Temporal and Spatial Variation of Water Yield Modulus in the Yangtze River Basin in Recent 60 Years

Xiaoqing Shi¹,², Baisha Weng¹,², * and Tianling Qin¹,²

¹State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
²Department of Water Resources, China Institute of Water Resources and Hydropower Research, Beijing 100038, China

*Corresponding author e-mail: baishaweng@126.com

Abstract. The Yangtze River Basin is the largest river basin of Asia and the third largest river basin of the world, the gross water resources amount ranks first in the river basins of the country, and it occupies an important position in the national water resources strategic layout. Under the influence of climate change and human activities, the water cycle has changed. The temporal and spatial distribution of precipitation in the basin is more uneven and the floods are frequent. In order to explore the water yield condition in the Yangtze River Basin, we selected the Water Yield Modulus (WYM) as the evaluation index, then analyzed the temporal and spatial evolution characteristics of the WYM in the Yangtze River Basin by using the climate tendency method and the M-K trend test method. The results showed that the average WYM of the Yangtze River Basin in 1956-2015 are between 103,600 and 1,262,900 m³/km², with an average value of 562,300 m³/km², which is greater than the national average value of 295,000 m³/km². The minimum value appeared in the northwestern part of the Tongtian River district, the maximum value appeared in the northeastern of Dongting Lake district. The rate of change in 1956-2015 is between -0.68/a and 0.79/a, it showed a downward trend in the western part but not significantly, an upward trend in the eastern part reached a significance level of α=0.01. The minimum value appeared in the Tongtian River district, the largest value appeared in the Hangjia Lake district, and the average tendency rate is 0.04/a in the whole basin.

1. Introduction

The WYM refers to the gross water resources amount (the amount of surface water and groundwater that does not overlap with surface water generated by precipitation) per unit area. It can eliminate the influence of the size of the basin, and explain the characteristics of the water resources change associated with the natural geographical conditions. The water resources in Yangtze River Basin are rich, and it occupies an important position in the national water resources strategic layout. The famous Three Gorges Project and the South-to-North Water Diversion Project are located here. This basin is located in the subtropical monsoon climate zone, which is affected by the monsoon climate. The spatial and temporal distribution of precipitation is uneven, the inter-annual variation is large and concentrated on
the year. Combined with global climate change and human activities, the floods are frequent, the effective utilization of water resources needs to be improved.

For the previous study in the Yangtze River Basin about water resources, mostly focused on rainfall and runoff analysis. Some scholars have studied the whole Yangtze River Basin. Zhang et al. (2006) used the M-K trend test and linear regression analysis to study the characteristics of water and sediment in the runoff stations in the Yangtze River basin [1]. Xu et al. (2008) used the rainfall-runoff model to analyze the hydrological-climatic data of the entire Yangtze River Basin for nearly 40 years [2]. Chen et al. (2014) divides the Yangtze River Basin into three parts: upper, middle and lower reaches, then analyzed the changes in precipitation, temperature and runoff during 1955-2011 and the relationship between them [3]. Some other scholars have studied only the tributaries of the Yangtze River. Yan et al. (2016) using the cumulative anomaly method and the M-K trend test method to analyze the trend of the long series of annual flow in the typical stations of the Hanjiang River Basin, and use the moving t-test method and sequential cluster method to analyze the mutation of annual runoff [4]. Shao et al. (2012) based on the measured data of three hydrological stations and 80 rainfall stations in Wujiang River Basin, used the M-K test and Kendall-τ correlation test method to analyze the variation trend of annual runoff and precipitation [5].

At present, there are few studies on the WYM. Gao et al. (2005) selected the WYM as an indicator to evaluate the natural water availability in a region for water resources assessment [6]. While the runoff modulus is relatively more. Xiong et al. (2011) using the DELTA method to calculate the increase and decrease of runoff modulus in Guizhou Province under the A2 and B2 scenarios according to the HadCM3 model, so as to provide the basis of optimizing the allocation of water resources and determining the key areas of soil and water conservation management [7]. Wen et al. (2013) selected the runoff modulus as an indicator to study the effect of land use change on the water yield characteristics of the basin [8].

Throughout the previous studies, we found that most scholars only analyze the temporal and spatial distribution characteristics of surface runoff in the Yangtze River Basin, and rarely involve the gross water resources amount. WYM as an evaluation indicator not only includes the gross water resources amount, but also can eliminate the influence of the size of the basin, and the water resources evaluation is more accurate. To identify the spatial and temporal distribution and evolution of WYM in the region, can provide a strong scientific basis of maintaining the sustainable use of water resources and water resources management.

