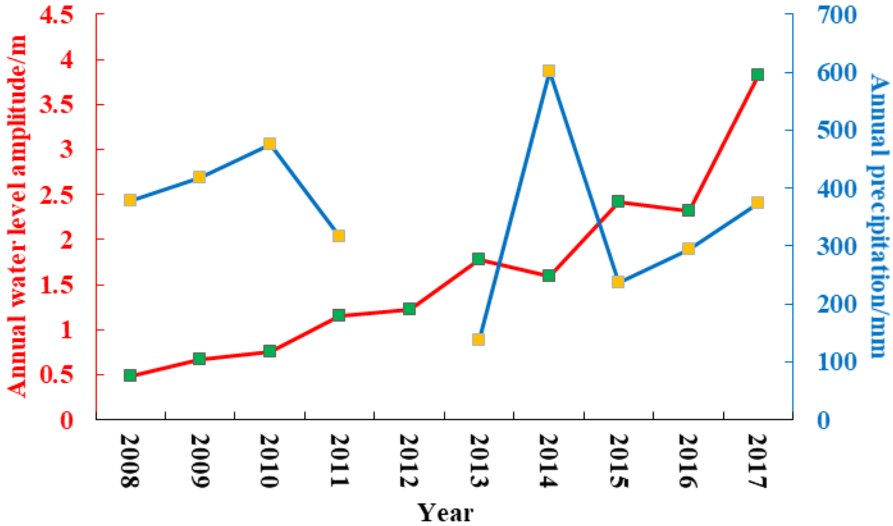

Figure 5. Annual precipitation and variations in water level at the Well Yu-11 observation station.

Table 2. Analyzing the correlation between annual precipitation and annual variations in water level at the Well Yu-11 observation station between 2008 and 2017.

	Correlation coefficient r	p
Correlation between annual well-water-level amplitude and annual precipitation	-0.268	0.485

Figure 5 reveals that the annual water-level amplitude of Well Yu-11 increased year by year, while the annual precipitation fluctuated without any clear increasing or decreasing trend. The year with the largest annual precipitation was 2014, with 601.1 mm of rain, while the year with the smallest annual precipitation was 2013, with just 136.7 mm.

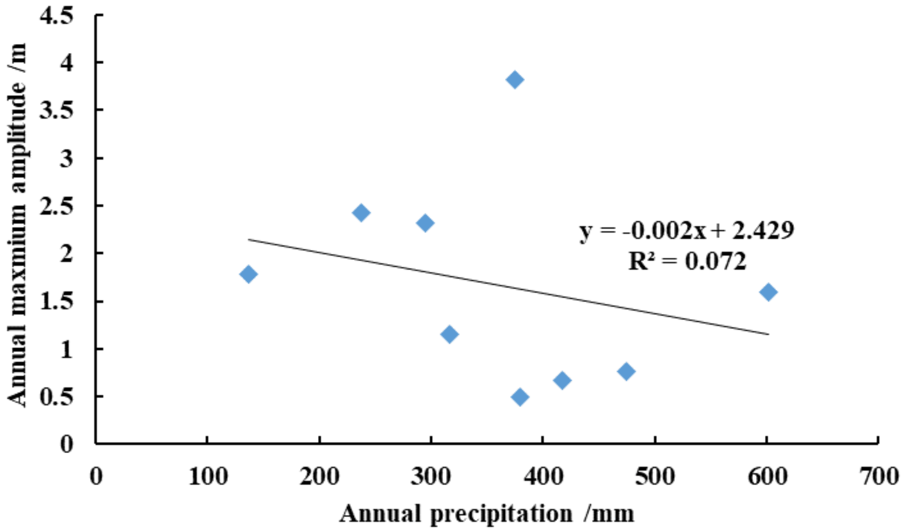

Figure 6. Correlation between annual precipitation and annual variations in water level at the Well Yu-11 observation station.

The linear regression result (figure 6) reveals that the annual water-level amplitude and the annual precipitation at Well Yu-11 are poorly correlated, with an R^2 value of 0.072. In addition, Pearson correlation analysis provided a correlation coefficient, r, of -0.268, indicating that the annual water-level amplitude and the annual precipitation at Well Yu-11 are uncorrelated. From these results, we conclude that no correlation exists between the annual well-water-level amplitude and the annual precipitation.

