Evaluation of river hydrological regime changes under the influence of Gangkouwan Reservoir

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Abstract. The construction of the reservoir has met human needs to a certain extent, but it has caused serious threats to river ecosystems, especially for the hydrological regime. In order to deepen the understanding of the impact of the reservoir, this paper introduces the Indicators of Hydrologic Alteration (IHA) method, constructs an indicator system that describes the changes in hydrological regime, and uses the Range of Variability Approach (RVA) to quantitatively evaluate the changes of 5 groups of 33 indexes after the construction of Gangkouwan Reservoir, thus realizing the quantitative change of the river hydrological regime. The results show that the Gangkouwan Reservoir affects the frequency and duration of high and low pulses highly, as well as in rate and frequency of water condition changes, and the integral change degree of hydrological regime is moderate.

1. Introduction
Climate change and human activities are the most critical factors affecting hydrological process, with reservoirs being the most prominent[1]. The construction of reservoirs has met social needs of humans such as agricultural irrigation, domestic water use, power generation and flood control to some extent, which furthermore has a more significant effect on the natural runoff process. Hydrological regime differences caused by runoff process change will break river ecosystem stability and cause damage to the ecosystem at different degrees. In order to quantitatively evaluate hydrological situation differences, scholars from various countries will construct or select different indexes[2-5].

Based on daily flow data of Gangkouwan Station from 1974 to 2012, hydrological indexes at the daily scale were calculated and analyzed their change characteristics in this paper.
2. Study Area and Methodology

2.1. Study area
The Gangkouwan Reservoir is the backbone control project for the flood control in the Shuiyang River Basin, which is the first-level tributary of Yangtze River[6, 7], and the schematic diagram is shown in Figure 1[8]. It is primarily used for flood control and has comprehensive utilization functions such as power generation, irrigation, urban water supply, aquaculture and tourism development. The reservoir controls a basin area of 1,120 km² with the normal water level of 135m, a reservoir area of 32.8 km² and a total storage capacity of 9.40×10⁸m³, and the flood control storage capacity is 4.30×10⁸m³. The hydropower station has an installed capacity of 60×10³kW and annual power generation is 1.10×10⁸kWꞏh. In October 2002, the project was completed and accepted and the gate was closed to store water. Based on the multi year measured data of Gangkouwan hydrological station which was downstream of Gangkouwan Reservoir, hydrological situation differences under the influence of Gangkouwan Reservoir was analyzed statistically in this paper.

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

2.2. Methodology
Foreign scholars Richter et al. have established a set of IHA methods to assess the process of ecological hydrological changes[5,9,10]. The RVA method is proposed by Richter et al. on the basis of IHA to evaluate effects of hydraulic projects on natural runoff [11]. This method can determine the RVA threshold range on the basis of various indexes results before and after being affected by human activities by the IHA method, and then determine change degree of integral river hydrological regime. Hydrological situation differences before and after the construction of Gangkouwan Reservoir was evaluated by RVA in this article. The runoff time series is affected by the construction of the reservoir and is divided into two sections before and after the construction of the reservoir (Pre-dam and post-dam, respectively).

The RVA method mainly includes the following steps:
① The RVA target threshold of each hydrological index was calculated based on the reference period data (pre-dam series). The upper and lower limits of the RVA threshold were determined by the statistical parameters method, and the calculation formula is:

\[ RVA_{X,upper} = \bar{X}_i + \sigma_i \]
\[ RVA_{X,lower} = \bar{X}_i - \sigma_i \]

In the formula, \( \bar{X}_i \) is the average value of reference period samples of the \( i \)-th index; \( \sigma_i \) is the standard deviation of reference period samples of the \( i \)-th index.

