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Enhanced potential ecological risk induced by a large scale water diversion project

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Abstract

River regulation by the construction of reservoirs represents one of the greatest challenges to the natural flow regime and ecological health of riverine systems globally. The Danjiangkou (DJK) Reservoir is the largest reservoir on the Hangjiang River and commenced operations in 1967. The reservoir was upgraded in 2012 to provide water resource for the South-North water transfer project through central China. However, the effect of the reservoir operations on the downstream hydrological regime and ecological health of the Hanjiang River following the upgrade (increase in dam height and reservoir capacity) has not been examined thus far. The daily discharge series from four stations along the main stem of the Hanjiang River, including a site upstream, were examined from 1950-2017. The study series was divided into three periods based on the difference stages of the reservoir operation: i) 1950-1966, ii) 1967-2012 and iii) 2013-2017. The nature of hydrological alteration, ecological flow requirement and potential ecological risk during the different periods were investigated. The results clearly indicate that the DJK reservoir has significantly modified the hydrological regime in the middle and downstream section of the Hanjiang River, with most significant modifications recorded immediately downstream of the reservoir. None of the observed 'Range of Variability Approach' hydrological indicators fell within the expected range at Huangjiagang following the increase in reservoir capacity. As a result, the ecological flow requirements could not be guaranteed, and the frequency and intensity of ecodeficit increased. The river ecosystem immediately downstream of the dam was observed to be at high risk of ecosystem degradation during the post-dam periods considered.

Keywords: Ecological risk; Hydrological alteration; Danjiangkou reservoir; South-North water transfer project; Ecodeficit

Declarations

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Authors' contributions M.Y., P.W. and X.L. were the main contributors to this work and was responsible for developing and implementing the methods, data generation, and analysis; N.G., Q.L., G.W. and J. Z. supervised the research

1 Introduction

Water resource management during the twentieth century has often involved large infrastructure projects such as the construction of dams and river diversions (WCD, 2000). Dams and diversions that were built to provide hydropower and irrigation, and to manage floods have significantly altered watersheds across the globe (Nilsson et al., 2005; Li et al., 2011; Grill et al., 2019). While dams, weirs and diversions facilitate water resource management, they have also modified hydrological regimes (Zhang et al., 2011; Zhao et al., 2012), interrupted longitudinal river and habitat connectivity (Suen et al., 2009; Wang et al., 2018; Grill et a., 2019), disconnected rivers from adjacent wetlands and floodplain habitats (Nilsson et al., 2005; Rheinheimer et al., 2016), and changed sediment erosion, transport and deposition processes (Li et al., 2011,2012; Yu et al., 2013). The sustainability of water resources has been threatened in many locations by the continual expansion of anthropogenic socio-economic activities, including agricultural production, urbanization and industrialization (Xu et al., 2002; Archer et al., 2010; Casadei et al., 2018). Many of these activities have competing demands for the same finite resources, raising the need to manage trade-offs. In water-stressed countries, there are competing demands for water for urban, industrial, agriculture and ecosystems upon which livelihoods depend. In addition, water disputes have arisen over inter-basin water transfers, which may also present serious environmental challenges for water quality and movement of biological resources between catchments (ESCAP, 2010). The United Nations have reported that 60% of the world’s 227 largest rivers are moderately to greatly fragmented by dams or channel diversions (UNEP, 2007), and the rate of dam/reservoir construction continues to increase worldwide (Ansar et al. 2014). These pressures have become particularly acute in China where rivers such as the Hanjiang River, the largest tributary of the Yangtze River, already support 15 cascade reservoirs/hydropower stations. These reservoirs have all been designed and constructed along the main stream since 1958. As a result, the natural river continuum has been disrupted and its flow, sediment and hydraulic regime have been modified. This has resulted in a series of ecological and environmental concerns (Li et al., 2009) including: the modification and loss of aquatic habitat, extirpation of anadromous fish, severe water shortages in downstream areas of the basin (Jiang et al., 2015) and the eutrophication of the reservoir and river downstream of the dam (Chen et al., 2016a). Following the upgrade of the Danjiangkou (DJK) Reservoir in 2012 (increasing the dam wall height), the largest reservoir on the Hangjiang River to provide the primary water resource for the South-North Water Transfer Project through central China (SNWTP) was completed and the world's attention on the Hanjiang River increased (Liang, 2018).

Currently, the effect of the DJK dam on river discharge at specific locations (Lu et al. 2009; Song et al. 2018; Wang et al. 2015), water resource availability and risk (Chen et al. 2012; Gu et al. 2012) and sediment regime has been considered (Lu et al. 2012). However, to the best of our knowledge, research on the spatio-temporal effects of the increase in height and reservoir capacity of the DJK dam on the hydrological regime and ecological risk on the middle and lower reaches of the Hanjiang River basin has been limited. Given that the DJK reservoir currently diverts water to the northern parts of China, a spatio-temporal assessment of its long-term effects (observed data series from 1950-2017) on the downstream hydrological regime and ecological risk for biodiversity is critical.

Therefore, the aims of the study were to i) quantify the hydrological alterations associated with DJK on the Hanjing River; ii) assess the ecological flow demand and ecological risk for the Hangjiang River. The subsequent sections of the paper are organized as follows: the study region and datasets are outlined in section 2; a detailed description of the methods used are presented in Section 3; the results and implication of these are discussed in relation to the wider literature in Section 4; and the manuscript finished with a summary and conclusion in Section 5.

2 Study region and data

The Hanjiang River, with a total length of 1,577 km and a catchment area of ~159,000 km^2, is the longest tributary of the Yangtze River rising south of Qinling mountain and accounts for 8.8% of the Yangtze River basin area. It confluences with the Yangtze River at Wuhan, a city with a population of more than 10 million. The city has played a critical role in the socio-economic development of the Hangjiang River basin. Located in the sub-tropical monsoon zone, the Hanjiang River basin has an average rainfall of 873 mm and an average annual runoff of 51.7 billion m^3, with 75% falling between May-October. As a result of anthropogenic activities, the flow regime has been modified, particularly following the construction of DJK Reservoir. The DJK Reservoir, came into operation in 1967 and its normal operational level was increased from 157m to 170 m in 2012 following an increase in the dam height. This increased the capacity of the reservoir from 17.45 billion m^3 to 29.05 billion m^3 and transformed the storage from seasonal to a multi-year capacity. As the primary water source of the central route of China's SNWTP, the DJK reservoir has transferred more than 15 billion m^3 annually to the North since 2014. The middle route is the largest water diversion project ever built in China. It transfers water from the DJK Reservoir on the Hanjiang River at Hubei and diverts it through Hubei, Henan, and Hebei before reaching Beijing and Tianjin. The planned volume of water transfer was 9.5 billion m^3 per-year, increasing up to 13 billion m^3 by 2030.

