Reasons for the homogenization of the seasonal discharges in the Yangtze River

Yuanfang Chai, Boyuan Zhu, Yao Yue, Yunping Yang, Sixuan Li, Jinqiu Ren, Haibin Xiong, Xin Cui, Xia Yan and Yitian Li

ABSTRACT

Allocations of water discharges between dry and flood seasons along the Yangtze River have significantly homogenized during the past decades, mainly due to precipitation change, regulation of key hydraulic works on the mainstream like the Three Gorges Reservoir (TGR), and the construction of numerous dams scattered in sub-basins. To reveal the specific roles of these three major factors in changing the seasonal discharges of the whole Yangtze River, this paper analyzes daily discharges during 1961–2014 at 16 hydrological stations from the far upper reach (the Jinshajiang Reach) to the estuary. We found that precipitation has only homogenized in areas 427 km downstream of the TGR, contributing 9.5–23.6% to the homogenized discharges. Even though the TGR is the largest hydraulic works in the world, it only contributes 17.5–27.2% to the downstream homogenization of seasonal discharge. By comparison, dams in sub-regions are a major contributor (61.1–100%) in the homogenized reach either upper or lower to the TGR. Of all the sub-basins, dams in Hanjiang River basin has the most significant effect (16.9%) on changing the allocations of seasonal discharges to the sea, followed by Wujiang (11.5%), Jialingjiang (10.1%), Yalongjiang (9.4%), Qingjiang (8.4%), and Daduhe-Minjiang (4.7%) river basins.

INTRODUCTION

Seasonal hydrological processes in rivers all around the world have significantly changed under the impacts of rapid climate change and intensified human activities during recent decades (Miao et al. 2011). As the Earth’s surface temperature increases, glaciers melt earlier than before (Sorg et al. 2012), and peak discharges shift from summer to spring or even winter, as being observed in the Rhine, Rhone, Danube (Huss 2011), Yellow (Li et al. 2008) and Naryn (Gan et al. 2015) rivers. By comparison, variations in precipitation affect seasonal discharges in a faster and more violent way, often leading to flood and drought disasters which can cause huge economic loss and heavy casualties. On the other hand, the impacts of human activities on seasonal water discharges are also widespread. By storing water discharges in flood seasons and releasing in dry seasons, dams effectively regulate the intra-year distribution of river flows. Moreover, water-soil conservation projects conducted worldwide progressively alter the surface of watersheds,
making the characteristics of seasonal water discharge more complicated.

With a drainage area of \(1,800,000\) km\(^2\) and a length of 6,300 km, the Yangtze River is the largest river in China and the world's third longest river. Recent studies have shown that the allocations of discharges between dry and flood seasons are significantly homogenized (i.e. gap in seasonal discharge narrows) across a vast area of the Yangtze River Basin extending from the estuary to the gauging station of Zhutuo in the upper reach (Guo et al. 2018). Precipitation change and dam operation, in particular, the operation of the Three Gorges Reservoir (TGR), are believed to be key factors behind such rapid changes. Dai et al. (2008) found that climate variability was the dominant factor for the homogenized discharges downstream of the TGR in 2013 when severe droughts occurred. During the period of 2003–2014, the operation of the TGR was generally believed to be responsible for the changes in the intra-year distribution of discharges.