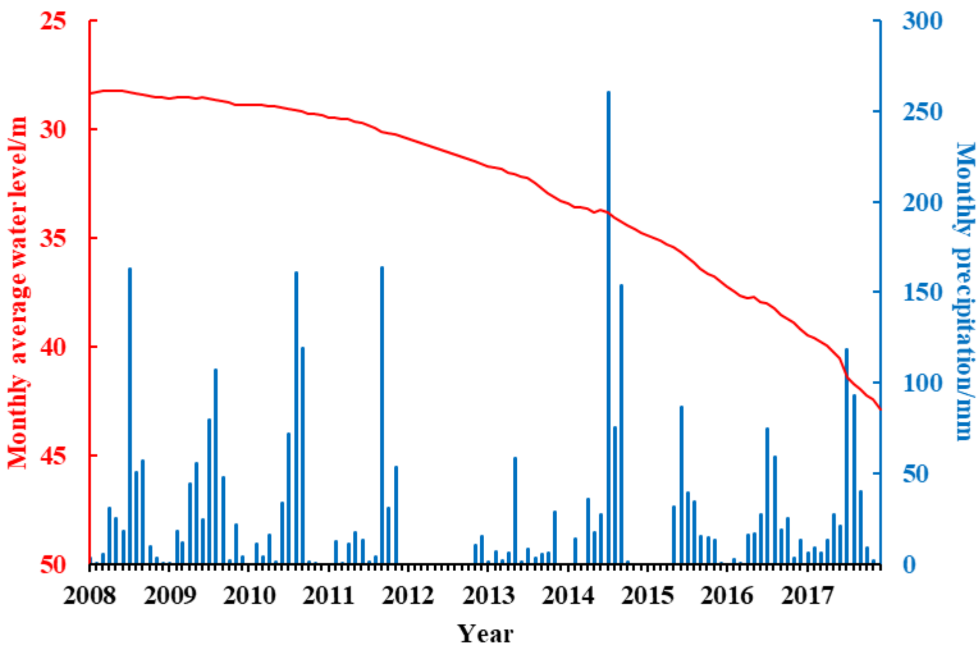

Figure 7. Monthly precipitation and mean water level at the Well Yu-11 observation station.

4.2.2 Relationship between precipitation and monthly variations in water level. The daily water-level and precipitation data at Well Yu-11 were treated to obtain monthly well-water-level and precipitation data, respectively; these data are shown as a coaxial plot in figure 7. The maximum and minimum values of the daily water-level data in each month were used to determine the well-water level amplitude in each month. Monthly water-level amplitude and precipitation plots for Well Yu-11 are displayed in figure 8, with the regression analysis results on the two sets of data shown in figure 9.

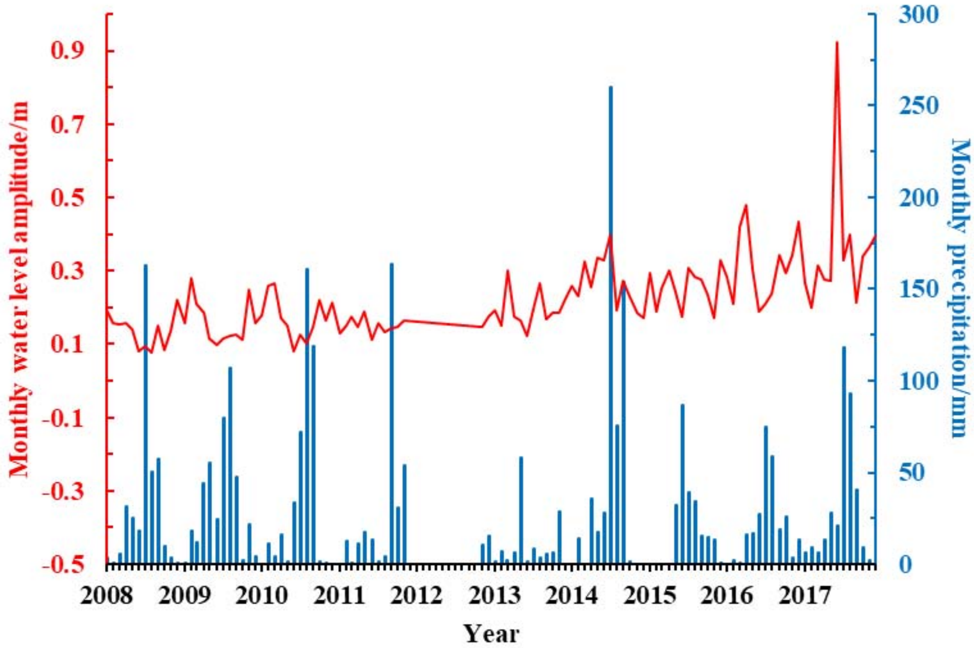

Figure 8. Monthly precipitation and monthly variations in water level at the Well Yu-11 observation station.