To assess the nature of hydrological alterations associated with the operation of the DJK Reservoir, four hydrological stations on the main channel of the Hanjiang River were examined: these comprise i) Baihe (BH), ii) Huangjiagang (HJG), iii) Huangzhuang (HZ) and iv) Xiantao (XT) (Figure 1). The BH station represents the inflow and acts as upstream reference station on the DJK system (although it is still subject to significant anthropogenic impacts and water resource management activities). The HJG station is located 6 km downstream of the DJK and provides the monitoring station for the outflow from the DJK. The HZ station is located approximately 241 km below DJK and characterizes the downstream Hanjiang River. The XT station is the furthest downstream hydrological station on the Hanjiang River located 530 km below the DJK reservoir.

The daily time series of river discharge (m^3/s) from 1950-2017 for BH, HJG, HZ and XT were obtained from the Changjiang Water Resources Commission (CWRC), China. The homogeneity and reliability of the flow discharge data were checked and quality controlled by the CWRC prior to its release (Table 1). The whole study period was divided into three subperiods according to the reservoir storage: i) Period I - 1950-1966 – prior to reservoir operation, ii) Period II - 1967-2012 – operational stage and iii) Period III - 2013-2017 – post increase in dam height and reservoir capacity respectively.

3 Methodology

To address the aims of the research, three approaches and indices outlined below were used to characterize the modification of the flow regime, the ecological flow requirements and the ecological risk: i) the Range of Variability Approach method (Richter et al., 1997) was used to directly investigate hydrological alteration; ii) the Flow Duration Curve approach proposed by Vogel et al. (2007) and Gao et al. (2012) was used to calculate the ecosurplus and ecodeficit (See definitions below); and iii) The Dundee Hydrological Regime Alteration Method (Black et al., 2005) was used to characterize the potential ecological risk for the Hanjiang River.

3.1 Range of variability approach

The Range of Variability Approach (RVA) methodology was developed to assess the hydrological modifications caused by anthropogenic activities including dam operations, water diversion, groundwater abstraction, or intensive land-use/cover changes. It compares different sets of flow discharge time series representing near-natural or reference conditions and impacted conditions at the same gauging stations. It uses 33 parameters and is organized into five facets of the flow regime. The hydrological alteration of the different hydrological parameters can be computed as follows:

$$D_i = \frac{N_{o,i} - N_{e,i}}{N_{e,i}} \times 100\% \qquad (1)$$

where $N_{o,i}$, $N_{e,i}$ denote the observed and expected frequency of post-impact values for the ith hydrological parameter in the RVA target range, respectively. A positive D_i indicates that reduced indicator values within the RVA target window are more common during the post-modification period, whilst a negative value indicates that the values are less common than expected.

The integrated degree of hydrological alteration of all parameters was proposed by Shiau and Wu (2007) as follows:

$$D_o = \left(\frac{1}{n}\sum_{i=1}^{n} D_i^2\right)^{1/2} \qquad (2)$$

where n is the total number of the indicators; low alteration if D_o belongs to low alteration if its value less than or equal to 33%, moderate alteration if D_o in the range of 34% to 67%, high alteration if D_o greater than 67%.

3.2 Ecosurplus and ecodeficit

The concept of ecodeficit and ecosurplus was introduced by Vogel et al. (2007) with the aim of evaluating the potential ecological effects of reservoir regulation on flow regimes based on examination of the Flow Duration Curve (FDC). FDCs are frequently used in a variety of instream flow assessment methods (Wang et al., 2017; Zhang et al., 2018). A FDC is a plot of the ordered daily streamflow Q_i (where i=1 is the largest flow) as a function of their exceedance probability

$$p_i = \frac{i}{n+1} \times 100\% \qquad (3)$$

where n is the number of days of flow and i is the rank. The daily stream flow series of the Hanjiang River were separated into three subseries according to the construction time of the DJK reservoir. Many scientists contend that a natural hydrological regime provides a sound basis for aquatic ecosystem health, deviations from which may be associated with failures to achieve the required ecological status. In this paper, streamflow during Period I (1950-1966) was regarded as near-natural or (reference condition) and the FDCs were prepared using daily streamflow over Period I with 25% and 75% percentiles used as threshold values. The area below the unregulated FDC for the 25% percentile and above the regulated FDC was used to define the ecodeficit; while the area above the unregulated FDC for the 75% percentile and below the regulated FDC was used to define ecosurplus.

3.3 Dundee hydrological regime alteration method

The Dundee Hydrological Regime Alteration Method (DHRAM) was developed based on the RVA approach due to its ability of characterizing ecologically relevant hydrological regime changes (Black et al., 2005). By applying the RVA approach, DHRAM establishes potential links to ecological impact through the concept of risk, assuming the risk of damage to ecosystem health rises in direct proportion to the cumulative disturbance to the hydrological regime. The percentage change of RVA groups was calculated by the average deviation of means or coefficients of variation (Cv) for each RVA group during the pre- and post-modification periods. Impact points were allocated based on the means and Cv values for each group, i.e. impact points falling within the range of 1-4 represents for low hydrologic change, 5-10 represents for intermediate hydrologic change, and 11-20 represents for high hydrologic change (Black et al., 2005). Based on the total impact points for the five IHA groups (means and Cv values), the DHRAM ecological risk classes were obtained (Table 2). The final output takes the form of a DHRAM class, i.e. Class 1 (Un-impacted condition), Class 2 (Low risk of impact), Class 3 (Moderate risk of impact), Class 4 (High risk of impact) and Class 5 (Sever risk of impact). The higher classification classes indicate that there is a greater risk of ecological objectives not being satisfied, and may provide the basis for future ecological assessments and the foundation for potential mitigation measures (Black et al., 2005).

4 Results and discussion

4.1 Hydrological alterations of the DJK

The nature of the recorded hydrologic alteration based on the RVA and between Period I and II, Period I and III are presented in Table 3. In addition, variations in hydrological extremes (high flow 1% and 10% and low flow 90% and 99%) are shown in Table 4.