As the most intensively regulated catchment in the world, the Yangtze River Basin contains more than 50,000 dams in addition to the TGR and these dams are scattered in all the major sub-regions, such as the Daduhe-Minjiang River Basin, the Jialingjiang River Basin, the Wujiang River Basin, the Qingjiang River Basin, the Hanjiang River Basin, and the two lake areas of Dongting and Poyang. Given that the total capacity of those numerous dams is very large (154 km\(^3\), Yang et al. 2015), they may also lead to significant homogenization effect on the seasonal discharges. However, most previous studies mainly focused on the effects of TGR and precipitation change (Dai et al. 2008; Han et al. 2014). The role of hydraulic works in each sub-basin in changing the allocations of seasonal water discharges, especially by comparison with precipitation change and the TGR, has not been quantitatively indicated. This paper extends the study area to the far upper reach of the Yangtze River, the Jinshajiang Reach, and tests the changing trend of discharge allocations between dry and flood seasons during 1961–2014 of the whole Yangtze River. Then, specific roles of all the major factors, such as changes in precipitation, operation of the TGR operation, and constructions of numerous other dams in eight major sub-regions of the Yangtze River Basin, in modifying the patterns of seasonal discharges are estimated, providing a step toward adaptive management of water resources in a changing environment.

**METHODS AND DATA**

**Division of sub-regions**

The Yangtze River is divided into the upper reach, the middle reach, and the lower reach by the hydrological gauging stations of Yichang and Hukou, with lengths of 4,504 km, 955 km and 938 km, respectively (Figure 1(a)). Located 44 km upstream of the Yichang station, the TGR is regarded as the largest reservoir in the world, which has effectively flattened the intra-year distribution of discharges downstream of the dam since it became operational in 2003. The present study involves ten hydrological stations on the mainstream, including Panzhihua, Pingshan, Zhutuo, and Cuntan stations on the upper reach, Yichang, Zhicheng, Shashi, Luoshan, and Hankou stations on the middle reach, and Datong station on the lower reach (Figure 1(a)). Control stations of major tributaries, such as Hukou, Huangzhuang, and Chenglingji, and outlet stations, such as Songzikou, Taipingkou, and Ouchikou, are also included (Figure 1(b)). Thus, the whole Yangtze River Basin is divided into eight sub-regions by these stations, i.e. the Yalongjiang River Basin, the Daduhe-Minjiang River Basin, the Jialingjiang River Basin and the Wujiang River Basin in the upper region, and Qingjiang River Basin, Dongting Lake Area, Hanjing River Basin, and Poyang Lake Area in the middle and lower regions (Figure 1(c)). Water discharges of these sub-regions can be either directly derived from the control stations of tributaries and outlets, or approximated by the difference between the two adjacent stations on the mainstream (Figure 1(c)). Collecting data from the meteorological stations in each sub-region (Figure 1(d)), the corresponding precipitation can also be calculated by Thiessen polygon method.

**Normalization of discharges in dry and flood seasons**

It is commonly recognized that the flood season of the Yangtze River Basin lasts from May to October, during which period the water discharge accounts for 67.9% of the annual total at the Datong station, and the period from November to next April is selected as the dry season (Gemmer et al. 2008). In order to reflect the relative importance of discharges in dry and flood seasons to the annual total of each year, a normalization method is proposed.
Figure 1 | Study area map showing (a) geographical positions of major hydrological gauging stations in the Yangtze River Basin and the TGD; (b) water system of the middle and lower reaches; (c) Jinshajiang Reach and the eight sub-regions corresponding to the drainage area between adjacent hydrological stations: 1 Jinshajiang Reach, 2 Yangtze River Basin, 3 Daduhe-Minjiang River Basin, 4 Jialingjiang River Basin, 5 Wujiang River Basin, 6 Qingjiang River Basin, 7-8 Dongting Lake and the diversion area, 9 Hanjiang River Basin, 10 Poyang Lake; (d) locations of meteorological stations in different sub-regions.
The discharges in dry and flood seasons are changed into dimensionless values between 0 and 1 by dividing through by the total (Equations (1) and (2)).

\[
Q_{N-D} = \frac{Q_D}{Q} \quad (1)
\]

\[
Q_{N-F} = \frac{Q_F}{Q} \quad (2)
\]

In Equations (1) and (2), \(Q_D\) and \(Q_F\) (\(m^3\)) denote the total discharges during dry and flood seasons, respectively; \(Q\) (\(m^3\)) is the total discharge in the year of interest; \(Q_{N-D}\) and \(Q_{N-F}\) (dimensionless) are the normalized discharges in dry and flood seasons, respectively. By normalizing the discharges in dry and flood seasons, it becomes possible to compare the characteristics of seasonal allocations during different periods.

