Study on Runoff Characteristics and Countermeasures of the Upper Reaches of Nanpanjiang River Under the Background of Drought in Southwest China

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Abstract: Climate change can cause strong fluctuations in the hydrological series. From 2009 to 2013, the continuous drought in southwest China had a very adverse impact on local climate and hydrological elements. In this paper, Xiaolongtan Hydrological Station, an important hydrological observation station on the Nanpanjiang River basin in southwest China, was taken as the research object. Mann-Kendall method was used to analyze the trend and abrupt change of the long series of runoff from 1961 to 2018 in Xiaolongtan. On this basis, the contribution rate of climate change and human activities to the runoff change of Xiaolongtan Hydrological Station in Nanpanjiang was quantitatively analyzed by using the double mass curve method. The results show that: (1) the runoff of Nanpanjiang River basin decreased from 1961 to 2018, and abruptly changed in 1980. Human activities were the main driving factor for the annual runoff reduction of Nanpanjiang River basin, contributing 96.23% to runoff reduction, and precipitation contributed only 3.77% to runoff reduction. (2) The construction of Chaishitan Reservoir played a crucial role in the annual redistribution of water volume in the Nanpanjiang River basin, which greatly reduced the adverse impact of successive droughts on the surrounding areas of the Nanpanjiang River basin. The results of this study can alleviate the adverse effects of continuous drought on the Nanpanjiang River basin and provide an important reference for the rational allocation of water resources in the Nanpanjiang River basin under drought conditions.

1. Introduction
With the increasing human influence, the global temperature has shown a significant trend of increase over the past hundred years. According to the fourth IPCC report, the global warming rate in the middle and late 20th century reached the highest value since the observation data [1-3]. Climate change has lead to changes in regional water cycle, which in turn has had an important impact on changes in river runoff [4-5]. In particular, extreme climate lead to frequent flood and waterlogging disasters, which caused violent fluctuation of runoff sequence and seriously restricted regional economic development and ecological civilization construction.

As a major tool for quantitative analysis of river runoff changes under different driving factors [6-7], watershed hydrological model can dynamically simulate hydrological processes under different scenarios [8-9]. Based on watershed hydrological simulation, Wang et al. [10] proposed a quantitative identification method of runoff change attribution under changing environment, and applied it to the
analysis of influencing factors of runoff change in Fenhe River basin in the middle reaches of the Yellow River, and found that human activities were the main reason for runoff reduction in Fenhe River basin. Wang et al. [11] diagnosed the main causes of runoff changes of Chaobai River in the Haihe River basin. The results showed that human activities were the main cause of runoff changes of Chaobai River. Jiang et al. [12-15] studied Weihe River, Laoha River, Lanyi River and other rivers in China, and the results showed that human activities were the main reason for the decrease of annual average runoff in northern rivers. Climate change was a secondary driver, but its influence was gradually strengthened. Zhou et al. [16] showed that human activities and climate change contributed 42% and 58% respectively to the runoff change of Dongjiang River in the Pearl River basin. Yang et al. [17] showed that climate change contributed 65-68% to the annual runoff reduction of Shiqian Hydrological Station in the Hanjiang River, and climate change was the main reason for the runoff reduction in the recent 56 years. Deng et al. [18] studied the runoff sequence of Tianshan Mountain area. The results showed that under the condition of global warming, the melting of mountain glaciers and snow cover was the main reason for the increase of runoff in the region over the past half century. At present, most of the studies on runoff change have only analyzed the main factors that cause runoff change, but the studies on corresponding countermeasures are relatively insufficient, especially under the extreme hydrological scenarios such as continuous drought and continuous flood.

Since the 21st century, the Nanpanjiang River basin has experienced several special years of drought, especially five consecutive years of drought after 2009, which resulted in extensive disasters to crops and difficulties in living water, and seriously affected the normal production and life of people in the Nanpanjiang River basin. In view of this, according to the measured runoff at Xiaolongtan Hydrological Station in the upper reaches of the Nanpanjiang River, this paper used the Mann-Kendall method to analyze the evolution law of runoff, and the double mass curve method was used to quantitatively analyze the impact degree of climate change and human activities. According to the changes of runoff before and after the construction of the upstream water conservancy project, this paper analyzed its influence on the runoff distribution in the basin, so as to provide an important reference for the water resources distribution in the Nanpanjiang River basin under the drought scenario.