(1) Magnitude of monthly flow conditions

From period I to period II, medians of monthly flow at Baihe gauge station were stable with slight changes, and the magnitude of change for most months was within 1%~14%, except June with an increase of 32%. No high hydrologic alteration occurred in all months, while moderate hydrologic alteration occurred in January, June, July and August with an average of 49%. For the monthly flow downstream of DJK, its variation differs at HJG, HZ and XT from that recorded at BH. Significant changes of median monthly flow at HJG were recorded for January (194%), February (174%), June (152%) and December (67%) ($p<0.01$). In contrast, the decrease in magnitude for all months was relatively small, with the greatest being 24% in October. In terms of hydrologic alteration, monthly flow in January, February, May, July, and December were found to be highly altered, with an average change of 80%; were moderately modified in April and June with an average reduction of 64%. Similar but weaker changes occurred at HZ, with the exception of high hydrologic alteration being recorded in October. Monthly flow at XT significantly increased during February (138%), January (109%), March (75%) and December (48%) ($p<0.01$). Meanwhile, January, February, April, May, June and August were found to be subject to high hydrologic alterations, with an average change of 86%; while July and December were subject to a moderate change of 54%. Generally, most significant magnitude changes and hydrologic alterations of monthly flow occurred at HJG due to the impact of the DJK, followed by XT, HZ after the initial construction phase and operation of the DJK reservoir.

Comparing period III to period II, the increased magnitude of monthly flow during period II reduced while the reduced amplitude was greater; most parameters were subject to high or moderate alterations. A significant increase of monthly flow was identified for June at BH, while the monthly flow from July to December displayed a decreasing trend; with the largest reduction being 62% for October. The monthly flow for January, February, August, September and December changed from moderate or low alteration to high alteration, respectively. The increase of monthly flow was significant for January (91%), February (70%) and July (62%) at HJG while only January (47%) and February (56%) were significant at HZ, and February (59%) at XT. Although the reduction of monthly flow in July (62%) was significant at HJG, the greatest reductions were recorded for October (65%). The degree of alteration increased most at HJG, with all months experiencing moderate or high alteration (degree >=40%), especially August-November, when the change reached -100%. This clearly demonstrates that no observed value fell within the expected RVA range after the DJK's second operational period. With the exception of September, all other months were subject to moderate or high alteration at HZ; the degree of alteration for January, February, May, July, October all reached -100%, all of them sustained high alteration from period II, and November changed from low to high alteration. All months were subject to moderate or high alteration at HZ except April and July; high alteration occurred in February, March, May, June, October-December. This included a change for March and October from 33% to 100% and a change from low to high alteration for November.

A significant increase of monthly flow occurred at HJG, HZ and XT over period II for January, February, June and December; while for period III, significant increases were only recorded in January and February at the three stations at lower levels of increase. This demonstrates that DJK exerted a significant impact on the downstream monthly flow during period II and period III (Figure 2). However, since the DJK was transformed from a seasonal into a multiple-year regulation reservoir following dam heightening, the impact on monthly flow variables was a little less in period III than in period II. The largest reduction was observed for October at HJG during both periods due to DJK storing water in the reservoir up to the end of October. More months experienced high hydrologic alteration during period III than in period II, and the degree of change was significantly higher at the three stations downstream of the DJK. Very high alteration occurred at HJG for August-December and demonstrates that HJG captured the operational impact of DJK immediately downstream. This reflects the storage of water in DJK from August to late October each year after dam heightening. During period II, water was only stored in DJK during October.

(2) Magnitude and duration of annual extreme flow conditions

During period II, all hydrologic descriptors at BH displayed a decreasing trend, except the annual 90-day minimum flow. However, no significant changes were recorded among the 11 indicators examined. Significant increases in the annual 1-, 3-, 7-, 30-, 90- day minimum flow and base flow index were recorded at HJG, HZ and XT during this period ($p<0.01$). The most significant increases occurred at HJG with an average increase of 122%, followed by XT with an average of 90%, and HZ with an average of 82%. These results illustrate that the flow regime was significantly altered at the daily, weekly, monthly and seasonal time scales during period II. In contrast, the remaining parameters: the annual 1-, 3-, 7-, 30-, 90- day maximum flow all displayed a decreasing but not significant trend. In addition, the reduction declined with distance with the average reduction at HJG (-48%) > HZ (-41%) > XT (-34%). The 1-, 3-, 7-day minimum, 7- and 30-day maximum flow at BH were highly altered with an average change of 73%, whereas the 1- and 3-day maximum were moderately altered with an average change of 50%. In comparison, high alterations were recorded for the 1-, 3-, 7-, 30-, 90-day minimum flow and based flow index at HJG; while 30-day minimum flow, 1-, 3- day maximum flow at

HZ, 1-, 3-, 7-, 30-day minimum flow at XT were highly altered. The average high alteration recorded was 81%, 75% and 83% at HJG, HZ and XT respectively. These results indicate that the flow regulation of the DJK reservoir increased low flows during the dry season by releasing more water than the average for period I. However, high flows were reduced in the late wet season due to storage of water in the reservoir to maintain high water levels. The DJK reservoir also decreased the annual extreme flows, with the greatest reduction at HJG.

Comparing period III with period II, the degree of change of both the extreme minimum and maximum flow downstream of DJK were subject to moderate or high alteration. The average increase in amplitude of extreme minimum flows was 52% between period I and III (120% for period I and II) at HJG, 57% between period I and III (78% for period I and II) at HZ, 63% between period I and III (87% for period I and II) at XT, while the average decrease in the magnitude of maximum flows was 74% between period I and III (48% for period I and II) at HJG, 75% between period I and III (41% for period I and II) at HZ, 67% between period I and III (34% for period I and II) at XT, respectively. The degree of alteration of all extremes ranged from -100~-53% at HJG, with 8 of 10 variable experiencing -100%. At HZ all extremes were reduced between -100~-51%, with 3 of 10 experiencing -100%. At XT all extremes were reduced between -100~-40%, 6 of 10 experiencing -100%. The increased magnitude and degree of alteration of the base flow index increased at HJG, HZ and XT, with the most marked changes at HJG. This indicates that after the second operational period of the DJK, most of the extreme values were outside the expected range of the RVA downstream of the DJK reservoir; with the most significant alterations at HJG. The change of annual minimum flow experienced a different pattern of variation at BH in comparison to the other three stations, with all extreme minimum flow indicators displaying a decreasing tendency, except the 90-day minimum flow. In contrast, at the BH station there were only slight increases in the decreased amplitude of extreme maximums as well as the base flow index and the degree of change of other parameters.

