Analysis of variation characteristics of runoff at multi-time scales under the influence of reservoir

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Abstract. Reservoirs play a significant role in changing the natural hydrological conditions. This paper studies the change characteristics of runoff fluctuation caused by the Gangkouwan Reservoir in Shuiyangjiang River, and collects the hourly flow data from two hydrological stations upstream and downstream of the reservoir. Through the comparison of the uneven coefficient ($C_v$) and concentration degree ($C_d$) of the two stations, reflect the impact of the reservoir on runoff changes at two-time scales of intra-annual and intra-month. The results shown the Gangkouwan Station has significant changes in runoff distribution at intra-annual and intra-month scales, affected by the reservoir. For the intra-month runoff, the runoff process at Gangkouwan Station is more uniform than Hulesi station in the flood season, because the reservoir has to store water. In the dry season, the opposite is realized, because the reservoir needs to discharge water to generate electricity. This paper is more conducive to deepening the understanding of the impact of reservoir operations on hydrological processes.

1. Introduction
With the rapid development of the social economy, the degree of human development of rivers is also increasing. The construction and operation of the reservoir is an important approach for mankind to transform rivers and make use of rivers [1]. Through the construction of reservoirs, humans have obtained huge social and economic benefits in flood control, power generation, shipping, fisheries, irrigation and tourism. At the same time, strong disturbance to rivers has also led to significant changes in rivers and surrounding ecosystems [2]. The hydrological process is the carrier that connects the river ecosystem. Due to the influence of reservoirs, the river ecosystem changes with the change of the hydrological process.

Studying the impact of reservoirs on the characteristics of hydrological conditions is an essential...
research content of river ecological hydrology. For a long time, in the process of managing the operation and operation of the reservoir, humans usually plan the scheduling of different time scales according to the scheduling objectives. Taking reservoir power generation as an example, typical reservoir management agencies will formulate different schedules according to annual power generation targets, water supply period (dry season) power generation targets [3], flood season (bump period) power generation targets [4], quarterly power generation targets [5], monthly power generation targets [6], and intraday power supply requirements [7]. The operational plan will affect the varying characteristics of river hydrological situation downstream of reservoirs from multiple time scales.

Aiming at this kind of problem, this paper selects important reservoirs in the Shuiyang River Basin as the research object, and strives to make some explorations on the law of hydrological situation change at multiple time scales. The results of this research are mainly analyzed from yearly and monthly scales considering the difficulty of data collection. The future variation of the intra-day runoff distribution will be studied in the future research.

2. Study area, data and methodology

2.1. Study area
The Shuiyangjiang River, drains an area of 10305 km$^2$ and flow for 254 km, is located at the south bank of the lower Yangtze River (figure 1). The upper reaches of Shuiyang River consists of 3 main tributaries named Dongjin River, Zhongjin River and Xijin River of which the Xijin River is the largest.

![Figure 1. A schematic diagram of the study area.](image)

The Gangkouwan reservoir, the largest reservoir in the basin with a total storage capacity of 9.41×10$^8$ m$^3$, was located at the upper river of Xijin River with a catchment area of 1120 km$^2$. It started operation in 2002 and its hydropower installed 2×30MW for annual power generation 1.13×10$^8$ kW·h. Gangkouwan reservoir is a backbone control project for flood control, power generation, water supply, irrigation, aquaculture, tourism, simultaneously its discharge affects downstream hydrological regime and river situation.

2.2. Study data
Two hydrological gauging stations, the Gangkouwan Station at downstream and the Hulesi Station at upstream of the reservoir, were selected as objects to study the effects of reservoir on hydrological regime at multi-time scale such as subdaily, daily, monthly and annual. The hydrological data of
Gangkouwan Station can reflect the impact of reservoir regulation.

The upstream Hulesi Station reflects the natural state (or near-natural state), the downstream Gangkouwan Station belongs to the river section affected by the reservoir, which can reflect the state of water regulation changed by the reservoir. The flow data of the two stations is shown in Table 1.

**Table 1. Flow records of the Gangkouwan and Hulesi stations.**

| Watershed Site | Data sequences |
|---------------|----------------|
| Shuiyangjiang River Gangkouwan Station | Monthly: 1974~2012, daily: 1974~2012, hourly: 2012.4~2013.3 |
| Hulesi Station | Monthly: 1974~2012, daily: 1974~2012, hourly: 2012.4~2013.3 |

2.3. Methodology

The dispatching operation of the reservoir has changed the distribution of river runoff under natural conditions to a certain extent. Taking the time of completion and operation of the reservoir as the demarcation point, the two periods before and after the construction of the reservoir are divided (pre-dam flow sequences and post-dam flow sequences). Comparing and analyzing the differences in runoff distribution characteristics before and after dam construction at the same station can directly reflect the impact of the reservoir on river runoff.