2. Overview of the Research Area and Data Sources

2.1. Overview of the Research Area

Nanpanjiang River belongs to the Pearl River Drainage system, and is the main source of the Pearl River. It originates from the southern foot of Maxiong Mountain in Wumeng Mountain range of Qujing City. Its source is 2444m above sea level. The main stream generally flows southward from the source to the west at Luliang, then turns southward after passing Yiliang. After passing Kaiyuan, it turns to the northeast and flows eastward along the boundary of Guizhou and Guangxi Province (Region) after leaving Yunnan at Sanjiangkou, and then flowing down to Beipanjiang River in Zhexiang, Guizhou Province, which is called Hongshui River.

The topography of the Nanpanjiang River basin is high in the northwest and low in the southeast. From its source to Shuangjiang Estuary in Wangmo, the length of the river is 914km, the average river ratio drops to 2.01‰, and the drainage area is 56880km². Where in Yunnan Province, the river length is 677km, the basin area is 433,42km², the average annual runoff is about 16.32 billion m³, and the drop is 1724m within the province.

The main stream and tributaries of the Nanpanjiang River are mostly curved, and the lakes and basins are mostly located on the tectonic line. The outcrops on the right side of the middle reaches are mainly sand shale and slates, and there are plateau lakes such as Fuxian Lake, Yangzong Lake, Xingyun Lake and Qilu Lake. The first level tributaries of Nanpanjiang River in Yunnan mainly include Haikou River, Qujiang River, Luijiang River, Dianxi River, Qingshui River and Huangni River, etc., whose catchment area is above 1000km².

The scope of this study is the basin above the river junction of Luijiang River in the middle of
Nanpanjiang River (excluding Lujiang River), with a total area of 15616km². There is Chaishitan Reservoir in the upstream. The research scope involves three four-level water resources subdivision areas: the first is Zhanquluyi District, covering an area of 6395.9km². The administrative areas include Zhanyi County, Malong District, Qilin District, Luliang County of Qujing City, Yiliang County and some areas of Shilin of Kunming City. The second is Qujiang District, covering an area of 5,972.7km², and its administrative districts include Hongta District, Chengjiang County, Jiangchuan County, Huaping County, Eshan County and Tonghai County of Yuxi City. The third is most of the lower section of the Nanpanjiang River main stream, which covers an area of about 3247.4km², mainly including parts of Shilin County of Kunming city, Kaiyuan City of Honghe Prefecture, and parts of Mile County. The research scope is shown in Figure 1.

2.2. Data Sources
Meteorological data were from China Meteorological Science Data Sharing Service Network. The annual precipitation data of Qujing, Malong, Shilin, Yiliang, Chengjiang, Jiangchuan, Huaning, Eshan and Tonghai stations from 1961 to 2018 were selected to calculate the average precipitation above the river junction of Lujiang River in Nanpanjiang River by using the Thiessen Polygon.

Xiaolongtan Hydrological Station was set on April 18, 1960 and moved 500m down in January 1967 as Xiaolongtan (II) Station. It is located at the foot of Xiaolongtan office, Kaiyuan City, with a collecting area of 15405km², longitude 103°11' and latitude 23°49' north and is an important national hydrographic station. The flow data series of Xiaolongtan Hydrological Station collected this time were measured runoff data from 1961 to 2018.

3. Research Method

3.1. Mann-Kendall Method
The Mann-Kendall method is a trend testing method, which is recommended by meteorologists and organizations at home and abroad and widely used in the non-parameter testing of meteorological data involving time series. This method is suitable for samples or populations with no distribution form, and has the characteristics of high quantization degree and wide detection range. Even if there is a small number of abnormal values, it does not affect the test results. As a non-parametric test method, the Mann-Kendall test is not affected by data distribution characteristics, and is widely used in the analysis of the variation trend of hydrological and meteorological time series [19-22].
Figure 1. Distribution of the upper reaches of Nanpanjiang River basin and hydrological stations.