(3) Timing of annual extreme flow conditions

During period II, no significant change in the variation of amplitude was recorded in the timing of annual extreme flow conditions. The timing of the annual minimum was highly altered at HJG, moderately altered at HZ and BH, and experience low alteration at XT; all stations experienced low alteration of the timing of annual maximum. During period III, there was no significant change of variation in the amplitude of the timing of annual extreme flow conditions. In general, the hydrologic alteration to the timing of annual extreme flow events increased during period III.

(4) Frequency and duration of high and low pulses

From period I to period II, the low pulse count was significantly altered, while the change to the high/low pulse duration and high pulse count was limited. The degree of hydrologic alteration of all indicators decreased, with the most significant alterations being recorded at HJG. The low pulse count increased significantly (225%, $p<0.01$) at BH, while significant reductions occurred at HJG, HZ and XT, all reaching 100%. This indicates that there were no low flow pulses during period II downstream of the DJK reservoir. The largest reduction of low pulse duration was recorded at HJG (86%), followed by 58% at HZ and 34% at XT. The high pulse count remained the same at BH, while it decreased slightly at HJG, and experienced a slightly larger reduction at HZ and XT. The high pulse duration at HJG and BH both decreased by around 33% whereas there was no change at HZ and XT. When considering the overall hydrological alteration, low/high pulse count and low pulse duration were highly altered and high pulse duration was moderately altered, with an average change of 75%; whereas only low pulse duration was highly altered at HZ with an average alteration of 50%, and moderate alteration at XT with an average change of 43%. The low pulse count was highly altered at BH.

Comparing period III with period II, the reduction in the amplitude and hydrologic alteration intensified with the most significant reduction at HJG. The low pulse count generally increased, with the most significant change at BH (425%, $p<0.01$), followed by HJG (25%). In contrast, the low/high pulse duration and high pulse count was generally reduced at the four stations, except there was no changes in the low/high pulse duration at HJG or the high pulse duration at BH. The most significant reductions were recorded for the high pulse count at HJG ($p<0.01$). The degree of change to the low/high pulse count and low pulse duration at HJG was high and reduced by -100%; the high pulse count and low pulse duration at HZ were highly altered, with the latter reaching -100%; the low/high pulse duration at XT were both reduced by -100%.

(5) Rate and frequency of water condition changes

From period I to period II, the rise rate decreased with significant reductions at HZ and XT, whereas the number of flow reversals increased significantly at all four stations; with the largest increase at HJG. The change of fall rate was relatively small except at BH. The rise rate (-72%) and number of reversal (-100%) were highly altered, and fall rate (-51%) moderately altered at HJG, with an average change of -74%; the rise rate experienced moderate alteration (-62%) and the number of reversal high alteration (-96%) at HZ, with an average change of -55%; the rise rate and number of reversals experienced high alteration (-78%, -72%) at XT, and fall rate a moderate alteration (-37%), with an average change of -62%. The number of reversals was highly altered and rise/fall rate were moderately altered at BH.

Comparison period II with period III indicated that the number of reversals at the four stations kept increasing (all significant at 0.01 confidence level), with the largest increase at HJG; the hydrologic alteration of the number of reversals continued to decline and all reached -100%. The other descriptors remained relatively stable except the alteration of rise rate at XT.

(6) Total hydrologic alteration

Examination of the 33 hydrological descriptors indicated that the operation of DJK reservoir and transfer significantly altered the monthly flow regime characteristics, the magnitude, duration, timing of annual extreme flow, the frequency and duration of high and low pulses, and the rate and frequency of water condition changes for the middle and downstream stations on the Hanjiang River. Between time Period I (control) and II, the greatest hydrologic alteration occurred at HJG (average change of 65.6%), followed by XT (61.1%), HZ (56.2%) and BH (47.9%). The flow regime in the Hanjiang River basin was highly modified due to flow regulation. The degree of flow modification at the middle and downstream sites of the Hanjiang River were much greater than that of the upper site (BH). The degree of flow modification along the Hanjiang River significantly increased during Period III (2013-2017) up to 80.9% at HJG, 77.2% at XT, 72.1% at HZ and BH (73%), respectively (Table 4). The effect of hydrological modification associated with the DJK increased significantly after the increase in reservoir capacity and dam height in 2012.

Similar results were obtained in relation to hydrological extremes – extreme high and low discharge conditions (Table 4). Floods with an exceedance probability of 1% declined dramatically at HJG -37% and -64% during time Period II and III respectively compared to time Period I; reductions at HZ and XT ranked second and third, respectively. For high flows with an exceedance probability of 10%, the most significant reduction was recorded during Period II, especially at HJG followed by XT and HZ but were most significant for Period III at XT. In contrast, the daily flow with an exceedance probability of 90% and 99% increased most at HJG 63% and 78% for Period III respectively, followed by HZ and XT. Extreme high daily flows downstream the DJK decreased, while low extreme low flows also increased significantly after the DJK came into operation and particularly after the reservoir's height and capacity was increased. The consistent reduction in extreme high flows may lead to degradation of floodplains and wetlands along the river, due to loss of lateral connectivity and loss of nutrient deposition during floods. However, the increase in extreme low flows will help mitigate drought during dry conditions and may be beneficial for ecological flow requirements downstream of DJK.

It should be noted that the change in discharge at XT was higher than that at HZ due to the

HZ-XT region being subject by intense anthropogenic catchment modification activities, particularly in the form of water diversion and agricultural irrigation. Almost 50% of the discharge was diverted into the Dongjing River and Tianguan River to reduce flooding and flood risk, associated with the narrow river channel downstream of HZ, during the wet season. The Jianghan Plain, downstream of HZ is also nationally famous as one of ten most important national commodity grain bases and one of the top five commercial cotton bases and as a result consumes large volumes of water for irrigation.

