

# Assessing the hydrologic alteration of the Yangtze River using the histogram matching approach

F Huang<sup>1,2,5</sup>, N Zhang<sup>3</sup>, L D Guo<sup>4</sup> and Z Q Xia<sup>1,2</sup>

<sup>1</sup> State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing, 210098, China

<sup>2</sup> College of Hydrology and Water Resources, Hohai University, Nanjing, 210098, China

<sup>3</sup> Yellow River Institute of Hydraulic Research, Zhengzhou, 450003, China

<sup>4</sup> Business School, Hohai University, Nanjing, 210098, China

E-mail: hfeng0216@163.com

**Abstract.** Hydrologic changes of the Yangtze River, an important river with abundant water resources in China, were investigated using the Histogram Matching Approach. Daily streamflow data spanning the time interval from 1955 to 2013 was collected from Yichang and Datong stations, which monitor the hydrologic processes of the upper and lower reach of the Yangtze River, respectively. The Gezhouba Dam, the first dam constructed at the main stream of the Yangtze River, started operations in 1981. 1981 was used to differentiate the pre-dam (1955-1980) and post-dam (1981-2013) hydrologic regimes. The hydrologic regime was quantified by the Indicators of Hydrologic Alteration. The overall alteration degree of the upper Yangtze River was 31% and the alteration degree of every hydrologic indicator ranged from 10% to 81%. Only 1, 5 and 26 hydrologic indicators were altered at high, moderate and low degrees, respectively. The overall alteration degree of the lower Yangtze River was 30%, and the alteration degree of every hydrologic indicator ranged from 8% to 49%. No high alteration degree was detected at the Datong station. Ten hydrologic indicators were altered at moderate degrees and 22 hydrologic indicators were altered at low degrees. Significant increases could be observed for the low-flow relevant indicators, including the monthly flow from January-March, the annual minimum 1, 3, 7, 30 and 90-day flows, and the base flow index.

## 1. Introduction

The natural hydrological regime is a basic driver of water ecosystems and vitally important for keeping the health of river, lake and wetland ecosystems. It is affected by both anthropogenic activities and the climate, both of which have been the subject of many studies investigating worldwide hydrologic changes [1-5].

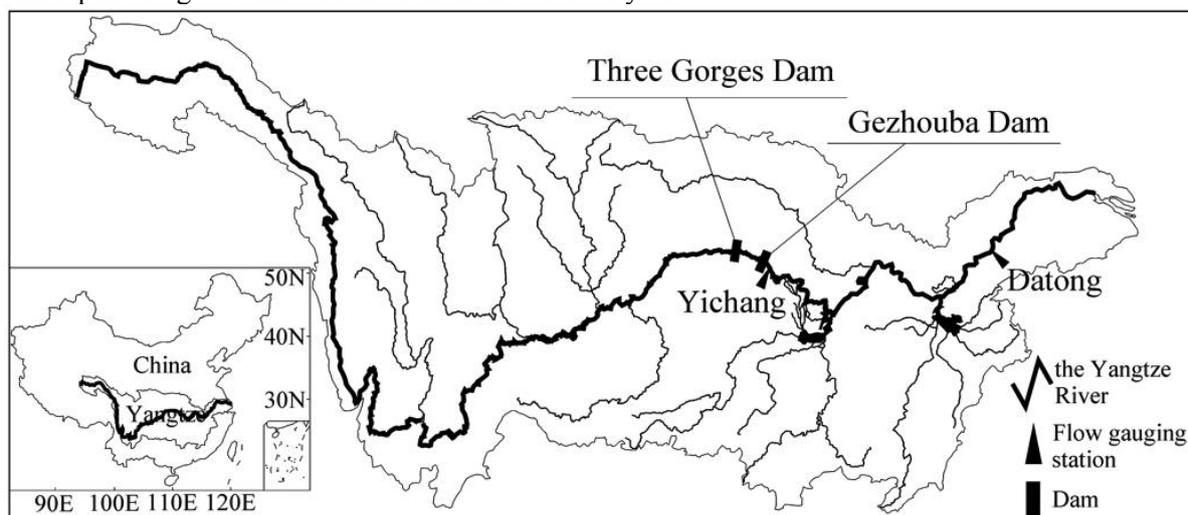
The Yangtze River plays an irreplaceable role in the ecological environmental protection and socio-economic construction of China, with its abundant water, hydropower, and biological resources. Over 50,000 dams/reservoirs have been built in the basin [6]. The total storage capacity of these dams is almost 180 billion m<sup>3</sup>, which amounts to approximately 20% of the annual runoff of the Yangtze River [7]. The impacts of these reservoirs on the hydrologic regime and its related ecological environmental implications have attracted considerable attention in recent years [8-12]. The present