Given the data of a certain time series, two sets of data sequences UFk and UBk can be calculated by Mann-Kendall method. If UFk > 0, the data sequence shows an increasing trend; if UFk < 0, the data sequence shows a downward trend; when it exceeds a significant level, it indicates a significant upward or downward trend. If there is an intersection point between UFk and UBk, and the intersection point is between significant horizontal lines, the time corresponding to the intersection point is the time when the mutation begins [23].

3.2. Double Mass Curve Method

The Double Mass Curve (DMS) method is currently the most intuitive and extensive method used to analyze the consistency of hydrological and meteorological elements or the evolution trend analysis of long series [24]. In the rectangular coordinate system, the continuous accumulation value of precipitation and the continuous accumulation value of runoff in the simultaneous period are plotted. If sudden change occurs in the hydrological sequence, the cumulative relation curve before and after will shift.

Set the linear relationship between the cumulative runoff amount (∑W) and cumulative precipitation (∑P) of the reference period as follows:

\[ \Sigma W = k \Sigma P + b \]  

(1)

Where, k and b are parameters.
Applying the above relationship of the reference period to the variation period (including the joint influence of precipitation and human activities), the total simulated cumulative runoff volume $\Sigma W$ can be calculated by the cumulative precipitation $\Sigma P$ of the variation period. At this point to calculate the amount of simulated runoff $\Sigma W$ if the same as the reference period where the conditions are approximately the same, in others words, no human activities affect the runoff.

### 3.3. Contribution Identification of Runoff Change Factors

At present, the main methods to quantitatively distinguish the contribution of climate change and human activities to surface runoff change at the watershed scale include: runoff reduction method based on hydrological model, elastic coefficient method, scenario simulation method, power exponential multiplication and multiple regression combination method, and cumulative slope method, etc. In this paper, runoff reduction method [25] based on hydrological models is adopted to quantify the contribution value of human activities and precipitation changes to runoff changes. The principle is as follows:

According to the abrupt change location of runoff, the reference period and the influence period of human activities were accurately divided, and then the meteorological, hydrological and land use data of the reference period were used to determine the hydrological model parameters. The meteorological data during the influence period of human activities were input into the model to restore the natural runoff $W_{sim}$ without land use change during the influence period of human activities, and the contribution value of human activities to runoff change $\Delta W_H$ and the contribution value of climate change to runoff change $\Delta W_C$ were calculated. The contribution rate $\eta_C$ and $\eta_L$ was calculated respectively using the runoff variation before and after the abrupt change. The specific calculation formula is as follows:

Total runoff change

\[
\Delta W_V = W_{post} - W_{pre} 
\]  

(2)

Runoff change caused by human activities

\[
\Delta W_H = W_{post} - W_{sim} 
\]  

(3)

Runoff change caused by precipitation change

\[
\Delta W_C = W_{sim} - W_{pre} 
\]  

(4)

Contribution rate of human activity

\[
\eta_C = \frac{\Delta W_H}{\Delta W_V} 
\]  

(5)

Contribution rate of precipitation

\[
\eta_L = \frac{\Delta W_C}{\Delta W_V} 
\]  

(6)

Where: $W_{post}$ is the measured multi-year average runoff in the period after the abrupt change; $W_{pre}$ is the measured multi-year average runoff in the period before the abrupt change; $W_{sim}$ refers to the multi-year theoretical average runoff simulated in the model of precipitation data input after the abrupt change.
4. Results and Discussion

4.1. Runoff Characteristic Value of Xiaolongtan Hydrological Station

Most of the major medium-sized reservoirs in the basin above the section of Xiaolongtan Hydrological Station were built in the 1950s. Among them, Huashan Reservoir was built in October 1958, Xihe Reservoir in May 1956, Xiaoxiang Reservoir in 1959, Dongfeng Reservoir in October 1960. Therefore, the operation of the above reservoirs had little influence on the consistency of the data series of Xiaolongtan Hydrological Station. However, the Chaishitan Large Reservoir was completed in 2001, with a catchment area of 4,656km², accounting for 30% of the controlled area of Xiaolongtan. The completion and operation of the reservoir had a significant impact on the consistency of the hydrologic data in Xiaolongtan.

