Assessment of rain-flood availability in the upper reaches of Hanjiang River and its water-constrained response

P X Deng¹,³, J P Bing¹, C J Xu¹, J W Jia¹ and M Y Zhang²

¹Bureau of Hydrology, Changjiang Water Resources Commission, 1863 Jiefang Avenue, Wuhan, Hubei Province, 430010, China
²Hubei Provincial Hydrology and Water Resources Investigation Bureau, Wuhan 430071, China
³E-mail: dpx_work@163.com

Abstract. In order to analyze the potential of rain-flood resources, and to reveal its water-constrained response to further develop the assessment method of rain-flood availability, based on the conceptual model, this paper takes the upper reaches of Hanjiang River (UHRB) as a demonstration area to carry out the assessment of rain-flood availability. According to the constraint factors, analysis of water-constrained response has been conducted. It is found that the average annual rain-flood availability amount during the flood season in UHRB is 17.30 billion m³, and the rain-flood utilization potential is 5.37 billion m³, showing a decreasing trend since the 21st century. Rain-flood utilization is directly constrained by regulation ability and necessary water requirements such as production, living and ecological environment, and there is an obvious non-linear response relationship. Based on scenario assumptions, the iso-curve of rain-flood resources availability and utilization potential that meet the practical needs of water resources utilization could be drawn. The findings enrich the evaluation theory of rain-flood resources and provide technical support for improving the water resources utilization efficiency.

1. Introduction

Driven by the dual factors of climate change and rapid social and economic development, the demand for water resources is increasing. Affected by the uneven distribution of water resources in time and space, the contradiction between supply and demand of water resources in China has become increasingly prominent. In recent years, many regions plan to enhance the utilization of water resources by enhancing the use of rainwater or flood resources as an important way to alleviate water shortages. Under this background, the relevant theories and methods of rain-flood resources utilization in the river basin have been developed [1-2].

Since the 1990s in China, much more research of rain-flood resources utilization has been made and continued in-depth. Along with the transformation of 'defense' to 'management' on rain-flood, study also transitions from the initial engineering utilization model based on 'storage, discharge, supplement, irrigation, regulation, distribution' to the availability evaluation of rain-flood resources, and an efficient, fair and sustainable water resources management strategy has been gradually obtained. Evaluation theory of rain-flood resources availability is the basis of water resources management strategy research, and many scholars have carried out relevant research. For example, Fang et al (2009) use subtraction method and system analysis approach to calculate the regional flood resources availability separately, and the advantages of two methods are compared[3]. Hu et al (2010) further optimized the assessment
method of basin flood resources availability and utilization potential based on the subtraction method, and macroscopically analyzed the relationship between flood resources utilization and river ecological environment security and flood control security[4]. Wang et al (2014) believed that flood resources availability is a function of the flood control capacity[5].

In reference [6], a conceptual model of floodwater resources utilization had been established based on the water balance equation, and several concepts and their quantitative relationships that are closely related to the evaluation of flood resource utilization potential had been reasoned and discriminated by using limit analysis theory. Obviously, evaluation theory of rain-flood resources availability is constantly being improved, especially the evaluation methods represented by flood resources are becoming more and more mature. However, it is not difficult to find that the current theoretical research is still in its infancy and needs to be improved through the application of specific experimental areas, especially the relevant constraint indicators that restrict the calculation of rain-flood availability. It is urgent to find out the internal response relationship with the available amount based on concept analysis to better guide the specific application of the theory of rain-flood resource availability evaluation.

In order to further improve the evaluation theory of rain-flood resources availability, and to deepen the understanding of rain-flood utilization, this paper takes the Hanjiang River basin above Danjiangkou (UHRB) as demonstration area, and uses the water balance equation to establish a conceptual model of rain-flood resources utilization. Taking the Huangjiagang hydrological station under the dam-site of the Danjiangkou reservoir as the exit node, the assessment of the availability and potential of rain-flood resources in the river basin was carried out. Aiming at the constraints that affect the quantity of resources, the response relationship with the available amounts was analyzed. By drawing the equivalence curves between rain-flood utilization indicators to guide the practice in the river basin, the evaluation theory of rain-flood resources availability has been further enriched. The work in this paper is the basis of the practice of using water resources in the river basin. The purpose is to analyze the potential of rain-flood resources in the Hanjiang River basin, and to reveal its water-constrained response to further complete the assessment method of rain-flood availability. The findings enrich the evaluation theory of rain-flood resources and provide technical support for improving the water resources utilization efficiency.