2. Materials and Methods

2.1. Study area and Data

The Yangtze River Basin is the largest river basin of Asia and the third largest river basin of the world, located in 91~122°E and 25~35°N, across three major economic zones in the eastern, central and western, contains 19 provinces and autonomous regions [9]. The Yangtze River originated in the Tibetan Plateau, the total length is about 6300km. There are 49 tributaries of the basin area more than 10,000 square kilometers, mainly includes Minjiang, Chishui, Tuojiang, Jialing River, Wujiang, Hanjiang, Yalong River, Xiangjiang River, Yuanjiang, Ganjiang and Qingjiang. As shown in Fig. 1. The Yangtze River Basin is a first-rank water resources district in China, contains 12 water resources secondary districts such as Tongtian River, The main stream below Shigu and Dadu River. The average annual precipitation is about 1100mm. Due to the vast territory, complex terrain, coupled with the typical monsoon climate, annual precipitation and the temporal and spatial distribution of heavy rain is very uneven, 60%-80% of the runoff concentrated in the flood season. The annual average amount of surface water resources of the basin is 985.6 billion m³, and the runoff depth is 552.9mm. The annual average amount of groundwater resources in the basin is 249.2 billion m³, and the gross water resources amount is about 995.8 billion m³, accounting for 35% of the national water resources, is an important water area in China [10-12].
The WYM is calculated based on the gross water resources amount (1956-2015) and the area of city collected by the Municipal Water Resources Bulletin. Using ArcGIS to find the center of the city and generate a point vector containing the WYM, and select the IDW (Inversed Distance Weighted) method [13] to generate a grid containing WYM with spatial resolution of 1 km×1 km.

2.2. Methods

2.2.1. Climate tendency method. The general linear climate tendency method can calculate the trend of a single grid, through the ArcGIS, the formula (1) can be used to calculate the trend tendency of each grid, thus reflects the distribution of the tendency of the entire space. This paper is based on the grid of the WYM from 1956 to 2015 in the Yangtze River Basin, using a linear regression method to analyze the tendency of data changes.

\[
Slope = \frac{n \times \sum_{i=1}^{n} (i \times K_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} K_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}
\]  

Where: \(Slope\) is the trend tendency of the time series, \(Slope > 0\) indicates that the trend of the time series is increasing and vice versa. The variable \(i\) is the year number, for example, when the data rate is calculated from 1956 to 2015, \(i=1\) for 1956, \(i=2\) for 1957. \(K_i\) is the value of \(i\) year. \(n\) is the number of years accumulated in the study period, in this paper, \(n=60\).

2.2.2. Mann-Kendal Test. Mann-Kendal (hereinafter referred to as M-K) test is a nonparametric statistical test method, can be used to analyze the trend of time series and mutation. This method does not need the sample to follow a certain distribution, and it is not disturbed by a few abnormal values, which can objectively characterize the overall trend of the sample sequence. In the M-K trend test method, define the statistical value \(Z\):
\[
Z = \begin{cases} 
\frac{(b-1)}{\sqrt{\frac{n(n-1)(2n+5)}{18}}} & b > 0 \\
0 & b = 0 \\
\frac{(b+1)}{\sqrt{\frac{n(n-1)(2n+5)}{18}}} & b < 0 
\end{cases}
\] (2)

For the random sequence \(X=(x_1, x_2, \ldots, x_n)\), given a significance level \(\alpha\), find the critical test value \(Z_{\alpha/2}\) in the normal distribution table. When \(|Z|<Z_{\alpha/2}\), the original hypothesis was accepted, indicating that the trend of sequence change was not significant. When \(|Z|>Z_{\alpha/2}\), reject the original hypothesis, indicating that the sequence changes significantly. When Z is positive, it indicates that the sequence is increasing and vice versa. The greater the absolute value of Z, the more obvious the trend of sequence change.