According to the analysis of the measured annual mean flow data of Xiaolongtan Hydrological Station, the statistical parameters of the 1961~2000 data series and the 1961~2018 data series did not change significantly (see Table 1). Mann-Kendall method was further used to analyze the annual runoff of Xiaolongtan to verify the influence of Chaishitan Reservoir on the annual runoff of Xiaolongtan.

Table 1. Statistical parameter comparison table of the annual mean flow of Xiaolongtan Hydrological Station.

| Series   | Mean value (m³/s) | Cv  | Cs/Cv | Design frequency flow (m³/s) |
|----------|-------------------|-----|-------|-----------------------------|
|          |                   |     |       | 20%  | 50%  | 75%  | 90%  | 95%  | 97%  |
| 1961~2000| 125               | 0.37| 2.0   | 161 | 119  | 91.5 | 70.6 | 59.8 | 53.5 |
| 1961~2018| 116               | 0.34| 2.0   | 147 | 112  | 87.5 | 69.2 | 59.6 | 53.9 |
| Relative error (%) | -7.2 | -8.1 | 0.0   | -8.7 | -5.9 | -4.4 | -2.0 | -0.3 | 0.7 |

Due to the regulating effect of the reservoir, the annual runoff distribution process of Xiaolongtan has changed significantly. After the construction of Chaishitan Reservoir, the amount of water in dry season has obviously increased. It can be seen from Table 2 that from 2001 to 2018, the average flow rate of Xiaolongtan was less than the average flow rate of many years, which was 116m³/s. However, the average flow of dry season (From December to May of the next year) was higher than the average flow of dry season before the reservoir construction. This indicates that the reservoir plays a compensating and regulating role in the dry season, which plays a crucial role in the annual redistribution of water volume in the Nanpanjiang River basin, and greatly reduces the adverse effects of successive droughts on the surrounding areas of the Nanpanjiang River basin.

Table 2. Comparison of the flow of Xiaolongtan Hydrological Station in dry season before and after the construction of the reservoir.

| Series   | Mean annual flow rate (m³/s) | Average flow from December to May (m³/s) |
|----------|-------------------------------|------------------------------------------|
| 1960~2000| 125                           | 41.9                                     |
| 2001~2018| 96.4                          | 44.7                                     |

4.2. Meteorological and Hydrological Elements of Xiaolongtan Hydrological Station

Based on the measured precipitation data, the annual variation process line of the average precipitation in the upper reaches of the Nanpanjiang River from 1961 to 2018 was drawn and linear fitting was performed, as shown in Figure 2. It can be seen from the figure that from 1961 to 2018, the annual precipitation of Xiaolongtan Hydrological Station showed a trend of decrease. The Mann-Kendall test was used to analyze the trend of significant changes in precipitation process. When the significance level α=0.1, calculate trend test statistics Z = -0.51, Zα/2 = 1.28, and |Z| < Zα/2, the decreasing trend of precipitation series is not significant.
According to the measured runoff data, the annual runoff change process line of Xiaolongtan Hydrological Station from 1961 to 2018 was drawn and linear fitting was performed, as shown in Figure 3. It can be seen from the figure that from 1961 to 2018, the annual runoff volume of Xiaolongtan Hydrological Station showed a trend of decrease. The Mann-Kendall test was used to analyze the significant variation trend of the measured annual runoff series in Xiaolongtan Hydrological Station. When the significance level $\alpha=0.01$, calculate trend test statistics $Z = -3.01$, $Z_{\alpha/2} = 2.58$ and $|Z| > Z_{\alpha/2}$. The runoff sequence showed a significant downward trend and had a high significance level.

4.3. Runoff Abrupt Change Test Results of Xiaolongtan Hydrological Station

The mutagenicity analysis of annual runoff of Xiaolong was carried out by using the Mann-Kendall mutation test method, and the Mann-Kendall mutation analysis statistics were plotted out the UFK and UBK curves, as shown in Figure 4. From the figure, it can be seen that from 1965, UFK value has been greater than 0, indicating that the annual runoff began to show an increasing trend. Since 1975, UFK value has been less than 0, indicating a downward trend in annual runoff. In 2010, it exceeded
the lower limit of 0.001 significance level, indicating that the rate of runoff decline accelerated and showed a significant downward trend during this period. At the same time, there is an intersection point of UFK and UBK curves in 1980, that is, the abrupt transition point is 1980, which further indicates that the construction of Chaishitan Reservoir in 2001 is not the factor affecting the abrupt change of annual runoff. The abrupt change year is taken as the cut-off point of the hydrological sequence, with 1959~1980 as the reference period and 1981~2018 as the variation period.