2. Study area and data

2.1. Study area

Hanjiang River Basin (HRB) is located at 106°15´~114°20´E longitude, 30°10´~34°20´N latitude within the area of about 159,000 km². It is about 820km long from northwest to southeast, 320km widest from north to south and 180km narrowest. Danjiangkou reservoir is the core project of rain-flood resources utilization in the HRB. Taking it as the boundary, the area above the Danjiangkou reservoir is the upper reaches of the Hanjiang River (UHRB). UHRB is between the Qinling mountains and Daba mountains within the area of about 952,000 km², and has the main river of 925km long, accounting for 59% of the total length of the Hanjiang River. The topography is generally high in the west and low in the east, and gradually descends from the middle and low mountainous areas in the west to the hilly plain area. The water system of the basin is developed, showing a vein shape. The tributaries from the left and right banks are generally short and unbalanced [7].

UHRB belongs to the east Asian subtropical monsoon region. Affected by eurasian cold high pressure and the western pacific subtropical high, the climate has obvious seasonality, with severe cold in winter and extremely hot in summer. The average annual temperature in the basin is 12~16°C, the average annual wind speed is 1.0~3.0m/s, and the average annual precipitation is 867mm. Rainfall is unevenly distributed during the year and the total precipitation for the maximum four consecutive months accounts for 55% to 65% of annual precipitation, showing a spatially decreasing distribution from south to north and west to east. The main flood season is from July to October, and there are obvious summer and autumn flood stages. Among them, the floods between June 20 and August 20 are summer floods, and the floods between August 20 and October 15 are autumn floods.
2.2. **Data collection**

The daily data from 1956 to 2016 in the 56 rainfall gauges and Huangjiagang hydrological station (HJG) across the whole UHRB were collected as the inputs to construct SWAT model (Figure 1). The data excerpts from the published Hydrological Yearbook, and has undergone quality control, containing the analysis of consistency, reliability and representativeness. Little rainfall gauges have missing data in some years, and had been filled by establishing the correlation between monthly precipitation at adjacent stations. Based on these hydrological data, the established SWAT model of the basin [8] is driven to restore and calculate the natural runoff process of HJG.

![Figure 1. Location of UHRB and the spatial distribution of hydrological gauges.](image)

3. **Assessment method of rain-flood availability**

3.1. **Hydrological model**

A distributed hydrological model is needed in the research. In our study, the Soil and Water Assessment Tool (SWAT) was selected, which is a semi-distributed, eco-hydrologic model and easy for establishing and operating. SWAT model requires three basic inputs: a digital elevation model (DEM, 90 m×90 m, https://glovis.usgs.gov/), a land use cover map (LULC, http://westdc.westgis.ac.cn/), and a soil map (http://westdc.westgis.ac.cn/). These inputs are integrated for delineating watershed into sub-basins. Our team has built the SWAT model in the Hanjiang River Basin and performs good accuracy, which the Nash–Sutcliffe efficiency (NS) and percent bias (PBIAS) is up to the satisfactory levels (0.50<NS<0.65, |PBIAS|<10%) [8].

In this study, hydrological model is only an auxiliary tool, which is mainly used for the calculation of natural rain-flood process. Because of the widely using of the SWAT model, the specific modeling process will not be described in detail. If necessary, refer to the literature of Deng et al., 2019 [8].

3.2. **Basic content of evaluation indicators**

There are four evaluation indicators that need to be defined, which is rain-flood resources amounts, rain-flood utilization amounts, rain-flood availability amounts and rain-flood utilization potential. The specific meaning of each index is as follows.

(1) **Rain-flood resources amounts.** On the watershed, the amount of rain-flood resources is the sum of the local natural runoff formed by precipitation during the flood period and the inflow from the outer basin. The corresponding mathematical expression is:

\[
W_p = \int_{t_i}^{t_f} I(t) \, dt + \int_{t_i}^{t_f} I_f(t) \, dt
\]  

(1)
Where: $W_F$ is the rain-flood resources amounts; $I(t)$ is the local natural rain-flood during the flood period of $t$; $I_b(t)$ is the inflow from the outer basin during the flood period of $t$; $t_1$ and $t_2$ are the start and end of the rain-flood process.

(2) Rain-flood utilization amounts. Under the rain-flood control capacity (FCC) of $x$, it is the water storage variables of the basin during the flood season, which is recorded as:

$$W_{ly}(x) = W_F - \int_{t_1}^{t_2} Q_{s(x)}(t) dt = W_F - W_{s(x)}$$

Where: $W_{ly}(x)$ is rain-flood utilization amounts; $W_{s(x)}$ represents the amount of water released or discharged from the node during the flood season under the FCC of $x$.