study seeks to evaluate the hydrologic changes of the Yangtze River using the Histogram Matching Approach (HMA). The results of this research will provide reference for water resource utilization and for the protection of riverine ecosystems.

## 2. Study site and data

The Yangtze River originates in the Qinghai-Tibet Plateau in western China (figure 1). Its length is about 6300 km and its catchment area is approximately 1.8 million km<sup>2</sup>. The basin lies in the monsoon region of East Asia, which is a subtropical climate zone. The monsoon-driven precipitation is unevenly distributed throughout the year, which causes seasonal variability in river runoff. The rainy season starts in April and determines the hydrologic year. The Yangtze River's hydrologic year begins from April and goes until March of the next calendar year.



**Figure 1.** Locations of the Yangtze River and flow gauging stations.

The Yichang and Datong flow gauging stations were selected for assessing hydrologic alteration. The Yichang station is located at the outlet of the upper reach, approximately 6 km below the Gezhouba Dam and 44 km below the Three Gorges Dam. It monitors the hydrologic regime of the upper Yangtze River. The Datong station distributes at the lower reach where the annual mean runoff is 896.4 billion m<sup>3</sup> and the annual mean sediment load is 0.39 billion t.

The Changjiang Water Resources Commission (China) provided daily streamflow data spanning from 1955 to 2013. The Gezhouba Dam, which was the first dam constructed at the main stream of the Yangtze River, started operations in 1981. 1981 was used as the dividing point between the pre-dam (1955-1980) and post-dam (1981-2013) hydrologic regimes. The hydrologic regime during 1955-1980 may not be wholly unaltered because some dams were constructed at the tributaries of the upper Yangtze River prior to 1981 [12,13]. This assessment aims to reveal the degree of alteration of the hydrologic regime from 1981 to 2013 compared with the hydrologic regime during the pre-dam era.

## 3. Methods

### 3.1. Indicators of Hydrologic Alteration (IHA)

The IHA method is widely applied to characterize the various components of hydrologic regimes [14]. It contains 33 hydrologic parameters that are grouped into five categories of hydrologic features. These are, group 1: magnitude of monthly water conditions, group 2: magnitude and duration of annual extreme water conditions, group 3: timing of annual extreme water conditions, group 4: frequency and duration of high and low pulses, and group 5: rate and frequency of water condition changes. The parameter “number of zero-flow days” was not applied because no zero-flow events

occurred during the study period. Each IHA parameter was calculated for every hydrologic year, and the results were used to assess hydrologic alteration.

### 3.2. Histogram Matching Approach

The Range of Variability Approach (RVA) has been widely applied in worldwide assessments of hydrologic alteration and environmental flow design [15-18]. Shiau and Wu [19] have noted that the RVA method has two main limitations: (1) it only considers the frequency of the hydrologic parameters that fall within the target range, and ignores variation; and (2) it ignores the frequency and variation of the hydrologic parameters that fall above the upper-target or below the lower-target. These limitations might potentially lead to a false assessment of hydrologic alteration. The HMA method has been proposed to address the limitations of the RVA method. Its detailed procedure can be found in the literature of Shiau and Wu [19].

The hydrologic alterations were assessed by applying the HMA method. Then, following the class evaluation system [20], the degrees of hydrologic alteration for individual hydrologic indicators were classified into the categories “little alteration” (ranging from 0 to 33%, denoted by the letter “L”), “moderate alteration” (ranging from 34 to 67%, indicated by the letter “M”), and “high alteration” (ranging from 68 to 100%, indicated by the letter “H”).