The rapid increased in the alteration of the river flow regime at BH, upstream of the DJK, can be attributed to the increased intensity of hydropower development in the upper reaches of the Hanjiang River. According to available statistics, four large reservoirs, the Shiquan reservoir (1974), Ankang reservoir (1992), Xihe reservoir (2006) and Shuhe reservoir (2009) were constructed and came into operation during Period II, and three large reservoirs (one in operation-Xunyang reservoir (2016) and two in construction) during Period III on the main channel upstream of the BH station. This clearly emphasises the difficulty of identifying reference stations for exploring the wider effects of the DJK reservoir on the ecohydrological regime in the middle and lower sections of the Hanjiang River basin.

4.2 Alterations in ecosurplus and ecodeficit

The significant modification of the natural flow regime could have affected instream habitats of species, due to the aquatic system being adapted to the natural or pre-modification conditions (Zalewski, 2012; Wang et al., 2015). Each species may have an ‘optimal environmental window’ for reproductive success and recruitment (Cury and Roy, 1989; Roy et al., 1992; Baumgartner et al., 2008). To better understand the ecological effects of the hydrological alterations, the ecosurplus and ecodefict, was explored.

The temporal variations of annual ecosurplus and ecodeficit along the Hanjiang River basin 1967~2017 are presented in Figure 3. The most marked variability of annual ecosurplus was recorded at upstream of the DJK reservoir at BH, with the maximum reaching 1.0. At the other three stations downstream, the changes were less marked and the annual ecosurplus was always less than 0.7. This reflects the fact that the upper Hanjiang River is a mountainous region which is dominated by rainstorm runoff and most hydroelectric projects are run of river hydropower stations; flow discharge at HJG, HZ and XT is not only affected by the operation of the DJK reservoir, but are also influenced by rainfall and runoff processes from upper catchment.

There were 5-year when an ecodeficit was recorded upstream of the DJK reservoir at the BH station. These were all relatively low values - comprising four years in late 1990s and early

2000s and 2016. The former four years can largely be attributed to the less than normal precipitation in the upper Hanjiang River basin; while the ecodeficit in 2016 reflects both increased water consumption as well as reduced rainfall (Deng et al. 2018). During Period II, 12-yeasr out of the 33-year for which data were available experienced ecodeficit at HJG (except 1987~1999 for which data were not available), 6-years and 4-years experienced ecodeficit at the HZ and XT stations respectively. The ecodeficit increased markedly during period III, with 4 out of 5-years recording an ecodeficit at HJG. The annual ecodeficit for 2014 and 2016 were all less than -12%, with the historical minimum reaching -17% in 2016. HZ also experienced 4-years of ecodeficit but with much lower values (-17%); and XT experienced 2-years of ecodeficit.

Temporal variations of annual ecosurplus and ecodeficit indicated that the ecological flow requirements of the river downstream of the DJK reservoir were significantly affected following its construction and operation. Given that the HJG gauging station is located immediately downstream of the reservoir, it had the highest frequency and accumulated amount of ecodeficit among all of the sampling stations investigated. The ecodeficit at the middle and downstream sampling stations on the Hanjiang River significantly increased after the height of the dam and reservoir capacity was increase in 2012. The reservoir inflow decreased as the upper Hanjiang River experienced persistent drier conditions. In addition, a greater volume of water has been stored in the reservoir since the DJK reservoir was transformed from a seasonal to an interannual regulation reservoir. Much of the water has been diverted to support increase flow for the central route of the NSTP. Therefore, the reservoir outflow significantly declined and was even lower than the planned minimum ecological flow for the middle and downstream reaches of the Hanjiang River. 2015 was an extremely dry year in the upper Hanjiang River and to secure the water supply of the central route of the NSTP, the DJK reservoir outflow was reduced to 450 m^3/s in October. This was also lower than the planned ecological flow (490 m^3/s) for the middle and downstream sections of the Hanjiang River (Peng et al. 2016). The ecodeficit recorded at HZ and XT were both notably higher than BH between 1987~1999, clearly illustrating the increased frequency and magnitude of ecodeficit in the downstream regions of the basin. This can also be attribute to the 218 sluice gates and 1461 pumping stations in the middle and downstream reaches of the Hanjiang River, which could all contribute to the elevated ecodeficit at HZ and XT, respectively.

4.3 Ecological risk in the Hangjiang River basin

The increased frequency of occurrence of ecodeficit indicated that the ecological flow requirements downstream of the DJK could not be satisfied. This may threaten the native aquatic flora and fauna of the middle and lower sections of the Hanjiang River. In addition, the low discharge and flow velocity may exacerbate sedimentation and water pollution effects in the middle and lower reaches of the Hanjiang River basin. The negative effects on the local river biodiversity may result in a greater risk of ecological deterioration and degradation.

The ecological health of the river at HJG was found to be at high ecological risk (Class=4), whereas that at HZ and XT were at moderate ecological risk (Class=3) during Period II. During Period III, the HJG remained in Class 4, HZ experience increased risk and moved to Class 4 (high ecological risk), while XT remained at Class 3 (Table 5). However, the total impact points at both HZ and XT increased. An impact class 3 value during both Period II and III at BH indicates moderate risk to ecological health due to anthropogenic impacts on the upper river above the reservoir. Analysis of the ecological risk categories indicated that between Period I and II the DJK reservoir posed a significant risk to ecological health, with the highest ecological risk recorded directly downstream of the reservoir at HJG; during Period III, following the increase in height of the dam, the DJK exerted a much greater effect on the middle and downstream reaches of the Hangjiang River basin with HJG and HZ both at high risk of ecological damage.