If $W_{s(x)}$ represents the actual discharge of the node, then $W_{ly}(x)$ represents the actual rain-flood utilization amounts.

(3) Rain-flood availability amounts. Emphasizing the rain-flood amount that can be used under the ability of rain-flood control. It is calculated using the subtraction method, recorded as:

$$W_{kly}(x) = W_F - \max\left[\int_{t_1}^{t_2} Q_{qu(x)}(t) dt, \int_{t_1}^{t_2} Q_{b}(t) dt\right] = W_F - \max[W_{qu(x)}, W_b]$$

Where: $W_{kly}(x)$ is rain-flood availability amounts under the FCC of $x$; $W_{qu(x)}$ is the uncontrollable rain-flood due to the FCC, and $W_b$ is the necessary water demand, including the water of production, living, ecological environment in the downstream.

If it is assumed that the FCC of $x$ reaches infinity, then the uncontrollable water volume is 0, that is, the rain-flood availability amount is $W_{kly}(x) \rightarrow \infty \Rightarrow W_F = W_b$.

(4) Rain-flood utilization potential. It represents the increment of water resources that can be further tapped under the necessary water requirements for flood control, production, living, ecological environment, etc., which can be expressed by the following formula:

$$R_x = W_{kly}(x) - W_{ly}(x) = \begin{cases} W_{s(x)} - \max[W_{qu(x)}, W_b], & \text{if } R_x \geq 0 \\ 0, & \text{if } R_x < 0 \end{cases}$$

Where: $R_x$ is rain-flood utilization potential under the FCC of $x$.

3.3. Relationship between evaluation indicators

According to the conceptual model of rain-flood resources utilization [4-6], taking the watershed exit section as an example, the relationship between evaluation indicators can be expressed as showed in Figure 2.

During the flood period of $[t_0, t_1]$, rain-flood resources amounts is the area enclosed by line ① and the abscissa, which is recorded as $W_i=A+B+C+D$. If the process is the actual rain-flood process line, the actual utilization of rain-flood is the area enclosed by line ① and line ②, which is recorded as $W_{ly}(x)=A$. Then the rain-flood availability amount is the area enclosed by Line ① and Line ③, which is recorded as $W_{kly}(x)=A+B$. Rain-flood utilization potential is the area enclosed by Line ② and Line ③, which is recorded as $R_x=A$.

If the process is the rain-flood process line under the optimal control mode of basin, and the line is between line ② and line ④, then the rain-flood utilization amounts is the area enclosed by line ① and line ③, which is recorded as $W_{ly}(x)=A+B$. Then the rain-flood availability amount is the area enclosed by Line ① and Line ④, which is recorded as $W_{kly}(x)=A+B+C$. Rain-flood utilization potential is the area enclosed by Line ② and Line ④, which is recorded as $R_x=C$. Obviously, rain-flood utilization of basin is how to change the flow process at the exit section from line ② to line ③ and gradually approach line ④ under the necessary water requirements for flood control, production, living, ecological environment.
3.4. Evaluation program of rain-flood availability

Assessment of rain-flood availability always follows the four basic criteria of safety, system, efficiency and coordination. Safety principle refers to that the risks of flood control and ecological environment are within the controllable range. Systematic principle refers to generalize the basin into a black box model, and characterizes it by the discharge process of outlet. Efficiency principle refers to the principle of maximizing benefits, and believes that the regulation capacity of rain-flood is not affected by artificial storage and the abundance of inflow. In fact, there are deviations in the operation of water conservancy projects, and they are not strictly operated in accordance with the scheduling regulations. Coordination principle refers to avoid the excessive development of rain-flood resources. When evaluating and calculating, it is necessary to consider the water production requirements for production, living and ecological environment coordinately, and the rationality of water use in the upstream and downstream.

Based on the analysis of criteria, the evaluation program of rain-flood availability is as follows:

1. Calculate the natural rain-flood process. According to the design flood or the typical rain-flood inflow, the rain-flood process affected by the current project can be appropriately restored. The subentry questionnaire reduction [9], hydrological model [10] and other methods can be used to estimate the natural rain-flood process.