## 4. Results and discussion

The pre-dam and post-dam hydrologic regimes of the Yichang and Datong stations were compared in the histograms in figure 2 and figure 3, respectively, and the results of the hydrological alteration for every hydrologic indicator are shown in figure 4.

At the Yichang station, the overall degree of hydrologic alteration was 31%, which is classified as “little alteration.” The deviations of the median flow in August, January, and March ranged from 37% to 43%, and this range is within the classification of “moderate alteration.” The median flow deviations of the other months ranged from 10% to 31%, categorized as “little alteration.” Figure 2 shows the change characteristics of the post-dam histograms as compared to the pre-dam histograms. The histograms of the median flow of January and March displayed similar change patterns. The post-dam histogram moved to the right of the pre-dam histogram, indicating an increased flow in January and March. The alteration degree of magnitude and duration of annual extreme flow ranged from 10% to 33%, classified as “little alteration.” Similar change patterns were observed in the annual minimum flow and the base flow index. The relative frequencies of the post-dam histogram were distributed to the right of the relative frequencies of the pre-dam histogram, indicating an increased flow in the dry season. The alteration degree of the Julian calendar date of the annual 1-day minimum flow was 35% (“moderate alteration”) and the alteration degree of the Julian calendar date of the annual 1-day maximum flow was 13% (“little alteration”). The annual 1-day minimum flow usually occurred in January, February or March in the pre-dam years, but after 1981, it sometimes occurred in December of the previous calendar year (figure 2 (24)). The alteration degree of frequency and the duration of high and low pulses fell about 20%, which is classified as “little alteration.” The rise rate was found to have “moderate alteration” and the fall rate had “little alteration.” The number of reversals showed “high alteration,” and this was the only hydrologic indicator that exceeded 67% deviation. The number of reversals increased drastically after 1981.

At the Datong station, the overall degree of hydrologic alteration was 30%, which was very close to the alteration degree at the Yichang station. According to the data, no hydrologic indicators experienced “high alteration” at the Datong station. The median flows in January, February and March showed “moderate alteration”, and during the other months the median flows showed “little alteration.” The alteration degree of the annual minimum flow’s relevant indicators ranged from 36% to 49% (“moderate alteration”). The annual maximum flow’s relevant indicators ranged from 19% to 32% (“little alteration”). An increased flow in the dry season was also observed at the Datong station (figure 3), which was similar to the change features at the Yichang station. All of the hydrologic indicators in Group 3 and 4 had “little alteration.” The rise and fall rates showed “little alteration,” but

the number of reversals was found to have “moderate alteration.” Different features of hydrologic alterations at the lower reach, as compared with hydrologic alterations at the upper reach, might have been influenced by the runoff from tributaries such as the Hanjiang River, as well as hydraulic regulation of the river channels and lakes between the Yichang and Datong stations, e.g. the Dongting and Poyang Lakes.

The hydrologic regime of the Yangtze River represents a catchment response to climate input and anthropogenic activities. Precipitation may be a dominant factor in hydrologic changes. The spatial distribution of the precipitation regime can lead to spatial patterns of alterations in runoff [21]. Reservoir regulation is another important factor that affects the hydrologic regime. The significant increase of the low-flow relevant indicators may be caused by the water supply function of the reservoirs in the dry season [22-24]. The assessment results of the HMA method showed that the alteration degree of the hydrologic regime was affected by both climate change and anthropogenic activities, but this model was unable to definitively differentiate the individual roles of the two factors.