**Trend in allocations of normalized discharges between dry and flood seasons**

The Mann-Kendall trend test with trend-free pre-whitening (TFPW-MK method) that eliminates the effects of positive or negative autocorrelation was applied in this study to analyze the variation trends in the normalized river flow (Su et al. 2018). The confidence level is 90% in this study.

**Separating the impact of precipitation change**

Under ‘natural’ conditions that human interference is relatively weak, precipitation change is supposed to be the dominant factor for changes in seasonal discharge in the Yangtze River Basin, explaining over 89% of the variations (Chen et al. 2016). Combined with historical records on national projects of large hydraulic works and water-soil conservation measures in the Yangtze River Basin, the TMPW-MK mutation point test (Miao et al. 2010) was used to determine the natural period when no abrupt changes in discharges occurred (Figure 2). The following years were further divided into the pre-TGR period which was before the impoundment of TGR in 2003, and the post-TGR period afterwards. By setting up linear regressions between precipitation and discharges during the natural period, seasonal water flow series without human interference can be reconstructed for the pre- and post-TGR periods, respectively (Li et al. 2019). Thus, the impact of precipitation change on the homogenized seasonal discharges (\(\Delta Q_p\), dimensionless, see Figure 2) in the pre- or post-TGR periods can be separated by comparing the reconstructed discharges with the observed discharges in the natural period.

**Separating the effects of TGR and dams in each sub-region**

By comparing the reconstructed discharges based on the linear regressions with the observed discharges in the pre- and post-TGR periods, respectively, the variation in normalized discharge induced by human interference can further be separated (\(\Delta Q_{nh}\), dimensionless, see Figure 2). In the
The average absolute value of the relative error between the simulated water level and discharge at the four hydrological stations are in good agreement with the measured data. The simulated water level and discharge at the four hydrological stations and that station controlling the lower boundary. Station controlling the upper boundary of the small catchments without gauges, which can be represented by the discharges at the gauges, there are also inflows from small catchments without gauges, which can be represented by the differences between the discharges at the hydrological stations controlling the upper boundary of the small catchments and that station controlling the lower boundary. The simulated water level and discharge at the four hydrological stations are in good agreement with the measured data. The average absolute value of the relative error between the simulated and measured discharges was only 0.8%, and the value of the water level was 3.1%, which demonstrates that the reconstructed discharges are reliable. The reconstructed discharge without TGR operation was also normalized. Thus, the differences between the reconstructed series without TGR operation and the observed series during the post-TGR period can be estimated (ΔQh,TGR, dimensionless, see Figure 2).

Upon deriving the individual effect of the TGR (ΔQh,TGR), the remaining human impacts can be regarded as being induced by dam constructions in basin areas. The impact of each sub-region (Qh-sub) can be similarly separated by comparing the two Qh in adjacent stations.

Data sources

Daily discharges from the major hydrological gauging stations of the Yangtze River Basin during 1961–2014 were collected from Changjiang Water Conservancy Commission, Ministry of Water Conservancy of China. In particular, daily inflow and outflow discharges of the TGR from 2003 to 2016 were offered by China Three Gorges Corporation (http://www.ctg.hk/sxjt/sqqk/index.html). Data on daily precipitation from 145 meteorological stations during the period from 1961 to 2014 were provided by Resource and Environment Data Cloud Platform (http://www.resdc.cn/UserReg.aspx). In addition, the topographic data between Yichang and Datong stations in 2011 were collected from the Hydrological Bureau of Changjiang Water Conservancy Commission.

