Analysis of the influence of reservoir regulation on the multi-scale periodic effect of runoff time series

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Abstract. The periodic effect of runoff time series is a basic characteristic that reflects the change law of river hydrological situation. In order to reveal the influence of power station regulation on the periodic change of runoff process, the Gangkouwan Station, the controlling reservoir of the Shuiyangjiang River, was taken as the object in this article, based on the Morlet wavelet analysis technique, the influence of the reservoir on the periodic characteristics of natural runoff was analyzed and the influence of the reservoir on the periodic effect of runoff process of downstream channel on different time scales was revealed. The results show that the Gangkouwan Station significantly affects the periodic change of runoff on the 1-year, 4-month and 1-day scales, and among them, periodic change on the 1-day scale shows change law of day night alternative wetness-dryness.

1. Introduction
Hydrological periodic cycle is an important basic characteristic of runoff change, and under natural conditions, the periodic change of runoff is mainly influenced by multiple factors such as atmospheric circulation, climate evolution, geographic change, etc[1]. However, with the intervention of human activities, especially the construction and operation of hydraulic engineering, the periodic change of channel runoff may have changed accordingly. Scholarly researches on the periodicity of runoff have been always focused on the annual scale[1-3], while relatively few researches on the monthly, daily and subdaily scales. Therefore, in this article, the controlling reservoir in the upstream Shuiyangjiang River which is the first grade tributary of the Yangtze River-the Gangkouwan Reservoir was taken as the object, and it was analyzed using the Morlet wavelet analysis technique that the periodic effect of flow change on the monthly, daily and hourly scales in the downstream hydrological station before and after the construction of the Gangkouwan Reservoir as well as the upstream and downstream hydrological stations after the construction of the Gangkouwan Reservoir to reveal the influence of the reservoir on the runoff change periodicity on multi-scales.
2. Study Area and Methodology

2.1. Study area
The Shuiyangjiang River, which drains an area of 10305 km$^2$, is located at the south bank of the downstream Yangtze River (figure 1)[4]. The upper reaches of the Shuiyangjiang River consists of 3 main tributaries named Dongjin River, Zhongjin River and Xijin River of which the Xijin River is the largest.

The Gangkouwan reservoir, the largest reservoir in the basin with a total storage capacity of 9.41×10$^8$ m$^3$, is located at the upstream 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 of 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 hydrological regime [5].

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

2.2. Data
In order to study the influence of the Gangkouwan Reservoir on the periodic effect of the hydrological regime of the downstream channel of the Shuiyangjiang River. The data on hourly water level, daily and monthly flow of Gangkouwan Station and Hulesi Station at the Shuiyangjiang River were collected in this article (Table 1). Corresponding water level-flow relationship curves of each hydrological station were also collected in order to convert the collected hourly water level data into hourly flow data.

| Watershed | Stations     | Coordinates          | Distance from dam site | Water level-flow curve | Water level and flow data                                      |
|-----------|--------------|----------------------|------------------------|------------------------|---------------------------------------------------------------|
| Shuiyang River | Gangkouwan Station | [30°34′N,18°52′E] | 1km below the dam     | Water level-flow curve in 2012 and 2013 | Monthly flow data 1991~2012 daily flow data 1991~2012 hourly water level data 2012.4~2014.4 |
|           | Hulesi Station | [30°23′N,18°46′E] | 55km above the dam    | Water level-flow curve in 2012 and 2013 | Monthly flow data 1974~2012 daily flow data 1974~2012 hourly water level data |

Table 1 Hydrological data
3. Methodology

3.1. Data standardization processing
Before analyzing the runoff data, the data are usually standardized (Normalization) to achieve the dimensionless form of runoff series. Since the maximum and minimum values of runoff time series change over time, considering the uncertainty of extreme value, the flow series data was standardized by the Z-score method in this article.

\[
Q'_i = \frac{Q_i - \bar{Q}}{\sigma_Q}
\]

where \(Q'_i\) is the standardized value; \(Q_i\) is the flow value of the series; \(\bar{Q}\) is the mean value of the series; \(\sigma_Q\) is the variance of the series.