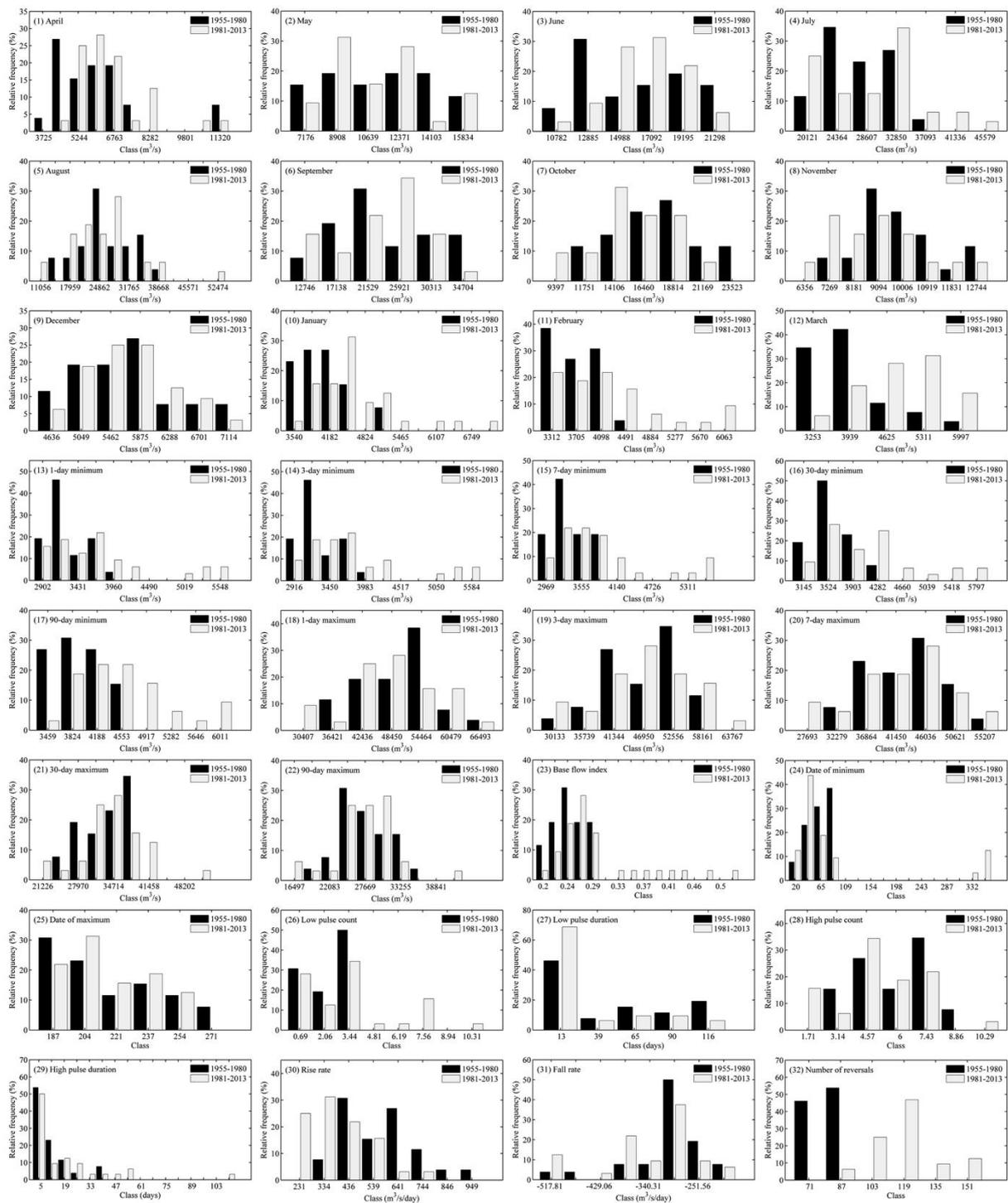


Figure 2. Histogram comparisons of the hydrologic regimes at the Yichang station.