RESULTS

Allocations of discharges between dry and flood seasons along Yangtze River

According to the results of TFPM-MK trend test method, the gap in percentages of discharges between dry and flood seasons has decreased during 1961–2014 with a confidence level over 95% (|Z| > 1.96) at all the concerned stations except Panzhuihua (Figure 3). Obviously, homogenization effect has occurred along the whole Yangtze River except the Jinshajiang Reach upstream of Panzhuihua Station. Dai et al. (2008) analysed the variation characteristics of
seasonal runoff in the mid-lower reaches of the Yangtze River in 2006 and found similar phenomenon, which provided evidence to the long-period trend revealed by this paper. In the Jinshajiang reach upstream of Panzhihua station, no larger-scale dams have been constructed before 2014 (Yuan & Xu 2014), which may be the reason why seasonal discharges have not been homogenized.

By conducting the TFPW-MK mutation point analysis, no abrupt changes have occurred before 1980 at all concerned stations. In addition, no large dams had been built on the mainstream of the Yangtze River before 1980, neither had the national key projects for water–soil conservation been carried out. Therefore, the period from 1961 to 1980 was selected as the natural period. The following period can be further divided into a sub-period from 1981 to 2002 during which the TGR has not been constructed (the pre-TGR period), and that from 2003 to 2014 (the post-TGR period).

Impact of precipitation change on homogenized seasonal discharges

To analyze the role of precipitation change, we select stations with homogenized seasonal discharges (Pingshan and the downstream stations), and set up linear correlations between precipitation and discharge during dry and flood seasons of the natural period to reconstruct baseline discharge series. Figure 4 shows that all the correlations are significant at the level of \( p < 0.01 \), except at Zhutuo \( (p < 0.05) \) and Luoshan \( (p < 0.2) \) in dry seasons. At Pingshan station, the precipitation and discharge had poor correlations \( (p < 0.7 \) in dry season), and the linear relationships
at this station cannot be used to reconstruct the seasonal runoff. However, agreeable correlations between seasonal discharges and precipitation ($p < 0.001$ in dry season, and $p < 0.20$ in flood season) was found in the Daduhe-Minjiang basin which is the major tributary between Pingshan and Zhutuo stations. Thus, we reconstruct baseline water discharges at Pingshan station using the difference between reconstructed discharge series of Zhutuo station and the Daduhe-Minjiang basin. Actually, the linear relationships could possibly lead to uncertainty under climate change, even though the correlations between precipitation and discharge were significant. The uncertainties introduced by the

**Figure 4** | Regression analysis between precipitation and the average discharge (represented by the runoff depth, i.e. dividing the average discharge by the drainage area) during dry and flood seasons at Pingshan, Zhutuo, Cuntan, Yichang, Zhicheng, Shashi, Luoshan, Hankou and Datong hydrological stations during the natural period (1961–1980). Confidence coefficient ($p$) and linear coefficient ($k$) are also given for each gauging station. Note: the first six figures represent the relationships during dry season, and the following six figures display the relationships during flood season.
linear approximation to the nonlinear processes will be covered in the discussion section.

The linear coefficients during flood seasons at each station are larger than those during dry seasons, showing that the effect of precipitation during flood seasons is more notable. Using the linear relationship derived from precipitation and runoff series during the natural period (Figure 4), the normalized discharges under the impact of climate variation during the pre- and post-TGR periods in dry and flood seasons have been reconstructed at the nine stations where seasonal discharges were homogenized (Figure 5). Compared with the observed series during the natural period (Figure 5), the effect of climatic factors on the variation patterns can be estimated. The results show that the intra-year in distribution became more uneven under the impact of precipitation at stations above Shashi.