② For a single hydrological index, the calculation formula of hydrological change degree recommended by RVA method is:

\[ D_i = \frac{N_{0,i}-N_{e}}{N_e} \]

In the formula, \( D_i \) is the hydrological change degree of the \( i \)-th hydrological index; \( N_{0,i} \) is the number of observation years falling within the RVA threshold during the evaluation period of the \( i \)-th index.
hydrological index; \( N_e \) is the expected hydrological index sample number falling within the RVA target during the evaluation period (post-dam series). In General, \( D_l \) between 0 and 33% means no or slight change degree (Low); \( D_l \) between 33% and 67% means moderate change degree (Middle); \( D_l \) between 67% and 100% means high change degree (High).

③ After calculating change degrees of all hydrological indexes, the calculation formula of integral change degree of hydrological regime is

\[
D_{RVA} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} D_i^2}
\]  

In the formula, \( n \) is the number of all evaluation indexes.

3. Results and Discussion

Through IHA software, statistical values of various eco-hydrological indexes before and after the construction of Gangkouwan Reservoir was calculated and obtained by inputting daily flow data of Gangkouwan Reservoir from 1974 to 2012.

The calculation results of hydrological indexes are the basis of evaluating hydrological regime change under the influence of reservoirs. For the analysis of hydrological regime differences at the daily scales, eco-hydrological regime differences under the natural conditions and the action of reservoirs was evaluated by the RVA method based on statistical results of various indexes by the IHA method before and after the construction of Gangkouwan Reservoir. For the analysis of hydrological situation differences at the daily scale, eco-hydrological index differences of Gangkouwan Station was analyzed and evaluated by non-parametric statistical test through the analysis and comparison of the distribution of various hydrological parameters.

3.1. Evaluation results of hydrological indexes at the daily scale

Based on the results of various hydrological indexes of Gangkouwan Station calculated by the IHA method, the change degree of hydrological situation was counted by the RVA method and the calculation results are shown in Table 1. It can be seen that the index change degree of February, July, August and December is moderate change and that of the remaining months is low in index group 1. In index group 2, change degree of the minimum flow for 1-day mean, 3-day mean and 7-day mean as well as that of the maximum flow for 1-day mean and 3-day mean is high, and change degree of the minimum flow for 1-day mean has reached 100%. In index group 3, change degrees of extreme hydrological events occurrence time are all moderate change. In index group 4, change degrees of the remaining indexes are high except that duration of low pulses is low and change degree of number of low pulses within each water year has reached 100%. In index group 5, change degrees of fall rates and hydrologic reversals number are both high and change degree of hydrologic reversals number has reached 100%. In general, change degrees of 8 indexes are moderate change, change degrees of 9 indexes are high and that of the remaining 15 indexes are low.

3.2. Analysis of the change degree of hydrological regime at the daily scale

In index group 1, the mean value for July is the index disturbed by the reservoir at the most degree and the change degree is 49.3%, which is moderate change degree. The change process is shown in Figure 2. It can be seen that the the average flow and annual change range of the month decreases significantly after the construction of the reservoir, indicating that regulation and storage of the reservoir has a definite effect on the runoff process on the monthly scale to some extent.

In index group 2, the minimum flow within 1-day mean is the index disturbed by the reservoir at the most degree and the change degree is 100%, which is high change degree. The change process is shown in Figure 3. It can be seen that the upper limit of the standard deviation of the minimum flow process within 1-day mean is smaller than the lower limit of the RVA target threshold (before the construction of the reservoir) and the average value as well as annual change range decreases significantly after the construction of the reservoir, indicating that water storage of the reservoir has a significant effect on the extreme flow index on the daily scale to some extent.
In index group 3, change degrees of Julian date of the minima and maxima are both moderate change degree. From the perspective of the average value, the average occurrence time of the minimum flow rate is brought up to the middle ten days of February (post-dam) from the first ten days of July (pre-dam) and the average occurrence time of the maximum flow rate is pushed backwards to the first ten days of July (post-dam) from the middle ten days of June (pre-dam).