The analysis indicates that aquatic biodiversity within the upper, middle and downstream sections of the Hanjiang River have probably experienced increased hydrological pressure from 1950 to 2017; with much more significant responses within the middle and lower reaches since the construction of the DJK reservoir. Following the increase in the capacity and height of the DJK dam (Period III), larger fluctuations in hydrological characteristics were recorded, such as the rate of rising/falling and flow velocity patterns around the DJK reservoir. Flow patterns are crucial for the spawning of many fishes particularly for those which rely on eggs drifting within the water column. Four carp species, comprising black carp (*Mylopharyngodon piceus*), grass carp (*Ctenopharyngodon idellus*), silver carp (*Hypophthalmichthys molitrix*) and big-head carp (*Aristichyths nobilis*), occur in the Hanjiang River and have very specific requirements in relation to spawning. In the upper section of the DJK, the backwater effect of the reservoir has been extended and as a result the drift distance of eggs has been reduced so that most will sink before they can hatch. The spawning grounds at Qianfang and Yunxian may disappear or be dramatically altered due to the raised water level and reduced flow velocity. Downstream of the DJK reservoir, many spawning grounds disappeared between the 1970s to 2000s. The young of the four carp species decreased significantly to 0.27×10^{8} in 2006 from 4.7×10^{8} in 1978 (Bao, 2013). The spawning activities of the many fish species are also sensitive to water temperature. Chen et al. (2016b) found that the increase in the height of the DJK dam wall modified water temperature seasonally, leading to fish spawning periods lagging and optimal spawning locations moving further downstream. Since the central route of the SNTP began operation in 2014, ~10 billion m^3 of water from the DJK had been transferred to the North of China up until May 2017 (MWR, 2018). It is anticipated that the quantity of water diverted will increase to the designed volume in coming years. In addition to the DJK, many hydropower stations and large water diversion projects, such as the Longyangxia diversion project are under construction on the upper Hanjiang River (Li et al., 2016). Runoff in the upper region of the basin also displays an obvious downward trend (Xia et al., 2017). It is likely that there will be a further severe reduction of fishery resources as more fish are confined the main channel but experience higher flows during water transfer. Although some optimization models for supporting the reservoir operations of the SNWTP have been proposed (Wang et al., 2014; Lian et al., 2016; Li et al., 2017), most were focused on the DJK reservoir. Therefore, to ensure the future river health and sustainable development of water resources in the Hanjiang River, there is a pressing need to develop an optimized integrated reservoir operation framework and strategy for the whole cascade reservoirs system that considers the ecological water demands for the whole Hanjiang River basin in the future.

5 Summary and conclusions

This paper investigated the hydrological alterations in the Hanjiang River basin, before and after the increase in capacity dam height of the DJK reservoir, and the related flow alteration and ecological risk during three time periods were explored.

The implementation and operation of the DJK reservoir has significantly modified the hydrological regime of the middle and downstream sections of the Hanjiang River, with most significant alterations at HJG, particularly after the increase in capacity and dam wall heightening. Extreme flows were significantly modified with high daily flows reduced significantly downstream of DJK and extreme low flows were much higher after DJK operation commenced. The degree of alteration experienced by most hydrological alteration indicators at HJG were very high (even reaching -100%), and no observed RVA values fell within the expected range after the increase of reservoir capacity. These descriptors include monthly flow in February, August-November, 1-, 3-, 7, 30-, 90-day minimum, 1-, 3-, 30-day maximum, base flow index, low pulse count/duration, high pulse count and number of flow reversals.

The most significant effects on the downstream flow regime associated with the DJK occurred at HJG, particularly in recent years following the increase in reservoir capacity. The frequency and intensity of ecodeficit has been greatly enhanced as a result of the operation of the DJK reservoir. During the initial operation of the DJK, the river ecosystem at HJG was at high risk of impact based on the DHRAM classification with other sites at moderate risk.

Following the increase in capacity and height of the dam wall both HJG and HZ were identified as being at high risk of impact with all other sites at moderate risk of degradation.

Recommendation for future operations: The Danjiangkou reservoir was built for water supply, navigation, flood control, irrigation, hydropower generation. To balance the multiple objectives of the DJK operation, a comprehensive research program to identify the optimized water resources management strategy is required. Since the DJK is the primary water source of the middle route of China's South-to-North Water Diversion Project, water supply for the water diversion remains the first priority. However, the basic ecological flow requirement should also be satisfied in the middle and downstream sections of the Hanjiang River, especially during the dry years and this should be secured before the water is transferred to the north. In addition, the flood control, irrigation and navigation in its downstream section should also be guaranteed as much as possible.

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Tables

Table 1. Details of the hydrological data series used in the research.

Stations	Streamflow data range
BH	1950-2017
HJG	1960-1985, 2000-2017
HZ	1950-1972, 1974-2017
XT	1955-1967, 1971-2017

Table 2. Definition of DHRAM classes

Class	Point range	Class description
1	0	Un-impacted condition
2	1-4	Low risk of impact
3	5-10	Moderate risk of impact
4	11-20	High risk of impact
5	21-30	Severe risk of impact

Table 3. Results of the RVA analysis during three time periods at four stations

IHAs	Baihe				Huangjiagang				Huangzhuang				Xiantao			
	DM		HA		DM		HA		DM		HA		DM		HA	
	II	III	II	III	II	III	II	III	II	III	II	III	II	III	II	III
January	0.04	-0.05	-0.52	0.94	**1.94**	**0.91**	-0.89	-0.65	**0.99**	**0.47**	-0.68	-1.00	**1.09**	0.37	-0.72	-0.40
February	-0.07	-0.20	-0.31	-1.00	**1.74**	**0.70**	-0.86	-1.00	**1.34**	**0.56**	-0.68	-1.00	**1.38**	**0.59**	-0.79	-1.00
March	0.13	0.01	0.11	-0.03	0.76	0.05	-0.29	0.40	**0.77**	0.30	-0.30	0.46	**0.76**	0.39	-0.09	0.80
April	-0.06	0.12	-0.26	0.46	-0.04	-0.42	0.63	0.40	0.02	-0.17	0.08	0.46	-0.06	-0.20	0.74	0.20
May	0.06	-0.13	-0.05	0.46	0.24	-0.34	0.84	-0.53	-0.15	-0.42	0.67	-1.00	-0.22	-0.45	0.81	-1.00
June	0.32	**1.44**	-0.31	-0.51	**1.52**	0.38	-0.65	0.40	**0.81**	0.33	-0.14	0.46	0.30	0.17	1.02	0.80
July	0.03	-0.41	0.21	-0.03	-0.12	**-0.62**	0.70	-0.07	-0.32	-0.55	-0.68	-1.00	-0.31	-0.45	0.53	0.20
August	0.01	-0.57	-0.52	-1.00	0.13	-0.48	-0.22	-1.00	-0.15	-0.50	0.73	-0.51	-0.22	-0.51	1.23	-0.40
September	0.07	-0.46	-0.47	-1.00	-0.00	-0.60	0.27	-1.00	0.08	-0.42	0.24	-0.03	-0.08	-0.54	0.67	-0.40
October	-0.14	-0.62	-0.42	-0.51	-0.24	-0.65	0.20	-1.00	-0.22	-0.48	-0.78	-1.00	-0.15	-0.50	0.33	-1.00
November	-0.14	-0.26	-0.05	-0.51	0.01	-0.32	-0.08	-1.00	-0.04	-0.13	0.03	0.94	-0.07	-0.18	0.26	0.80
December	-0.05	-0.13	-0.10	0.94	**0.67**	-0.01	-0.72	0.40	**0.52**	0.19	-0.51	0.46	**0.48**	-0.04	-0.55	0.92
1-day minimum	-0.39	**-0.64**	-0.72	-1.00	**0.94**	**0.51**	-0.79	-1.00	**0.72**	**0.57**	-0.62	-0.58	**0.91**	**0.65**	-0.79	-1.00
3-day minimum	-0.31	**-0.49**	-0.77	-1.00	**1.22**	**0.59**	-0.79	-1.00	**0.78**	**0.61**	-0.57	-0.51	**0.91**	**0.67**	-0.79	-1.00
7-day minimum	-0.21	**-0.42**	-0.68	-1.00	**1.37**	**0.62**	-0.79	-1.00	**0.92**	**0.69**	-0.62	-0.51	**0.95**	**0.67**	-0.86	-1.00
30-day minimum	-0.04	-0.11	-0.26	-0.03	**1.49**	**0.56**	-0.86	-1.00	**0.96**	**0.72**	-0.68	-1.00	**0.95**	**0.71**	-0.86	-1.00
90-day minimum	0.01	0.14	-0.05	-0.03	**0.96**	**0.30**	-0.72	-1.00	**0.52**	0.26	-0.51	-0.51	**0.61**	0.44	-0.30	-0.40
1-day maximum	-0.32	-0.45	-0.52	-0.51	-0.57	-0.88	-0.51	-1.00	-0.46	**-0.85**	-0.78	-1.00	-0.27	**-0.72**	-0.23	-0.40