In addition, considering the randomness of floods in small watersheds, the upstream hydrological station with similar runoff variation characteristics and the same meteorological conditions is selected as reference station. The runoff distribution patterns of different stations under the influence of reservoir regulation and natural conditions in the same period are compared. The results can reveal the differences between the natural condition and the condition under the influence of the reservoir.

Uneven coefficient ($C_v$) was used to assess the non-uniformity of runoff sequences [8,9], and Concentration degree ($C_d$) was employed to quantitatively assess the concentration of runoff sequences [10,11]. The t test has been widely used in the field of hydrology, and it was used to evaluate whether the runoff before and after the construction of the reservoir is significantly different [12,13].

3. Results and discussion

3.1. Intra-annual distribution characteristics of runoff

According to the monthly flow data from 1974 to 2012 at the Gangkouwan Station (located downstream of the dam site of the Gangkouwan Reservoir), the annual unevenness coefficient and concentration are calculated, respectively. Taking the construction and operation time of the Gangkouwan Reservoir (2002) as the demarcation point, the whole study period is divided into two sub-periods before and after the construction of the reservoir, and the multi-year averages of the unevenness coefficient and concentration of the two periods are counted respectively (figures 2(a) and 2(b)). The multi-year average of the uneven coefficient of the pre-dam sequence was 0.96, and the multi-year average of the uneven coefficient of the post-dam sequence was 0.93. The multi-year averages of the concentration sequence of the pre-dam and post-dam sequences were 0.43 and 0.36, respectively. After the completion of the Gangkouwan Reservoir, the uneven coefficient and concentration of the monthly flow sequence of Gangkouwan Station decreased, but the uneven coefficient did not decrease significantly.

According to the monthly flow data from 2002 to 2012 in Hulesi Station (upstream of the Gangkouwan Reservoir, which is almost unaffected by the regulation of the Gangkouwan Reservoir), the uneven coefficient and concentration degree of each year are separately counted. 1.15 and 0.40 are both larger than the multi-year average of the uneven coefficient and concentration of the Gangkouwan Station at the same time sequences.
Comparing the uneven coefficient and concentration degree of the Gangkouwan Station before and after the construction, and the uneven coefficient and concentration of the Gangkouwan Station and the Hulesi Station after the reservoir construction, it is found that both the uniformity coefficient and the concentration degree have decreased after the reservoir construction, indicating that the Gangkouwan Reservoir has homogenized the monthly flow sequence during the runoff period to a certain extent, which makes the unevenness and concentration of the runoff distribution significantly reduced during the year.

In order to further analyze the impact of large reservoirs on the monthly distribution of runoff during the year, the changes of Gangkouwan Station in runoff distribution during the year before and after the construction of the Gangkouwan Reservoir were analyzed (figure 3), and the analysis of the runoff distribution during the year under the condition of reservoir regulation (Gangkouwan Station) and the natural condition (Hulesi Station) was shown in figure 4. The difference value in the figure is the multi-year average of the pre-dam sequence minus the multi-year average of the post-dam sequence, or the monthly flow percentage of the downstream station (Gangkouwan Station) minus the upstream station (Hulesi Station).

In terms of the monthly average flow rate, it can be seen from figure 3 that the average monthly flow of the Gangkouwan Station has decreased except for the three months of August, November and December. The most falling months occurred in June and July, and the difference were -35.4 m³/s and -23.4 m³/s, respectively. In terms of the monthly average flow rate as a percentage of the whole year, it can be seen from figure 4 that the monthly flow percentage of the Gangkouwan Station was less than the Hulesi Station, except for January, February, March, June, and July. The rest of the month is greater than the Hulesi Station in the same period, with a maximum difference of 7.1% in February.

However, under natural conditions (figure 5), the Gangkouwan Station and Hules station (1974-2001) at the same time were basically consistent in the percentage of runoff during the year. It shows
that the Gangkouwan Reservoir has a significant impact on the runoff distribution of the Xijin River, a tributary of the Shuiyang River.

Figure 5. Distribution of runoff during the year before and after the construction of the reservoir in the Gangkouwan reservoirs.