Figure 5 | Comparison between the reconstructed series of the normalized discharges and the observed series at Pingshan, Zhutuo, Cuntan, Yichang, Zhicheng, Shashi, Luoshan, Hankou and Datong hydrological stations during the period from 1961 to 2014. The first nine panels show the normalized discharge in dry season, and the last nine panels depict the normalized values in flood season.
(185 km below TGR) in the pre- and post-TGR periods, with the percentage of the dry-period discharge slightly decreased, and that of the flood-period increased (Table 1). However, in the reach downstream of the Shashi station, the changes in precipitation have contributed to the homogenization effect, with the contribution rate varying from 20.5% to 23.6% in the pre-TGR period, and 9.5% to 21.4% in the post-TGR period. Dai et al. (2008), who provided the first step towards determining the reasons for the homogenized discharges between dry and flood seasons in 2006, reached the conclusion that climate variation was the dominating factor in homogenization effect. By making an idealized assumption that apart from the impact of the TGR, all the remaining effects could be attributed to climatic factors by Dai et al. (2008). However, flow regulation by numerous dams in sub-basins could also lead to homogenization of seasonal discharges. This will be analyzed in the next section.

Impact of TGR and dams scattered in each sub-region

In the pre-TGR period, the total impact of human activities, which can be separated out by comparing the reconstructed discharge series (Figure 5) based on the linear relationships (Figure 4) and the observed series, was mainly induced by dam constructions in the basin areas. The results show that the total effect of dams scattered in each sub-region increased the percentage of discharges in dry seasons, but decreased that in flood seasons. This resulted in more homogenized allocations of the whole river basin (Table 1). In the reach upstream of the Shashi station, the homogenization effect of dams in sub-regions overwhelmed the impact of climate variation which brought about more uneven allocations between dry and flood seasons (i.e. explaining 100% of the homogenization effect of seasonal discharges). In the reach downstream of the Shashi station, dams in sub-regions generally explained 76.4–79.5% of the homogenized discharges. Moreover, such impact basically shows an increasing trend with time. All the concerned sub-regions except Qingjiang and Daduhe-Minjiang basins contributed to the downstream homogenization of seasonal discharges. Further analyzing discharges at Datong station which is nearest to the estuary, Poyang Lake Area made the largest contribution (34.8%), followed by Dongting Lake (26.8%), Yalongjiang basin (8.1%), Hanjiang basin (5.6%), Wujiang basin (2.2%) and Jialingjiang basin (2.1%) (Table 1). Part of the homogenization effect was due to changes of water flow diversions through the three outlets of Songzikou, Taipingkou and Ouchikou during the pre-TGR period. The normalized discharge at the three outlets in dry season reduced by 26.5% compared with the natural period, and that in flood season increased by 2.3%. The inflow water at Chengeiligji station increased by 5.5% in dry seasons and decreased by 12.8% in flood seasons during the pre-TGR period, which contributed to the homogenization effect with the contribution up to 12.6–24.6%.

In the post-TGR period, the impact of the TGR was separated by rebuilding water flows at each downstream station without impoundment of the TGR, contributing 17.5–27.2% to the homogenization effect from Yichang to Datong stations (Table 1). Although the TGR is the largest hydraulic structure in the world (Han et al. 2017), it has less importance than the total effect of numerous dams scattered in sub-basins, which have not been sufficiently emphasized in previous studies (Dai et al. 2008). The huge total water storage ($1.540 \times 10^9$ m$^3$, Yang et al. 2015) of all the dams in the sub-regions, which is ~4 times as much as that of the TGR, explains why the effect of the sub-region dams overwhelms the TGR. Nevertheless, the contribution of TGR was higher than the individual effect of every single sub-region.