3-day maximum	-0.28	-0.49	-0.47	-0.51	-0.52	-0.87	-0.43	-1.00	-0.48	**-0.86**	-0.78	-0.51	-0.31	**-0.72**	-0.02	-0.40
7-day maximum	-0.29	-0.52	-0.79	-0.51	-0.52	-0.81	-0.22	-0.53	-0.44	**-0.83**	-0.62	-0.51	-0.40	-0.71	0.05	-1.00
30-day maximum	-0.32	-0.47	-0.68	-0.51	-0.44	-0.65	-0.51	-1.00	-0.41	**-0.71**	-0.46	-1.00	-0.39	-0.62	-0.30	-1.00
90-day maximum	-0.14	-0.19	-0.05	-0.51	-0.34	-0.50	-0.36	-0.53	-0.25	-0.49	-0.08	-0.51	-0.31	-0.59	0.53	-0.40
Base flow index	-0.12	-0.25	-0.16	-0.03	**1.35**	**1.62**	-0.93	-1.00	**1.03**	**1.46**	-0.57	-1.00	**1.04**	**1.16**	-0.65	-1.00
Date of minimum	-0.23	3.44	-0.58	-0.51	-0.10	0.39	-0.72	-0.53	-0.31	4.08	-0.43	-0.58	0.26	0.09	0.19	-0.40
Date of maximum	-0.08	-0.11	-0.31	-0.51	-0.05	-0.03	0.06	0.40	0.01	-0.07	-0.19	-0.51	0.04	-0.04	-0.22	-0.52
Low pulse count	**2.25**	**4.25**	-0.77	-1.00	**-1.00**	0.25	-0.79	-1.00	**-1.00**	-0.67	-0.41	-0.62	**-1.00**	0.00	-0.49	-0.60
Low pulse duration	-0.48	-0.74	-0.45	-1.00	-0.86	-0.86	-0.86	-1.00	-0.58	-0.77	-0.84	-1.00	-0.34	-0.83	-0.37	-1.00
High pulse count	0.00	-0.10	-0.22	0.36	-0.11	**-0.67**	-0.79	-1.00	-0.38	-0.50	-0.51	-0.66	-0.38	-0.69	-0.51	-0.40
High pulse duration	-0.33	-0.33	-0.43	0.13	-0.33	-0.33	-0.58	-0.07	0.00	-0.33	-0.24	-0.15	0.00	-0.27	-0.35	-1.00
Rise rate	-0.08	0.07	0.64	1.43	-0.57	-0.62	-0.72	-0.53	**-0.65**	-0.49	-0.62	-0.51	**-0.61**	-0.61	-0.78	-1.00
Fall rate	0.55	0.82	-0.37	-0.39	-0.14	-0.28	-0.51	-0.53	-0.10	0.03	-0.06	-0.15	-0.31	-0.29	-0.37	-0.40
Number of reversals	**1.22**	**1.63**	-0.89	-1.00	**1.40**	**1.63**	-1.00	-1.00	**0.66**	**1.04**	-0.96	-1.00	**0.31**	**0.76**	-0.72	-1.00
Do (I vs II, I vs III)		47.9%,	73%			65.6%,	80.9%			56.2%,	72.1%			61.1%,	77.2%	

Note: DM is for the deviation of median values, DM=abs ((Post-impact value) - (Pre-impact value))/(Pre-impact value); HA = hydrological alteration; II and III for the differences between Periods II and I, and between Periods III and I respectively; Numbers in bold mean sign. level is less than 0.01. Do(%) is for the total hydrologic alteration degree of each station during period I and II, or period I and III

Table 4. Mean daily flow discharge under different exceedance probabilities during three time periods (m^3/s)

Stations	Exceedance probability (%)	Period I	Period II	Period III
BH	1	7670	6590	5423
HJG		10800	6850	3860
HZ		13050	8305	7054
XT		8350	6440	6178
BH	10	1930	1490	1434
HJG		2980	1658	1318
HZ		3940	2330	1728
XT		3535	2020	1398
BH	90	158	134	125
HJG		244	456	397
HZ		356	560	515
XT		331	521	454
BH	99	95	59	30
HJG		182	207	324
HZ		215	295	359
XT		213	292	274

Table 5. Ecological damage categories at four stations along the mainstream of the Hanjiang River Basin during three periods