2. Calculate the rain-flood control capacity or regulation ability. In order to determine the representative rain-flood control capacity, the largest actual rain-flood utilization in the past 20 years was selected to approximate the rain-flood control capacity, as follows:

   \[ W_{b0} \approx \max(W_b(k)), \quad k = 1, 2, 3\ldots, 10 \]  

3. Calculate the necessary water requirements. According to the eco-environmental goals and production needs, calculating the basic water requirements for production, living and ecological environment during the flood period separately. The water demand for production and living can use statistical survey methods, covering watershed water transfer, agricultural irrigation, residential water use, aquaculture, hydropower, shipping, etc. Eco-environmental base flow can be calculated by Tennant method and frequency method [11], and its outsourcing value is taken. The necessary water requirements are the sum of the production, living and eco-environmental water amounts.

4. Calculate the rain-flood availability amounts and its potential. According to the basic connotation of evaluation indicators, rain-flood availability amounts and its potential are calculated.

4. Result and discussion
4.1. Assessment of rain-flood availability
Figure 3 shows box-plot and inter-annual change of the rain-flood utilization indicators in the UHRP from 1956 to 2016. On the multi-year average statistical scale, rain-flood resources amount in the flood season (June to October) is 33.05 billion m$^3$, rain-flood utilization amount is 12.67 billion m$^3$, rain-flood availability amount is 17.30 billion m$^3$, and the rain-flood utilization potential is 5.37 billion m$^3$.

![Figure 3. Box-plot and inter-annual change of the rain-flood utilization indicators in the UHRP from 1956 to 2016.](image)

From the perspective of the inter-annual change, the rain-flood utilization during the flood season in the UHRP generally increases first and then decreases, while the rain-flood availability is constrained by the rain-flood control capacity and the necessary water requirements. Only in 1966, 1959, 1997, 1999 and other dry years, there were reduced fluctuations. Rain-flood utilization potential is related to the water amount and utilization, showing a decreasing trend in the past years. Especially since the 21st century, driven by the rapid development of social economy and the demand for water resources, the inter-basin water transfer projects represented by the middle line of the South-to-North Water Diversion Project have been put into operation, resulting in an increase in the actual rain-flood utilization. In addition, in recent years, it coincided with the continuous dry season, which forced the reduction of rain-flood utilization potential under the existing control capacity.

4.2. Water-constrained response of rain-flood utilization
The core of the assessment of rain-flood availability is to determine the current regulation ability ($W_{ly0}$) and the basic constraints of the downstream water demand ($W_b$). Among them, $W_{ly0}$ is mainly subject to water conservancy project regulation and its own flood control safety constraints, while $W_b$ is closely related to the water requirements of downstream production, living, and ecological environment. Owing to the construction and regulation scheme of water conservancy projects are not invariable, and the necessary water demand is also affected by the regional social economy. Therefore, values of $W_{ly0}$ and $W_b$ have certain uncertainties.

(1) water-constrained response to $W_{ly0}$
Now only change the values of $W_{ly0}$, keep other parameters unchanged, set different scheme for calculations, and draw the relationship between $W_{ly0}$ and evaluation indicators, as showed in Figure 4. It can be seen from the figure that $W_{ly0}$ has a clear proportional relationship with the rain-flood availability and utilization potential, which can be quantitatively expressed by nonlinearity, and the correlation coefficient is as high as 0.99.

Figure 5 further plots the iso-curve between $W_{ly0}$ and evaluation indicators under different scenarios of $W_b$. Obviously, under a certain regulation capacity, the greater the necessary water demand, the lower the rain-flood availability amount and utilization potential.
Figure 4. Relationship between $W_{b0}$ and evaluation indicators.

Figure 5. Iso-curve between $W_{b0}$ and evaluation indicators under different scenarios of $W_b$.

(2) water-constrained response to $W_b$

Now only change the values of $W_b$, keep other parameters unchanged, set different scheme for calculations, and draw the relationship between $W_b$ and evaluation indicators, as showed in Figure 6. It is indicated that $W_b$ has a non-linear proportional response relationship with rain-flood availability and utilization potential, which can be expressed quantitatively using a quadratic polynomial. When $W_b$ reaches the maximum value, the rain-flood availability and utilization potential tend to be extremely small. On the basis, the iso-curve between $W_b$ and evaluation indicators under different scenarios of $W_{b0}$ is further drawn in Figure 7. It is showed that, under a certain value of the necessary water demand, the greater the regulation capacity, the higher the rain-flood availability amounts and utilization potential.