3. Results and Analysis

3.1. Temporal variations in the WYM

| No. | Water Resources District | Min slope | Max slope | Mean slope | Min WYM | Max WYM | Mean WYM |
|-----|--------------------------|-----------|-----------|------------|---------|---------|---------|
| 1   | Tongtian River           | -0.68     | 0.19      | -0.17      | 10.36   | 66.02   | 25.75   |
| 2   | The main stream below Shigu | -0.33     | 0.72      | 0.02       | 14.72   | 80.03   | 57.14   |
| 3   | Dadu River               | -0.42     | 0.10      | -0.12      | 19.47   | 106.96  | 58.28   |
| 4   | Above Guangyuan Zhaohua and Yichang | -0.37     | 0.23      | -0.10      | 12.20   | 63.23   | 40.72   |
| 5   | Mainstream between Yibin and Yichang | -0.36     | 0.20      | -0.07      | 41.34   | 81.85   | 56.49   |
| 6   | Below Sinan              | -0.28     | 0.15      | 0.00       | 48.73   | 84.07   | 61.17   |
| 7   | Above Danjiangkou        | -0.22     | 0.46      | -0.04      | 16.59   | 58.69   | 34.93   |
| 8   | The left bank of Wuhan to Hukou | -0.32     | 0.47      | 0.12       | 29.74   | 86.53   | 58.35   |
| 9   | Dongting Lake district   | -0.40     | 0.53      | 0.15       | 47.06   | 126.29  | 78.08   |
| 10  | Poyang Lake district     | 0.05      | 0.65      | 0.35       | 75.66   | 125.11  | 94.20   |
| 11  | Chaochuwan and rivers along Yangtze | 0.05      | 0.54      | 0.28       | 28.44   | 99.68   | 56.33   |
| 12  | Hangjia Lake district    | 0.27      | 0.79      | 0.43       | 35.61   | 78.34   | 52.73   |
| 13  | Yangtze                  | -0.68     | 0.79      | 0.04       | 10.36   | 126.29  | 56.23   |
As shown in Fig. 2(a) and Table 1. We found that during the period from 1956 to 2015, it showed a downward trend in the western part of the Yangtze River Basin, and it showed an upward trend in the eastern part. The tendency rate is between -0.68/a and 0.79/a, the minimum value appeared in the Tongtian River district, and the maximum value appeared in the Hangjia Lake district, the mean value is 0.04/a. For the water resources secondary district, the Hangjia Lake district, the Chaochuwan and rivers along Yangtze district, the Poyang Lake district, the Dongting Lake district, the east part of The left bank of Wuhan to Hukou district and the south part of The main stream below Shigu district showed an upward trend. The Tongtian River district, the Dadu River district and the Above Guangyuan Zhaohua district showed a downward trend. The trend in other area is not significantly. However, the M-K test showed that the trend of western part didn’t pass the significance level of 90%, so the change is not significantly. The eastern part showed an upward trend and reached a significance level of 99%. The results shown in Fig. 2(b). In the 12 water resources districts, the Tongtian River district showed significantly downward trend, the average tendency rate is -0.17/a. The whole area of Poyang Lake district, the Chaochuwan and rivers along Yangtze district and the Hangjia Lake district showed significant upward trend, the minimum values were all greater than 0 and the mean values were 0.35/a, 0.28/a and 0.43/a, respectively.

3.2. Spatial patterns of the WYM
As shown in Fig. 3, we can see that the spatial distribution is more regular, in addition to the central part, the rest are gradually increased from north to south. We roughly divide the WYM into six categories in space. Among them, the area for the WYM <0.2 million m^3/km^2 is 9.5% of the total area, mostly in the northern part of the Tongtian River district. The WYM between 0.2-0.4 million m^3/km^2 accounted for 14.7% of the total area, mostly located in the Above Danjiangkou district and the Above Guangyuan Zhaohua district. The WYM between 0.4-0.6 million m^3/km^2 accounted for 28.9% of the total area. Located in the central part of the Tongtian River district, the main stream below Shigu, the Dadu River district, the left bank of Wuhan to Hukou district, the Above Guangyuan Zhaohua district and the Chaochuwan and rivers along Yangtze district. Also contains the western part of the Mainstream between Yibin and Yichang district and the Below Sinan district, and the Hangjia Lake district. The WYM between 0.6-0.8 million m^3/km^2 accounted for 30.6% of the total area. Located in the southern part of the Tongtian River district, the main stream below Shigu district, the Dadu River district and the Chaochuwan and rivers along Yangtze district. Also including the eastern part of the Mainstream between Yibin and Yichang, the Below Sinan district and the left bank of Wuhan to Hukou district, and the western and northern part of the Dongting Lake district. WYM between 0.8-1.0 million m^3/km^2 accounted for 14% of the total area, concentrated in the Poyang Lake district and the south-eastern part of Dongting Lake district, the south-western part of the Dadu River district is also slightly distributed. The area for the WYM >1.0 million m^3/km^2 only accounted for 2.4% of the total area, located in the eastern part of the Poyang Lake district.