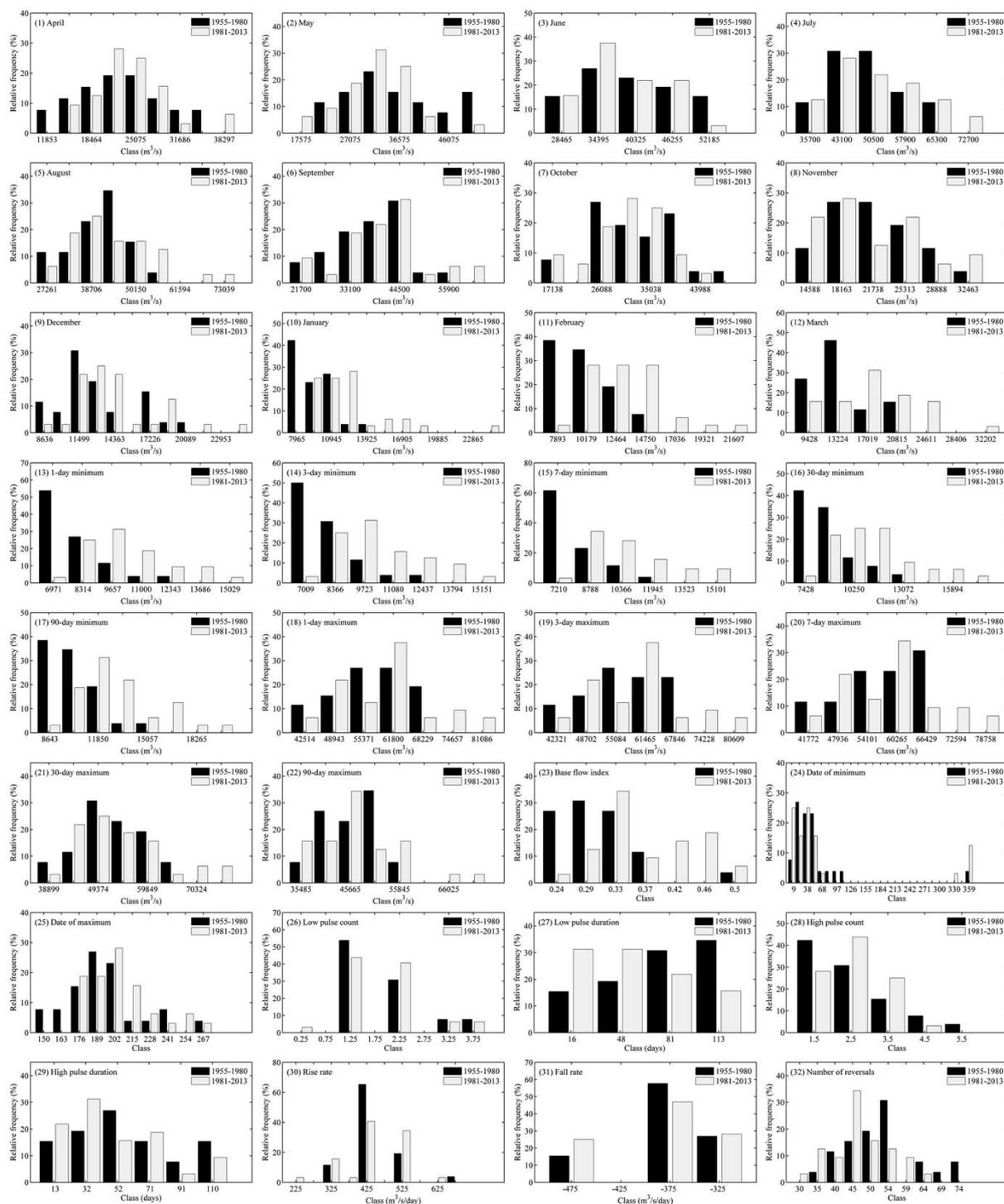
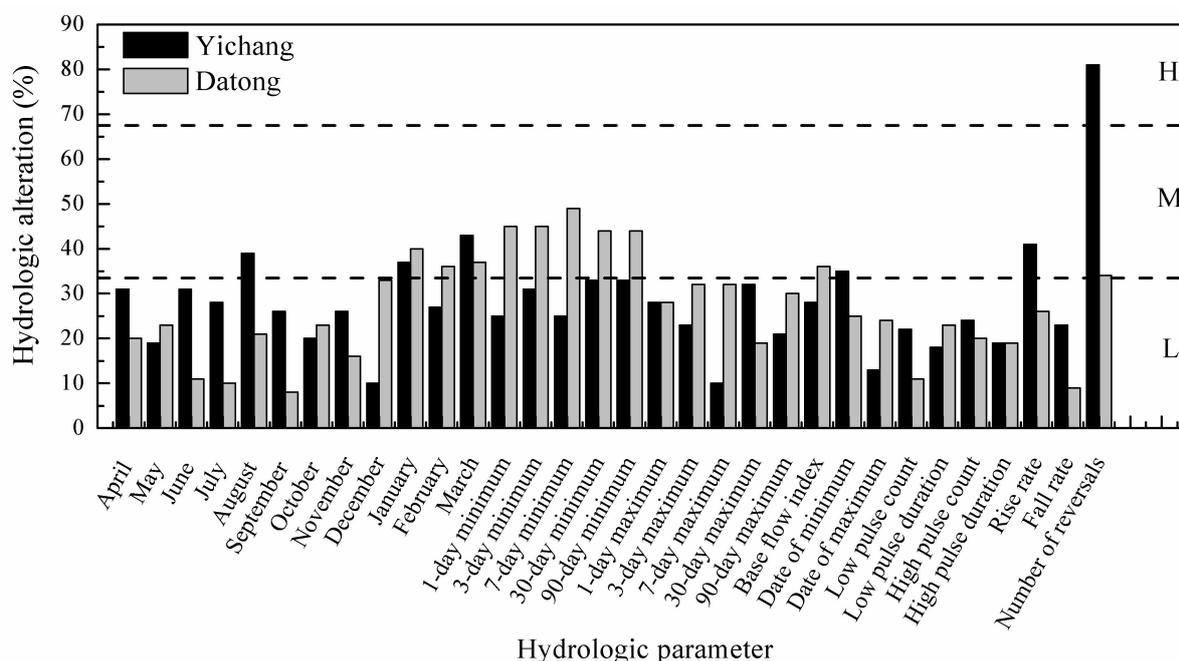