By subtracting the effect of the TGR, the total impact of dams in sub-regions on the homogenized seasonal water flow is calculated to be 72.8% at Yichang station, and decreasing to 61% at Datong station. By further analyzing the characteristics of discharges of the station nearest to the estuary, we find that the largest contribution is by dams in the Hanjiang Basin (16.9%), followed by the Wujiang Basin (11.5%), the Jialingjiang Basin (10.1%), the Yalongjiang Basin (9.4%), the Qingjiang Basin (8.4%), and the Daduhe-Minjiang Basin (4.7%). It should be noted that the contribution by the Qingjiang Basin sharply increased from zero in the pre-TGR period to 8.4–13.6% at its downstream stations in the post-TGR period, mainly due to the construction of larger-scale dams in this sub-region at the end of the pre-TGR period or during the post-TGR period (Xu & Yan 2004), namely the Geheyuan Dam (in 1995), the Gaobazhou Dam (in 2000), the Shuibuya Dam (in 2008).
Table 1  Estimated contributions of precipitation change, TGR operation, and water flow regulation effect on discharge allocations between dry and flood seasons in each of the eight sub-regions

<table>
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<tr>
<th>Stations</th>
<th>Precipitation change</th>
<th>TGR operation</th>
<th>Total sub-regions</th>
<th>Poyang Lake Area</th>
<th>Dongting Lake Area</th>
<th>Hanjiang Basin</th>
<th>Qingjiang Basin</th>
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and the Dalongtan Dam (in 2008). A similar situation occurred in the Daduhe-Minjiang Basin where larger-scale dams, such as Zipingpu (in 2005) and Pubugou Dams (in 2009), were built during the post-TGR period. In contrast, the storage capacity of the Dongting Lake significantly decreased from 191 × 10^8 m^3 in the pre-TGR period to 172 × 10^8 m^3 in the post-TGR period, which is 6.1% of the annual discharge of Chenglingji station, making the allocations of seasonal outflows from the Chenglingji station become more uneven rather than homogenized (Xu et al. 2015). In the Poyang Lake Area, the storage capacity decreased by 11 × 10^8 m^3 compared between the post-TGR and the pre-TGR periods, which also caused the outflow of the lake to be more uneven instead of homogenized (Zhang et al. 2013).

**DISCUSSION**

**Uncertainty analysis**

Although the linear correlations between precipitation and discharge have high confidence levels (Figure 4), the uncertainty still needs to be evaluated. By comparing between the discharges predicted by the linear relationship with the measured ones, the mean relative error of each station is found to vary from 0.6 to 1.2% (with standard deviation varying from ± 8.0 to 11.1%), which is acceptable. Furthermore, uncertainty introduced by the inherent relation of the discharge series is also analyzed by a cross test using regression equations of uneven and even years, i.e., the regression equations of uneven years to predict the discharge of even years, and vice versa. The maximum relative error is only −3.3% for the predictions of even years and 5.6% for those of uneven years, with standard deviations of ±10.5% and ±11.3%, respectively. Clearly, the impact of an inherent relation is relatively low, which implies that the reconstructed discharge series using linear regression equations are reasonable.

Measurement error of underwater terrain and precipitation may also affect the findings. To operate the MIKE 11 HD model, underwater terrain data was obtained from 1391 cross sections in the reach between Yichang and Datong hydrological stations (i.e. 1.18 sections/km). According to Yuan et al. (2014), a measurement error of 2–7% exists using cross-sections with an interval of ~800 m to replace the ‘real terrain’. Such small error brings little uncertainty in the calculation of discharges using MIKE 11HD model which is based on water balance equation. In addition, precipitation data from the 145 meteorological stations in the Yangtze River Basin is compared with the dataset from the Climate Research Unit (CRU). The difference between the two datasets is merely 3.6%, implying the linear regressions between precipitation and discharges in this study are reliable.

As a large-scale hydraulic dam on the Yangtze River, the Gezhouba Dam is another source of uncertainty. However, the storage capacity of the Gezhouba Dam (15.8 × 10^8 m^3) is relatively small compared with the annual discharge from the Yichang Station (4,264 × 10^8 m^3 in 2016). In addition, the Gezhouba Dam adopts a daily-regulation scheme (Yang et al. 2006), which also implies that the possible effect on the seasonal discharge of the Yangtze River could be very small.