Table 1. The result of RVA at Gangkouwan Station

| IHA parameters                                                   | Average RVA limits | $N_{\alpha,i}$ | $D_i$ | Evaluation |
|-----------------------------------------------------------------|-------------------|---------------|-------|------------|
|                                                                 | Pre-dam           | Post-dam      | lower | upper      | $N_{\alpha}$ | $D_i$ | Evaluation |
| Mean value for January                                          | 11.9              | 7.40          | 3.877 | 23.41      | 6.7          | 5     | 25.4        | Low        |
| Mean value for February                                         | 20.9              | 7.90          | 7.41  | 34.28      | 5.9          | 3     | 49.2        | Mid        |
| Mean value for March                                            | 43.5              | 35.2          | 19.81 | 67.14      | 8.3          | 6     | 27.7        | Low        |
| Mean value for April                                            | 43.4              | 35.7          | 20.41 | 66.48      | 7.1          | 7     | 1.4         | Low        |
| Mean value for May                                              | 37.9              | 36.2          | 9.767 | 66.12      | 8.3          | 9     | 8.4         | Low        |
| Mean value for June                                             | 75.5              | 40.1          | 13.17 | 137.8      | 8.3          | 8     | 3.6         | Low        |
| Mean value for July                                             | 57.2              | 33.9          | 13.46 | 101        | 6.7          | 10    | 49.3        | Mid        |
| Mean value for August                                           | 30.8              | 34.2          | 8.668 | 65.08      | 6.7          | 9     | 34.3        | Mid        |
| Mean value for September                                         | 23.8              | 12.9          | 2.165 | 45.42      | 9.04         | 9     | 0.4         | Low        |
| Mean value for October                                          | 14.0              | 13.1          | 4.054 | 34.77      | 7.1          | 9     | 26.8        | Low        |
| Mean value for November                                          | 12.36             | 17.4          | 2.577 | 27.19      | 6.7          | 7     | 4.5         | Low        |
| Mean value for December                                          | 7.345             | 14.6          | 2.745 | 14.55      | 7.1          | 4     | 43.7        | Mid        |
| Annual minima, 1-day mean                                       | 1.39              | 0.33          | 0.63  | 2.16       | 7.9          | 0     | 100         | High       |
| Annual minima, 3-day mean                                       | 1.50              | 0.51          | 0.65  | 2.35       | 7.9          | 1     | 87.3        | High       |
| Annual minima, 7-day mean                                       | 1.70              | 0.54          | 0.63  | 2.78       | 8.6          | 2     | 76.7        | High       |
| Annual minima, 30-day mean                                      | 2.845             | 1.46          | 0.99  | 4.70       | 9            | 5     | 44.4        | Mid        |
| Annual minima, 90-day mean                                      | 7.97              | 9.03          | 0.91  | 15.03      | 9.4          | 10    | 6.4         | Low        |
| Annual maxima, 1-day mean                                       | 696               | 172           | 299.5 | 1093       | 8.3          | 1     | 88          | High       |
| Annual maxima, 3-day mean                                       | 443               | 158           | 173.7 | 713        | 9            | 1     | 88.9        | High       |
| Annual maxima, 7-day mean                                       | 285               | 136           | 99.65 | 471.8      | 8.6          | 8     | 7           | Low        |
| Annual maxima, 30-day mean                                      | 126               | 83.8          | 50.68 | 201.5      | 9            | 8     | 11.1        | Low        |
| Annual maxima, 90-day mean                                      | 72.2              | 51.0          | 35.35 | 109        | 7.5          | 9     | 20          | Low        |
| Base flow index                                                 | 0.055             | 0.024         | 0.0224| 0.0874     | 7.9          | 6     | 24.1        | Low        |
| Julian date of each annual 1-day minimum                        | 189.5             | 44.36         | 93.78 | 285.3      | 7.1          | 3     | 57.7        | Mid        |
| Julian date of each annual 1-day maximum                        | 161.8             | 185.1         | 107   | 216.6      | 7.9          | 4     | 49.4        | Mid        |
| Number of low pulses within each water year                     | 7.964             | 34.91         | 2.705 | 13.22      | 9            | 0     | 100         | High       |
| Duration of low pulses (days)                                   | 12.69             | 5.447         | 4.003 | 21.37      | 9.04         | 9     | 0.4         | Low        |
| Number of high pulses within each water year                    | 9.643             | 4.182         | 5.929 | 13.36      | 8.3          | 2     | 75.9        | High       |
| Duration of high pulses (days)                                  | 2.235             | 4.291         | 1.749 | 2.722      | 7.9          | 2     | 74.7        | High       |
In index group 4, the number of low flow pulses is the index disturbed by the reservoir at the most degree and the change degree is 100%, which is high change degree. The change process is shown in Figure 4. It can be seen that the lower limit of the standard deviation of low flow pulse number is greater than the upper limit of the RVA target threshold (before the construction of the reservoir) and the average value as well as annual change range increases significantly after the construction of the reservoir, indicating that water storage of the reservoir has an effect on the hydrological regime on the daily scale to some extent.