3.2. Morlet wavelet analysis
Wavelet analysis introduces a window function based on the Fourier transform, and the wavelet transform allows a time series to be decomposed into time and frequency contributions based on the invariance of the affine group (the invariance of translation and expansion). It is very effective for obtaining the characteristic rule of a complex time series, diagnosing the inherent hierarchy of time series variation, and distinguishing the evolution characteristics of time series on multi-scales[6,7,8]. As a multiresolution analysis method, wavelet transform can perform time and frequency domain analysis at the same time with time frequency localization and multiresolution characteristics Therefore, it is particularly suitable for processing non-stationary signals and known as "mathematical microscope"[9].

In wavelet transform, the more commonly used wavelet functions are Mexican Hat wavelet, Dmey wavelet, and Morlet wavelet et al. Wavelet analysis of hydrometeorological time series was performed using the Morlet wavelet function [10, 11], and the specific method of morlet wavelet analysis has been introduced in many references, and this article will not introduce it[11, 12].

4. Results and Discussion

4.1. Periodic change characteristics of monthly flow series
Based on monthly data with the same time length before and after the construction of the Gangkouwan Reservoir, Z-standardizing the data to eliminate the influence of dimension and standardized monthly runoff series was analyzed using wavelet techniques. The wavelet variance plot and wavelet power spectrum of 11 years data (1991-2001) before and 11 years data (2002-2012) after the construction of the Gangkouwan Reservoir are shown in Figures 2 and 3, respectively. Since the Gangkouwan Reservoir is an annual regulation reservoir and its regulation performance is weaker compared to multi-year reservoirs, the intra-annual process redistribution of runoff was performed. From the wavelet variance plot, it can be seen that the influence on the quarterly and half-year runoff change periodicity is more obvious after the construction of the Gangkouwan than that before the construction of the reservoir. From the wavelet power spectrum, it can be seen that there exists differences in the occurrence time of runoff period in the runoff change with 1-year period. However, the frequency is essentially consistent. It is possibly because that the redistribution effect of the Gangkouwan reservoir on intra-annual runoff has changed runoff periodic process with 1-year period under natural conditions.

Therefore, the runoff regulation of reservoirs influences the periodic change of runoff on the monthly scale, which changes the original hydrological periodic law of rivers to some extent.
4.2. Periodic change characteristics of daily flow series

Due to the strong randomness of daily flow series, the comparison analysis of daily flow series is performed only for the upstream and downstream stations in the same time period considering the influence of other factors on the randomness of daily flow series.

Wavelet analysis of the standardized daily flow series was performed using the daily flow series of the Gangkouwan Station and Hulesi Station in 2012. The calculation results of wavelet variance (Figure 4) show that the Gangkouwan Station passes the test of significance level 0.05 on the 2-month, 3-month and 4-month period scales while Hulesi Station passes the test of significance level 0.05 on the 0.125-month and 0.25-month scales. From wavelet power spectrum (Figure 5(a), (b)), it can be seen that flow periodic fluctuation with the scale less than 15 days occurs in both June and August in Hulesi Station while in Gangkouwan Station, flow periodic fluctuation with the mutual nesting time scales from 1 month to 4 months occurs during the period from June to November and flow periodic fluctuation with the time scale of 4 months (120 days) occurs from February to October. Under the premise of conducting regulation and storage plan and power generation plan of the whole year, regulation and storage plan with the smaller time scale is conducted according to the incoming water of different periods, resulting in the periodic regulation and storage process with multiple mutual nesting time scales.
Figure 5. Wavelet power spectrum of the stations upstream and downstream of Gangkouwan Reservoir in 2012

Therefore, the runoff regulation of reservoirs influences the periodic change of runoff on the daily scale. Through regulation and storage of reservoirs, the original rising and falling process with smaller period and shorter duration of the flood is regulated into the runoff process of "opening the sluice to discharge and closing the sluice to impound" with larger period and longer duration, which changes the original hydrological periodic law of rivers to some extent.