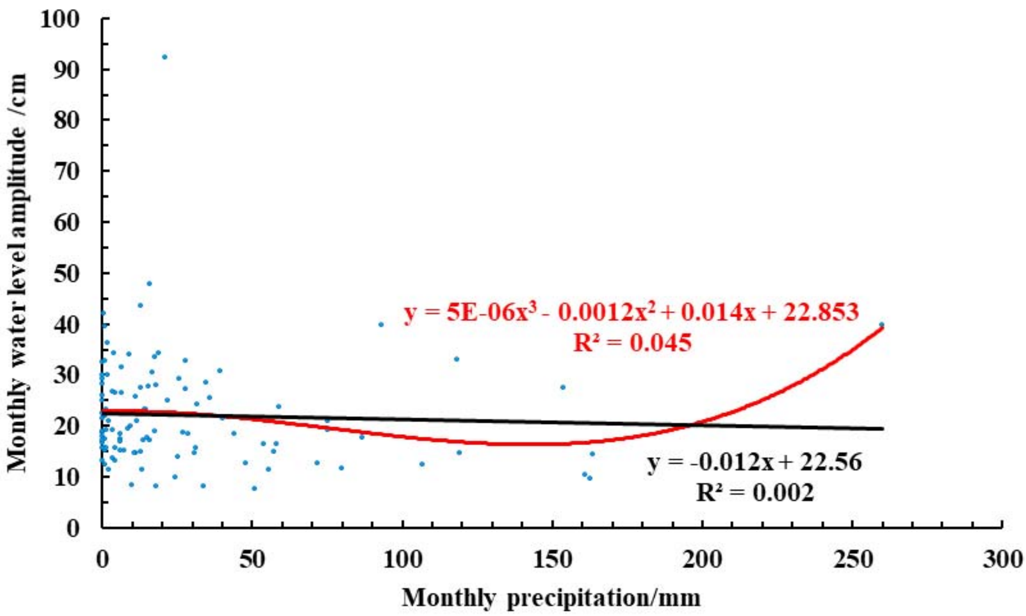

Figure 9. Correlation between monthly precipitation and monthly variations in water level at the Well Yu-11 observation station.

Table 3. Analyzing the correlation between monthly precipitation and monthly variation in the water level at the Well Yu-11 observation station between 2008 and 2017.

	Correlation coefficient r	p
Correlation between monthly well-water-level amplitude and annual precipitation	-0.048	0.618

The monthly mean water level of Well Yu-11 shows a significant decreasing trend from 2008 to 2017, from a depth of 28.33 m in January 2008 to a depth of 42.90 m in December 2017, with an average rate of decline of 0.12 m/month. Figure 7 reveals that, between 2008 and 2017, annual precipitation was mainly concentrated between April and September, but the corresponding well water level during this period shows no significant increasing trend due to increasing precipitation. The monthly well-water amplitude fluctuates, but with an increasing trend; except for June 2017, the monthly water-level amplitude lies in the 0–0.5 m range (figure 8).

In order to further investigate the relationship between the monthly well-water-level amplitude and monthly precipitation, the two sets of data are shown as a scatter plot (figure 9) and subjected to regression and correlation analysis (figure 9 and table 3). Linear regression analysis provides a linear correlation coefficient of 0.002, which reveals the lack of a linear relationship between the monthly water-level amplitude and monthly precipitation. In addition, the correlation coefficient from a cubic polynomial regression analysis was 0.045, which also reveals the lack of a good correlation between the two variables (figure 9). Pearson correlation analysis of the monthly well-water-level amplitude and monthly precipitation provided correlation a coefficient, r, of -0.048 ($p = 0.618$); correlation between these data are still not significant. Therefore, we can safely conclude that the monthly well-water-level amplitude of Well Yu-11 and the monthly precipitation at the well are not related according to the regression- and Pearson-correlation analysis results.

5. Conclusion

(1) The water level of Well Yu-11 declined at an average rate of 1.41 m/y between 2008 and 2017. Precipitation at Well Yu-11 in a single year followed a characteristic valley-peak-valley profile that was concentrated between April and September. Precipitation fluctuated slightly on an interannual basis, but no significant trend in annual precipitation was observed between 2008 and 2017.

(2) Correlation analysis reveals that the annual water-level amplitude of Well Yu-11 and the annual precipitation at the well are uncorrelated. Furthermore, the monthly well-water-level amplitude and the monthly precipitation at Well Yu-11 are also uncorrelated.

Therefore, the abnormal decline in the water level of Well Yu-11 between 2008 and 2017 is not the result of changes in precipitation.

Acknowledgement

Science for Earthquake Resilience(XH17021YSX) and The Science Foundation of Kaifeng (1708001).

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