Figure 2. The flow change process of Gangkouwan Station in July

Figure 3. The change process of Gangkouwan Station for Annual minima, 1-day mean

Figure 4. The change process of Gangkouwan Station for number of low pulses

Figure 5. The change process of Gangkouwan Station for number of hydrologic reversals

In index group 5, reversals number is the index disturbed by the reservoir at the most degree and change degree is 100%, which is high change degree. Reversals number mainly reflects alternating frequency of rising and falling. The change process is shown in Figure 5. It can be seen that the lower limit of the standard deviation of reversals number is greater than the upper limit of the RVA target threshold (before the construction of the reservoir) and the average value as well as annual change range increases significantly after the construction of the reservoir, indicating that water storage of the reservoir increases not only alternating frequency of rising and falling but also annual distribution instability of reversals number. It means that there exist greater differences in alternating frequency of rising and falling in different years after the construction of the reservoir compared to that before the construction of the reservoir, which will affect the stability of biological habitat.

The change degree of each index group and integral change degree of Gangkouwan Station were calculated using formula 4. The results are shown in Table 2. It can be seen that change degree of monthly average flow (Group 1) which is 29.2% (low). Change degrees of extreme hydrological magnitude and duration (Group 2) and extreme hydrological timing (Group 3) which are 62.1% (middle)and 53.5% (middle), respectively. The highest change degrees are that of the frequency and
duration of high and low pulses (Group 4) as well as the rate and frequency of water condition changes
(Group 5), which are 84.3% and 85.0%, respectively. In general, change degrees of hydrological regime
at daily scale are moderate changes.

| Group | D/% | Evaluation |
|-------|-----|------------|
| 1     | 29.2| Low        |
| 2     | 62.1| Mid        |
| 3     | 53.5| Mid        |
| 4     | 84.3| High       |
| 5     | 85.0| High       |
| Integral | 56.3 | Mid        |

### 4. Conclusions

The construction of the Gangkouwan Reservoir has produced drastic changes to the river hydrological
regime. By using the IHA indicator system and RVA evaluation method, the following conclusions are
obtained:

1. Reservoir operation has little effect on the index of Magnitude of monthly water conditions, and
it has a moderate impact on February, July, August and December, mainly due to the function of Store
the flood season water volume and supplement the dry season water volume.

2. The regulation function of the Gangkouwan Reservoir is bound to affect the occurrence of
extreme events of flow, especially for Annual minima, 1-day mean, 3-day mean and 7-day mean, as the
same as annual maxima, 1-day mean and 3-day mean.

3. Under the influence of Gangwanwan Reservoir, the number and duration of high-flow pulses and
the number of low-flow pulses have changed drastically, while the duration of low-flow pulses changed
slightly.

4. Rise rates and hydrologic reversals were disturbed by the reservoir to the most degree, and
the integral change degree of hydrological regime is moderate.

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