4.3. Periodic change characteristics of hourly flow series
Due to the limit of data, the comparison analysis of hourly flow series is performed only for the upstream and downstream stations in the same time period considering the influence of other factors on the randomness of temporal flow series.

Wavelet analysis of the standardized hourly flow series was performed using the hourly flow series of the Gangkouwan Station and Hulesi Station from April 2012 to March 2013. From wavelet power spectrum of the Gangkouwan Station (Figure 6), it can be seen that there exist significant fluctuations on the 1-day scale in the flood season of June and July and significant fluctuations on the half-day or 1-day scale in the dry season of November, December and February.

Figure 6. Hourly wavelet power spectrum at Gangkouwan Station from April 2012 to March 2013
From the hourly wavelet power spectrum of Hulesi Station in the same period (Figure 7), periodic fluctuation of short duration with the mutual nesting time scales from 3 hours to 2 days (48 hours) occurs from July 13 to July 18 in 2012, which is due to the rising and falling process of the flood caused by precipitation of the month. In addition, there exhibits no significant fluctuations on the the 1-day or half-day (12 h) time scales throughout the nearly 1-year hourly flow series.

In nature, the runoff process by snowmelt recharge tends to exhibit fluctuation change process of 1-day period. Because of higher daytime temperatures, the snow melts and thus the flow rate is higher, while the temperature is lower at night and the melt water decreases and thus the flow rate is lower, thus forming the periodic flow change process of day night alternative wetness-dryness. The runoff in the Yangtze River Basin is mainly recharged by rainfall, and the flow process seldom shows periodic changes on the 1-day scale. Through the above analysis, it is found that there exists periodic fluctuation on the 1-day scale downstream the Gangkouwan Reservoir. In order to increase the power generation benefits, power generation law of storage at night and discharge in the daytime is formed when there is no flood risk downstream, thus causing the flow change process similar to snowmelt recharge mechanism in the downstream flow process. In addition, reservoirs with different regulation capacities have different influences on the runoff periodicity. For multi-year regulating storage reservoirs, seasonal incoming water has little influence on the reservoir throughout the year, and the peak regulation process with 1-day period has considerable persistence. While the Gangkouwan Reservoir is an annual regulation reservoir, whose regulation capacity is weaker than multi-year regulating storage reservoirs. Therefore, the persistent peak regulation process with 1-day period can only be completed in certain months or seasons under the premise of considering flood control.

![Figure 7. Hourly wavelet power spectrum at Hulesi station from April 2012 to March 2013](image)

5. Conclusions

(1) Significant changes occurred in the runoff periodic characteristics on the 1-year, 4-month and 1-day scales in the downstream channel of the Gangkouwan Reservoir, which is influenced by the runoff regulation. Particularly on the one-day scale, the wavelet power spectrum of the Gangkouwan Station exhibits significant 1-day periodic fluctuations, while Hulesi Station has almost no signs of fluctuation.
The main reason is that the Gangkouwan Reservoir has developed the regulation and storage law of storage at night and discharge in the daytime.

2) During the period from June to November, flow periodic fluctuation with the mutual nesting time scales from 1 month to 4 months occurs in the downstream channel of the Gangkouwan Reservoir, and flow periodic fluctuation with the time scale of 4 months (120 days) occurs from February to October. Which may be related to the regulation and storage plan and power generation plan of the whole year. Under the premise of following the whole year-plan, regulation and storage plan with the smaller time scale is conducted according to the incoming water of different periods, resulting in the periodic regulation and storage process with multiple mutual nesting time scales.

3) The subdaily periodic peak regulation process is closely related to the regulation capacity of the reservoir. The Gangkouwan Reservoir is an annual regulation reservoir, thus the persistent peak regulation process with 1-day period can only be completed in certain months or seasons under the premise of considering flood control. There exist significant fluctuations on the 1-day scale in the flood season of June and July and significant fluctuations on the half-day or 1-day scale in the dry season of November, December and February.

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