**Dominated role of human activities on homogenized seasonal discharges**

The dominated role of human activities has been further confirmed by the number of larger reservoirs (storage capacity >10^8 m^3) in the entire river basin, which increased from 28 in 1961 to 140 in 2002, and then 220 in 2012 (Figure 6(a)), demonstrating a similar trend to changes in normalized discharges in dry seasons at the estuarine gauging station at Datong. In 2003, the TGR became operational, which further homogenized the allocation of water discharges between dry and flood seasons. According to the flow regulation rules of the TGR (Figure 6(b)), the peak discharge of the upstream is decreased by the dam in flood seasons to alleviate the pressure of flooding in the downstream reach, whereas water in the reservoir is released in dry seasons to meet the needs of irrigation, ecological restoration, and shipping. Therefore, the minimum discharge increased significantly since 2003, while the maximum discharge showed an obvious falling trend (Figure 6(c)).

Although anthropogenic factors are found to be more impactful than climate factors, climatic effects are likely to intensify, leading to the El-Niño/Southern Oscillation (ENSO)-related and North Atlantic Oscillation (NAO)-related variability of large-river runoff at inter-annual, decadal, or
multi-decadal time-scales (Labat 2008; Su et al. 2018). Ye & Wu (2018) pointed out that different regions of the Yangtze River Basin can be affected by the ENSO events in different periods of the year, implying the possibility of long-term effects of climate anomalies on the seasonal discharge of the Yangtze River.

TGR and droughts

Severe droughts in the Yangtze River Basin had become more and more frequent after the operation of the TGR. In addition, Poyang Lake and Dongting Lake (the largest and the second largest freshwater lakes in China) had also been shrinking at faster rates (Liu et al. 2016). It has been suggested that the frequent droughts since 2003, especially the extreme drought events in 2006 and 2011, might be attributed to the operation of the TGR (Li et al. 2015). However, according to our estimate of TGR’s contribution, the TGR has significantly increased the discharges in dry seasons, which helps to combat drought. Particularly, the TGR alleviated drought by increasing the normalized discharge in dry season by 1.04% in 2006, by 4.15% in 2011. Clearly, the TGR plays a positive role in dry periods.

CONCLUSIONS

A homogenization effect of seasonal discharges was found in the whole Yangtze River except the Jinshajiang Reach upstream of Panzhihua. By reconstructing the normalized discharges in dry and flood seasons in two circumstances (without any human interference, and only without the regulation of TGR) at each station considered in the pre- and post-TGR periods (1981–2002 and 2003–2014), precipitation change contributes 9.5–23.6% to the homogenized discharges in areas 427 km downstream of the TGR. As the largest hydraulic structure in the world, the TGR, only contributes 17.5–27.2% to the downstream homogenization of seasonal discharge, whereas the dams in sub-regions play the major role (61.1–100%) in the homogenized reach either upper or lower to the TGR. This paper has highlighted the impacts of numerous dams in sub-basins on homogenizing the allocations of discharges between dry and flood seasons. Our study also indicates that the TGR has played a positive role in alleviating droughts, rather than aggravating it.

COMPETING INTERESTS

The authors declare that they have no competing interests.

ACKNOWLEDGEMENTS

This work was supported by the National Key R&D Program of China [grant number: 2016YFA0600901], and the Youth Project of National Natural Science Foundation of China [Grant No. 41601275 and 51609015], National Natural Science Foundation of China [Grant No. 51809131]. The hydrological data for this study were provided by the Bureau of Hydrology, Changjiang Water...
Resources Commission, China and Yangtze River Waterway Bureau. We also highly appreciate the valuable insights from the reviewers. Boyuan Zhu, Sixuan Li, Can Xu, Yitian Li, Jinqiu Ren, Haibin Xiong, Xia Yan and Xuhai Yang contributed to the improvement of the manuscript.

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First received 25 August 2019; accepted in revised form 2 December 2019. Available online 22 January 2020.