4.4. Quantitative Assessment of Runoff Impact of Xiaolongtan Hydrological Station
In order to quantitatively analyze the influences of human activities and precipitation on runoff respectively, a double mass curve of precipitation and runoff from 1961 to 1980 was established, as shown in Figure 5. It can be seen from the figure that the basic relation between the two is \( \sum W = 0.1407 \sum P - 31.213 (R^2 = 0.9961) \). In this stage, the measured average annual runoff is 138.7 m\(^3\)/s, while the theoretical average annual runoff is 142.7 m\(^3\)/s, with an absolute error of 4.0 m\(^3\)/s and a relative error of 2.90%, indicating that the fitting accuracy of this method is relatively high. The theoretical value of the annual cumulative runoff in the abrupt year is obtained by substituting the precipitation in 1981~2018 into the reference relationship.

The concept of contribution rate is used to quantitatively analyze the impact of human activities and precipitation on runoff after 1980, as shown in Table 3. As can be seen from the table, the contribution rate of human activities to runoff reduction is relatively large, which is 96.23%. The contribution rate of precipitation to runoff reduction is only 3.77%. It shows that human activities have great influence on the decrease of the runoff of Xiaolongtan Hydrological Station.
5. Response Measures

(1) To further play the regulating role of water conservancy projects, especially reservoirs with annual regulating properties. The water storage should be increased as much as possible in the wet season to avoid the shortage of water for living and production due to the lack of water in the dry season.

(2) To further increase the intensity of water conservation and emission reduction, and constantly improve the watershed water ecological environment. The level of water saving in the Nanpanjiang area has not been fully matched with the economic and social development. It is suggested to further strengthen the reform of water supply side and strengthen the construction of water-conserving society. At the same time, the efforts to save water in industry should be intensified, especially in agriculture. We should continue to increase the proportion of ecological water use, especially in river courses, reduce water use and reduce emissions, so as to create conditions for the restoration and improvement of the ecological environment in river basins.

(3) To further handle the relationship between the newly added water supply and the total annual water supply. With the modification and improvement of the strictest water resources management system, strict control standards have been set for industrial, agricultural and domestic water use in various regions. In the process of using water, the regions should strictly follow the strictest water resource management system and use water according to water quantity.

6. Conclusions and Suggestions

Based on the continuous drought in southwest China in 2009-2013 of extreme climate conditions, this paper uses the Mann-Kendall test method to conduct a quantitative analysis of runoff sequence characteristics and influencing factors of Xiaolongtan Hydrological Station, an important hydrological...
observation station in the Nanpanjiang basin. Combined with the latest measures for water resources conservation, protection and management, corresponding countermeasures are proposed for the areas around the Nanpanjiang River under extreme drought conditions. The conclusions are as follows.

(1) From 1961 to 2018, the precipitation of Nanpanjiang River basin showed a decreasing trend, but the trend was not obvious. The runoff showed a trend of decrease and a highly significant level.

(2) The annual runoff of the Nanpanjiang River basin had a sudden change in 1980, with 1959~1980 as the reference period and 1981~2018 as the variation period. After the abrupt change of runoff, human activities are the main driving factor for the annual runoff reduction in the Nanpanjiang basin, contributing 96.23% to the runoff reduction, and precipitation contributing only 3.77% to the runoff reduction.

(3) The construction of Chaishitan Reservoir had little impact on the annual runoff sequence of Nanpanjiang River. At the same time, it played a crucial role in the annual redistribution of water volume in the Nanpanjiang River basin, which greatly reduced the adverse effects of successive droughts on the surrounding areas of the Nanpanjiang River basin.

(4) In view of the continuous drought situation in The Nanpanjiang River basin, combined with the current water resources conservation, protection and management system, this paper put forward suggestions on the utilization and conservation of water resources in the Nanpanjiang River basin for reference.

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