3.2. Intra-month distribution characteristics of runoff

- Comparative analysis of Gangkouwan Stations between pre-dam and post-dam sequences

According to the daily flow data of Gangkouwan Station from 1974 to 2012, the uneven coefficient and concentration degree of each month are calculated separately. Compare the average uneven coefficient (figure 6(a)) and concentration degree (figure 6(b)) of each month in pre-dam and post-dam sequences. It can be seen that from September to February in post-dam sequence, the uneven coefficient of each month increased significantly compared with that in pre-dam sequence, and the relative increase in January was the highest (186%). and from March to August, the monthly uneven coefficient decreased compared with that in pre-dam sequence, which decreased by 34.9% in July. The distribution characteristics of the concentration in each month are basically similar to the uneven coefficient in each month. From September to February, the concentration within the month in post-dam sequence was significantly higher than that in pre-dam sequence. In December, it increased by 67.7%. From March to August, the concentration in the month in post-dam sequence was reduced compared with that in pre-dam sequence, and it decreased by 35.1% in July.

Figure 6. Distribution of unevenness and concentration within the month before and after the construction of the reservoir.

The t-test was used to test the sequence of uneven coefficients and concentration degree in pre-dam and post-dam flow sequences. The "*" indicates that the difference between the two groups passed the significance test of 0.05. The results are shown in tables 2 and 3. After the construction of the reservoir, the uneven coefficient has changed significantly except March, April, June and August. The increase of the uneven coefficient in January is the most significant during the dry season. The
The most significant change was in January during the wet season. The concentration changed significantly in January, May, July and December, and the value of the concentration degree in January and December was significantly reduced, while significantly increased in May and July.

Table 2. Results of unevenness test t-test of the Gangkouwan Station during the month.

| Month  | January | February | March | April | May   | June  |
|--------|---------|----------|-------|-------|-------|-------|
|        |         |          |       |       |       |       |
| Pre-dam| 0.64    | 0.83     | 1.14  | 1.12  | 1.32  | 1.53  |
|        | 0.36    | 0.46     | 0.44  | 0.39  | 0.38  | 0.55  |
| Post-dam| 1.01    | 1.12     | 1.63  | 1.54  | 1.32  | 1.32  |
|        | 0.32    | 0.47     | 1.06  | 0.4   | 0.71  | 0.53  |
| t statistic | -7.93' | -4.03'   | 0.55  | 0.86  | 2.8'  | 1.56  |

Table 3. Results of the concentration t test of the Gangkouwan Station during the month.

| Month  | January | February | March | April | May   | June  |
|--------|---------|----------|-------|-------|-------|-------|
|        |         |          |       |       |       |       |
| Pre-dam| 0.29    | 0.36     | 0.4   | 0.37  | 0.46  | 0.51  |
|        | 0.18    | 0.19     | 0.17  | 0.14  | 0.14  | 0.22  |
| Post-dam| 0.46    | 0.45     | 0.34  | 0.33  | 0.34  | 0.41  |
|        | 0.21    | 0.26     | 0.17  | 0.22  | 0.17  | 0.17  |
| t statistic | -2.53' | -1.19    | 1.09  | 0.63  | 2.37' | 1.25  |

Taking the intra-month flow distribution process of the Gangkouwan Station as an example, the distribution characteristics of the monthly inner diameter flow in the dry season and the wet season are affected by the different degrees of reservoir regulation. The most significant change was in January during the day season, and the most significant change was in July during the wet season. Take January and July as examples to illustrate the interannual variation characteristics of the monthly distribution index (uneven coefficient, concentration) in these months, as shown in figure 7. It can be seen from figures 7(a) and 7(b) that the average value of the mean value and the concentration sequence of the uneven coefficient in the dry season of the Gangkouwan Station increased significantly after 2002, and the standard deviation of the upper and lower standard deviations of the two indicators also. It can be seen from figures 7(c) and 7(d) that the multi-year mean changes of the two statistical indicators in July during the wet season is opposite to that of January, and the mean values of the two indicators are significantly decreased. The amplitude has also been reduced. The main reason for this phenomenon is that the reservoirs during the wet season period play the role of impounding floods, and the process of discharging the flow is homogenized, so that the flow process with large fluctuations during the flood period is reduced, and the flow amplitude is stabilized. During the dry season, due to the power generation demand, the reservoir starts to discharge electricity according to the power generation plan, which will make the unstable dry water flow process unstable,
the flow rate increase, and the flow process tend to be uneven.

![Figure 7](image)

**Figure 7.** Unevenness and concentration changes of the Gangkouwan Station in January and July.

- Comparative analysis of Gangkouwan and Hulesi Stations at the same time

After the construction of the Gangkouwan Reservoir, the consistency of the uneven coefficient and the concentration degree of the two stations deteriorated, considering the length of the article, only the analysis of concentration is shown in figure 8. From the statistical results of the intra-month concentrations in figure 8(a), the intra-monthly concentrations of the two stations are quite similar, indicating that the intra-month runoff distribution of the two stations has good consistency. According to the statistical results (figure 8(b)), the intra-monthly concentrations of the Gangkouwan Station in September, October and December are quite different from Hulesi Station, after being affected by the reservoir.