Figure 3. Histogram comparisons of the hydrologic regimes at the Datong station.



**Figure 4.** Hydrologic alterations of the Yangtze River evaluated using the HMA method.

## 5. Conclusions

The hydrologic alteration degree of the Yangtze River was assessed by applying the HMA method to long-term daily streamflow data from the Yichang and Datong stations. The overall alteration degree was approximately 30%, which is in the range of “little alteration.” The alteration degree of the hydrologic indicators of the Yichang station ranged from 10% to 81%. 1, 5 and 26 hydrologic indicators were altered with high, moderate and low degree, respectively. The hydrologic indicator with the highest level of alteration was the number of reversals, which increased drastically after 1981. The alteration degree of the hydrologic indicators from the Datong station ranged from 8% to 49%. No hydrologic indicators showed high alteration. Ten hydrologic indicators exhibited “moderate alteration” and 22 hydrologic indicators showed “little alteration.” Significant increases were observed for the low-flow relevant indicators, such as the monthly flow from January-March, the annual minimum 1-, 3-, 7-, 30- and 90-day flow, and the base flow index. The increased flow in the dry season in the post-dam period has helped to preserve the environmental and ecological water requirements, and also to protect the riverine ecosystem.

## References

- [1] Liechti T C , Matos J P , Boillat J L , et al. 2015 Influence of hydropower development on flow regime in the Zambezi River Basin for different scenarios of environmental flows *Water Resources Management* **29**(3) :731-47
- [2] Chen Q H , Zhang X , Chen Y Y , et al. 2015 Downstream effects of a hydropeaking dam on ecohydrological conditions at subdaily to monthly time scales *Ecological Engineering* **77**: 40-50
- [3] Dyer F, ElSawah S, Croke B, et al. 2014 The effects of climate change on ecologically-relevant flow regime and water quality attributes *Stochastic Environmental Research and Risk Assessment* **28**(1) : 67-82
- [4] Gain A K and Giupponi C 2014 Impact of the Farakka Dam on thresholds of the hydrologic flow regime in the lower ganges river basin (Bangladesh) *Water* **6**(8) : 2501-18