In summary, rain-flood availability amounts and utilization potential are not only affected by the necessary water demand, but also restricted by the regulation ability. Among them, rain-flood utilization is proportional to the regulation ability, and there is an obvious non-linear response relationship. However, it is inversely proportional to the necessary water demand, and can be quantitatively expressed by the quadratic polynomial. By assuming different scenarios of necessary water demand and regulation ability, the iso-curve of rain-flood resources availability and utilization potential could be drawn, which provide a reference for the practice of water resources utilization in the river basin and further enrich the evaluation theory of rain-flood resources availability.
5. Conclusions

Based on the conceptual model of rain-flood resources utilization, the upper reaches of Hanjiang River (UHRB) is taken as a demonstration area to carry out the assessment of rain-flood availability. According to the constraint factors, analysis of water-constrained response has been conducted and the findings provide technical support for improving the water resources utilization efficiency. Conclusion is as follows.

(1) On the multi-year average statistical scale, rain-flood resources amount during the flood season in UHRB is 33.05 billion m$^3$, rain-flood utilization amount is 12.67 billion m$^3$, rain-flood availability amount is 17.30 billion m$^3$, and the rain-flood utilization potential is 5.37 billion m$^3$. Especially since the 21st century, driven by the rapid development of water demand and the operation of inter-basin water transfer projects, resulting in an increase of rain-flood utilization. In addition, it coincided with the continuous dry season in recent years, which forced the reduction of rain-flood utilization potential under the existing control capacity.

(2) Rain-flood resources utilization is directly constrained by regulation ability and the necessary water requirements such as production, living and ecological environment. Rain-flood utilization is proportional to the regulation ability, and there is an obvious non-linear response relationship. However, it is inversely proportional to the necessary water demand, and can be quantitatively expressed by the quadratic polynomial. Based on scenario assumptions, iso-curve of rain-flood resources availability and utilization potential could be drawn.
In this paper, Concept analysis and theoretical methods are used as guides, and UHRB is used as a research area to carry out demonstration applications to further understand the rain-flood utilization over the years. Aiming to constraints such as regulation ability and necessary water requirements, the analysis of water-constrained response has been conducted to further enrich the evaluation theory of water resources. In the future, we still need to further refine the spatial and temporal scale, and consider the impact of multi-factor constraints, then carry out deeper research on the assessment method of the rain-flood availability.

Acknowledgments
The authors appreciate Bureau of Hydrology, Changjiang Water Resources Commission for the support of data. This research work is financially supported by The National Key R&D Program of China (Item Nos. 2016YFC0400901, Item Nos. 2017YFC0405302) and Open research fund of Changjiang Academy of Sciences (Item Nos. CKWW2019766/KY). We also would like to express our gratitude to the eighth project of the Second Phase Research of the key technology of scientific operation of the Three Gorges Reservoir for their financial support.

References
[1] Ye A L, Wang Z Z, Zhang L L, Wang L and Wang K 2019 Assessment approach to the floodwater utilization potential of a basin and an empirical analysis from China Environ. Earth Sci. 78(2) 78-52
[2] Dahan O, Shani Y, Enzel Y, Yechieli Y and Yakirevich A 2007 Direct measurements of floodwater infiltration into shallow alluvial aquifers Elsevier B. V. 344(3) 157-70
[3] Fang H Y, Wang Y T and Hu Q F 2009 Method for estimating utilizable quantity of regional floodwater J. Hydraul. Eng. 40(07) 776-81
[4] Hu Q F, Wang Y T and Yang D W 2010 Assessment approach for flood resources availability and utilization potentiality and its application J. Hydroelectr. Eng. 29(04) 20-7
[5] Wang Z Z, Cheng L, Liu Y C and Liu K L 2014 Evaluation method for status and potential of flood resource utilization in a basin J. Hydraul. Eng. 45(04) 474-81
[6] Wang Z Z, Wang Y T, Hu S Y and Liu K L 2017 Theoretical framework of floodwater resources utilization in a basin I: Quantitative interpretation J. Hydraul. Eng. 48(08) 883-91
[7] Deng P X, Bing J P, Jia J W and Wang D 2018 Pattern of spatio-temporal variability of flood season precipitation in Hanjiang River Basin between 1956 and 2016 Resour. Environ. Yangtze Basin. 27(09) 2132-41
[8] Deng P X, Zhang M Y, Bing J P Jia J W and Zhang D D 2019 Evaluation of the GSMAp_Gauge products using rain gauge observations and SWAT model in the Upper Hanjiang River Basin Atmospheric Res. 219 153-65
[9] Jin X Y 2006 A method of restoring computation of runoff (Nanjing: Hohai University)
[10] Wei H B, Wang M N, Zhou Z H and Sang X F 2009 Evaluation of the surface water resources restoring based on distributed hydrological model hydrological Yellow River 31(03) 28-9
[11] Zhong H P, Liu H, Geng L H and Xu C X 2006 Review of assessment methods for instream ecological flow requirements Adv. Water Sci. 3 430-4