![Figure 8](image)

**Figure 8.** Intra-monthly concentration of Gangkouwan Station and Hulesi Station after the construction of the reservoir.

In order to further analyze the impact of the reservoir on the intra-month distribution of flow, taking the statistics of the two stations at the same time in the upstream and downstream sections of the Gangkouwan Reservoir as an example, the average annual intra-month \(C_v\) and \(C_d\) differences
between Gangkouwan Station and Hulesi Station after the construction of the reservoir were used to reflect the impact of the Gangkouwan Reservoir on the distribution characteristics of runoff, as shown in figure 9. The influence of the Gangkouwan Reservoir on the intra-month distribution of runoff is manifested in two modes: one is to make the runoff distribution tend to be homogenized, the uneven coefficient and concentration decrease, which is the negative value in the figure; the other is to make the unevenness and concentration of the intra-month runoff increase, as shown by positive values in the figure. The first case occurs mainly in the flood season, while the second case occurs mainly in the dry season.

![Figure 9](image)

**Figure 9.** The average annual intra-month $C_v$ (a) and $C_d$ (b) differences between the Gangkouwan Station and the Hulesi Station after the construction of the reservoir.

The first mode of reservoir impact intra-month distribution is the homogenization of runoff, which is mainly caused by the regulation and storage of the reservoir, especially during the flood season. The reservoir intercepts the upstream flood, reduces and fertilizes the flood peak, thereby reducing the degree of unevenness and concentration. A flooding process in July 2007 is shown in figure 10. Hulesi Station is located in the upper reaches of the Gangkouwan Reservoir and the catchment area is smaller than Gangkouwan Station. The flood peak flow level should be smaller than . After regulated by the Gangkouwan reservoir, the maximum flow of the Gangkouwan Station is less than Hulesi Station, and the intra-month distribution of runoff tends to be uniform.

![Figure 10](image)

**Figure 10.** Daily flow of the Gangkouwan and Hulesi Stations in July 2007.

![Figure 11](image)

**Figure 11.** Daily flow process of Gangkouwan and Hulesi Stations in December 2007.

The second mode is due to the power generation demand, the sharpening of the monthly inner diameter flow process after the reservoir is dispatched, resulting in an increase in the unevenness and concentration of the intra-month runoff. The flow process of the two stations in December 2007 is shown in figure 11. Due to the low precipitation during the dry season, the daily flow process of Hulesi Station is relatively stable, and the daily flow range varies from 0.72 to 2.57 m$^3$/s. The daily flow process at Gangkouwan Station have fluctuated drastically as the Gangkouwan Reservoir is in the state of power generation.
4. Conclusions
In this paper, the effects of the Gangkouwan Reservoir on the runoff process are evaluated by the two indicators of unevenness coefficient and concentration. By analyzing the two scales of intra-annual and intra-month, the differences between the two indicators show the impact of the reservoir on the runoff process at different time scales. The main conclusions obtained are as follows

- For the intra-annual runoff in Gangkouwan Station, the multi-year average of the uneven coefficient of the pre-dam and post-dam sequence were 0.96 and 0.93, respectively; the multi-year averages of the concentration of the pre-dam and post-dam sequences were 0.43 and 0.36, respectively.
- For the intra-month runoff in Gangkouwan Station, the uneven coefficient and concentration significantly increased in May and July after the construction of the reservoir, while the significant reductions occurred between September and February for uneven coefficient, and in December and January for concentration, respectively.
- Affected by the reservoir, the consistency of the intra-month runoff distribution of the Gangkouwan Station and Hulesi Station deteriorated, mainly because the runoff unevenness coefficient and concentration degree of Gangkouwan Station in the flood season became smaller, and the dry season became larger compared with Hulesi Station.

Acknowledgments
This work is funded by the National Key R&D Program of China (2018YFC1508002, 2017YFC0403600, 2017YFC0403606), National Public Research Institutes for Basic R & D Operating Expenses Special Project (No.CKSF2017061, No.CKSF2017008), the National Natural Science Foundation of China (No. 51779013, 51509009), Water Conservancy Science and Technology Innovation project of Guang Dong Province(2017-03), National Science Foundation of Hubei Province (2017CFB606, 2018CFB655). Special thanks are given to the anonymous reviewers and editors for their constructive comments.

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