- [5] Souter N J and Schultz M 2014 Using simulated data and the range of variability approach to assess changes to the flow regime of the river Murray at the South Australian border *Transactions of the Royal Society of South Australia* **138**(2) : 277-92
- [6] Yang S L, Milliman J D, Li P, et al. 2011 50,000 dams later: Erosion of the Yangtze River and its delta *Global and Planetary Change* **75**(1-2) : 14-20
- [7] Wei W, Chang Y and Dai Z 2014 Streamflow changes of the Changjiang (Yangtze) River in the recent 60 years: Impacts of the East Asian summer monsoon, ENSO, and human activities *Quaternary International* **336**(SI) : 98-107
- [8] Huang F, Xia ZQ, Li F, et al. 2013 Assessing sediment regime alteration of the upper Yangtze River *Environmental Earth Sciences* **70**(5) : 2349-57
- [9] Li Q F, Yu M X, Zhao J H, et al. 2012 Impact of the Three Gorges reservoir operation on downstream ecological water requirements *Hydrology Research* **43**(1-2) : 48-53
- [10] Zhang N, He H M, Zhang S F, et al. 2012 Influence of reservoir operation in the upper reaches of the Yangtze River (China) on the inflow and outflow regime of the TGR-based on the improved SWAT model *Water Resources Management* **26**(3) : 691-705
- [11] Li Q F, Yu M X, Lu G B, et al. 2011 Impacts of the Gezhouba and Three Gorges reservoirs on the sediment regime in the Yangtze River, China *Journal of Hydrology* **403**(3-4) : 224-33
- [12] Huang F, Xia Z Q, Zhang N, et al. 2011 Flow-complexity analysis of the upper reaches of the Yangtze River, China *Journal of Hydrologic Engineering* **16**(11) : 914-19
- [13] Gao B, Yang D W, Zhao T T G, et al. 2012 Changes in the eco-flow metrics of the upper Yangtze River from 1961 to 2008 *Journal of Hydrology* **448** : 30-38
- [14] Richter B D, Baumgartner J V, Powell J, et al. 1996 A method for assessing hydrologic alteration within ecosystems *Conservation Biology* **10**(4) : 1163-74
- [15] Richter B D, Baumgartner J V, Wigington R, et al. 1997 How much water does a river need? *Freshwater Biology* **37**(1) : 231-49
- [16] Yang T, Zhang Q, Chen Y D, et al. 2008 A spatial assessment of hydrologic alteration caused by dam construction in the middle and lower Yellow River, China *Hydrological Processes* **22**(18) : 3829-43
- [17] Babel M S, Chien N D, Mullick M R A, et al. 2012 Operation of a hydropower system considering environmental flow requirements: a case study in La Nga river basin, Vietnam *Journal of Hydro-Environment Research* **6**(1) : 63-73
- [18] Lian Y Q, You J Y, Sparks R, et al. 2012 Impact of human activities to hydrologic alterations on the Illinois River [J] *Journal of Hydrologic Engineering* **17**(4) : 537-46
- [19] Shiau J T and Wu F C 2008 A histogram matching approach for assessment of flow regime alteration: application to environmental flow optimization *River Research and Applications* **24**(7) : 914-28
- [20] Richter B D, Baumgartner J V , Braun D P, et al. 1998 A spatial assessment of hydrologic alteration within a river network *Regulated Rivers-Research & Management* **14**(4) : 329-40
- [21] Zhang Q, Singh V P, Xu C Y, et al. 2013 Abrupt behaviours of streamflow and sediment load variations of the Yangtze River basin, China *Hydrological Processes* **27**(3) : 444-52
- [22] Yu M X, Li Q F, Lu G B, et al. 2013 Investigation into the impacts of the Gezhouba and the Three Gorges reservoirs on the flow regime of the Yangtze River *Journal of Hydrologic Engineering* **18**(9) : 1098-106
- [23] Wang Y K, Wang D and Wu J C 2015 Assessing the impact of Danjiangkou reservoir on ecohydrological conditions in Hanjiang river, China *Ecological Engineering* **81** : 41-52
- [24] Jiang L Z, Ban X, Wang X L, et al. 2014 Assessment of hydrologic alterations caused by the Three Gorges Dam in the middle and lower reaches of Yangtze River, China *Water* **6**(5) : 1419-34

### **Acknowledgements**

This research is supported financially by the National Natural Science Foundation Projects of China (No.41401011, No.51309107 and No.41401010), the Fundamental Research Funds for the Central Universities of China (No. 2013/B13020312), and the Major Program of National Social Science Foundation of China (No.11&ZD168).