From the statistical value of WYM in each region (Table 1), the minimum value of 103,600 m^3/km^2 appeared in Tongtian River district, the maximum value of 1,262,900 m^3/km^2 appeared in Dongting Lake district. The highest average value of 942,000 m^3/km^2 is in the Poyang Lake District, and the lowest average value of 257,500 m^3/km^2 is in the Tongtian River District. The average value in the Tongtian River district, the above Guangyuan zhaohua district and the above the Danjiangkou district are all less than 500,000 m^3/km^2. The three districts are all located in the northern part of the Yangtze River Basin.

4. Summary and Conclusion
The time and spatial evolution characteristics of the WYM of the Yangtze River Basin from 1956 to 2015 were analyzed by the climate tendency method and the M-K trend test method. We conclude the following.

(1) The average annual WYM of the Yangtze River Basin in 1956-2000 is between 103,600 and 1,262,900 m^3/km^2, with an average value of 562,300 m^3/km^2, which is greater than national average value of 295,000 m^3/km^2. The minimum value is in the Tongtian River district, which is located in northwestern part of the basin. The largest value is in the Dongting Lake district, which is located in
The spatial distribution of the multi-year average WYM is more regular except the central part, the value gradually increased from north to south. The whole basin were generally divided into six categories, that is <0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.0, and >1.0 million m³/km², accounted for 9.5%, 14.7%, 28.9%, 30.6%, 14.0% and 2.4% of the whole basin, respectively.

(2) In the time variation, the variation range of WYM in the Yangtze River Basin from 1956 to 2015 is between -0.68/a and 0.79/a. The western part showed downward trend but not significant, the eastern part showed upward trend, reached a significance level of α=0.01. The minimum value of -0.68/a appeared in the Tongtian River district, the maximum value of 0.79/a appeared in the Hangjia Lake district, the average tendency rate is 0.04/a, indicates the whole basin showed an upward trend.

In this paper, the temporal and spatial evolution characteristics of WYM were analyzed across the 12 water resources secondary districts in the Yangtze River Basin. Then we will analyze the causes of its evolution, such as precipitation, temperature, NDVI, land-use/cover change and any other factors, to provide the scientific basis for the sustainable utilization and development of water resources in the Yangtze River Basin.

Acknowledgments
This work was financially supported by the National Key Research and Development Project (No. 2016YFA0601503). Thanks also to the anonymous reviewers and editors.

References
[1] Q. Zhang, et al. Sediment and runoff changes in the Yangtze River Basin during past 50 years. Journal of Hydrology. 331 (3–4) (2006) 511-523.
[2] J. Xu, D. et al. Spatial and temporal variation of runoff in the Yangtze River Basin during the past 40 years. Quaternary International. 186 (1) (2008) 32-42.
[3] J. Chen, et al. Variability and trend in the hydrology of the Yangtze River, China: annual precipitation and runoff. Journal of Hydrology. 513 (5) (2014) 403-412.
[4] D.F. Yan, et al. Trends and characteristics of runoff for upper Hanjiang River. Journal of Water Resources & Water Engineering. 27(6) (2016) 13-19.
[5] J. Shao, et al. Variation trend and driving factors of annual runoff in Wujiang River. Journal of China Hydrology. 32 (6) (2012) 86-41.
[6] G. Gao. Study of water resources annual assessment and its application in china. (2005).
[7] Y.L. Xiong, et al. Climate change effect on runoff modulus in Guizhou province. (2011).
[8] H. Wen, et al. Analysis of impact of land use change on runoff characteristics. (2013).
[9] Q. Zhang, et al. Precipitation, temperature and runoff analysis from 1950 to 2002 in the Yangtze Basin, china. Hydrological Sciences Journal. 50 (1) (2005) 65-80.
[10] C.Y. Xu, et al. Analysis of spatial distribution and temporal trend of reference evapotranspiration and pan evaporation in Changjiagang (Yangtze River) catchment. Journal of Hydrology. (2006).
[11] J.H. Ma. Situation of water resources in Yangtze River basin and countermeasures for sustainable utilization. Yangtze River. (2010).
[12] J.P. Liu, et al. Flux and fate of Yangtze River sediment delivered to the East China Sea. (2007).
[13] M. Garcia et al. Spatial interpolation of precipitation in a dense gauge network for monsoon storm events in the southwestern United States. Water Resources Research. 44(5) (2008) 782-781.
[14] L. Ye, et al. Hydrological Mann-Kendal multivariate trends analysis in the upper Yangtze River basin. Journal of Geoscience & Environment Protection. 3(3) (2015) 34-39.