Stations	IHAs Groups	Changing percentage(%)				Impact points				I vs II	I vs III
		I vs II		I vs III		I vs II		I vs III			
		Means	Cv	Means	Cv	Means	Cv	Means	Cv	Points (Class)	Points (Class)
Baihe	1	14.2	30.8	26.6	40.3	0	1	1	1	5(3)	10(3)
	2	18.6	44.4	36.9	49.7	0	0	0	0		
	3	3.6	18.3	23.5	24.4	0	0	2	0		
	4	70.0	29.6	130.5	50.2	2	0	3	1		
	5	49.3	59.3	84.7	26.5	1	1	2	0		
Huangjiagang	1	51.4	34.2	51.3	27.0	2	1	2	0	13(4)	13(4)
	2	70.0	72.5	62.9	45.4	1	0	1	0		
	3	2.0	85.6	9.4	120.4	0	3	1	3		
	4	50.0	86.1	84.0	112.7	1	2	2	2		
	5	86.3	69.2	110.6	19.8	2	1	2	0		
Huangzhuang	1	36.6	21.1	38.6	33.8	1	0	1	1	6(3)	12(4)
	2	57.0	36.8	53.1	74.5	1	0	1	0		
	3	3.9	10.1	20.6	5.1	0	0	1	0		
	4	39.5	57.2	127.8	139.5	1	1	3	3		

	5	64.6	52.7	87.0	10.4	1	1	2	0		
	1	37.4	20.3	37.3	34.4	1	0	1	1		
	2	53.6	30.2	43.5	68.3	1	0	1	0		
Xiantao	3	4.4	16.6	5.3	27.2	0	0	0	0	5(3)	9(3)
	4	48.0	39.4	101.7	113.1	1	1	3	2		
	5	41.6	52.7	73.5	12.9	0	1	1	0		

Note: In the IHAs Group, 1 represents Magnitude of monthly flow conditions, 2 represents Magnitude and duration of annual extreme flow conditions, 3 represents Timing of annual extreme flow conditions, 4 represents Frequency and duration of high and low pulses, and 5 represents Rate and frequency of water condition changes, respectively.

Figures

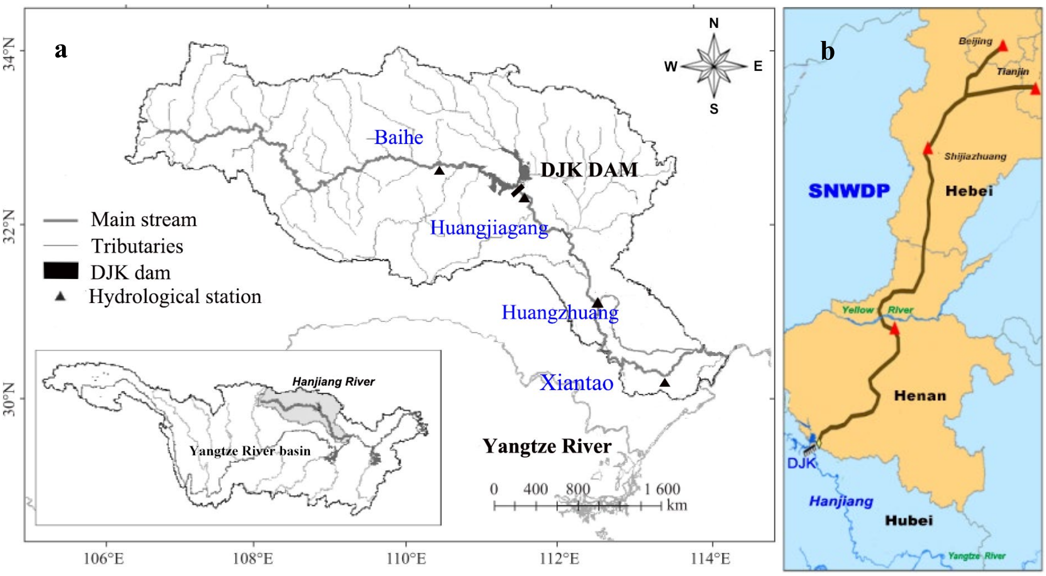

Figure 1. Map indicating (a) the location of the Danjiangkou reservoirs within the Hanjiang River basin and (b) the middle route of China's South-to-North Water Division Project (SNWDP).

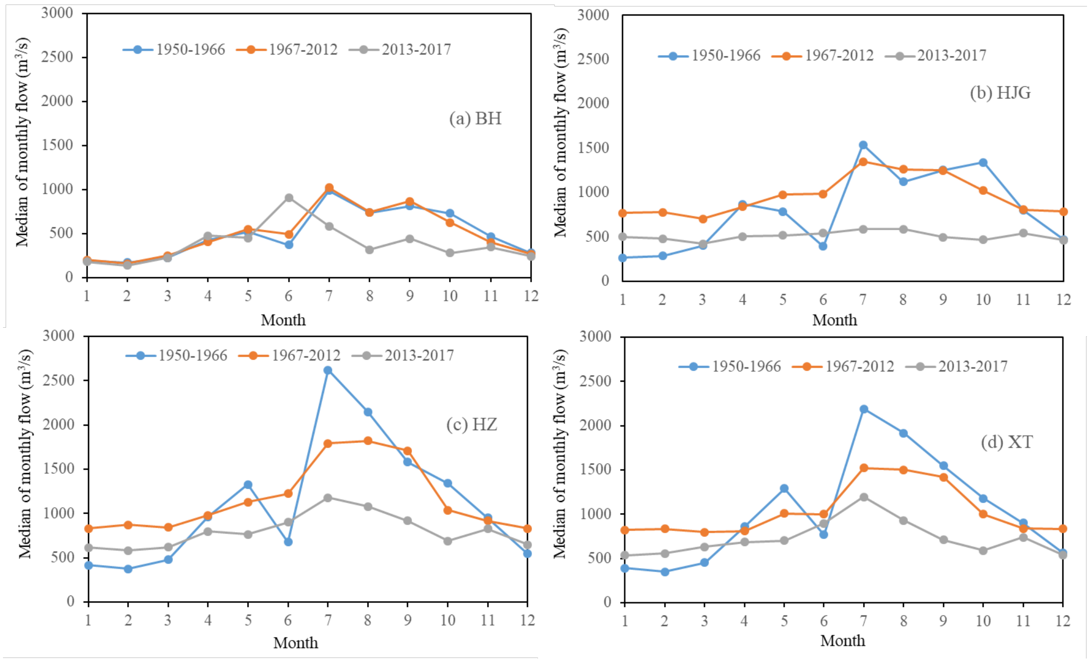

Figure 2. Monthly distributions of flow during three periods at four stations

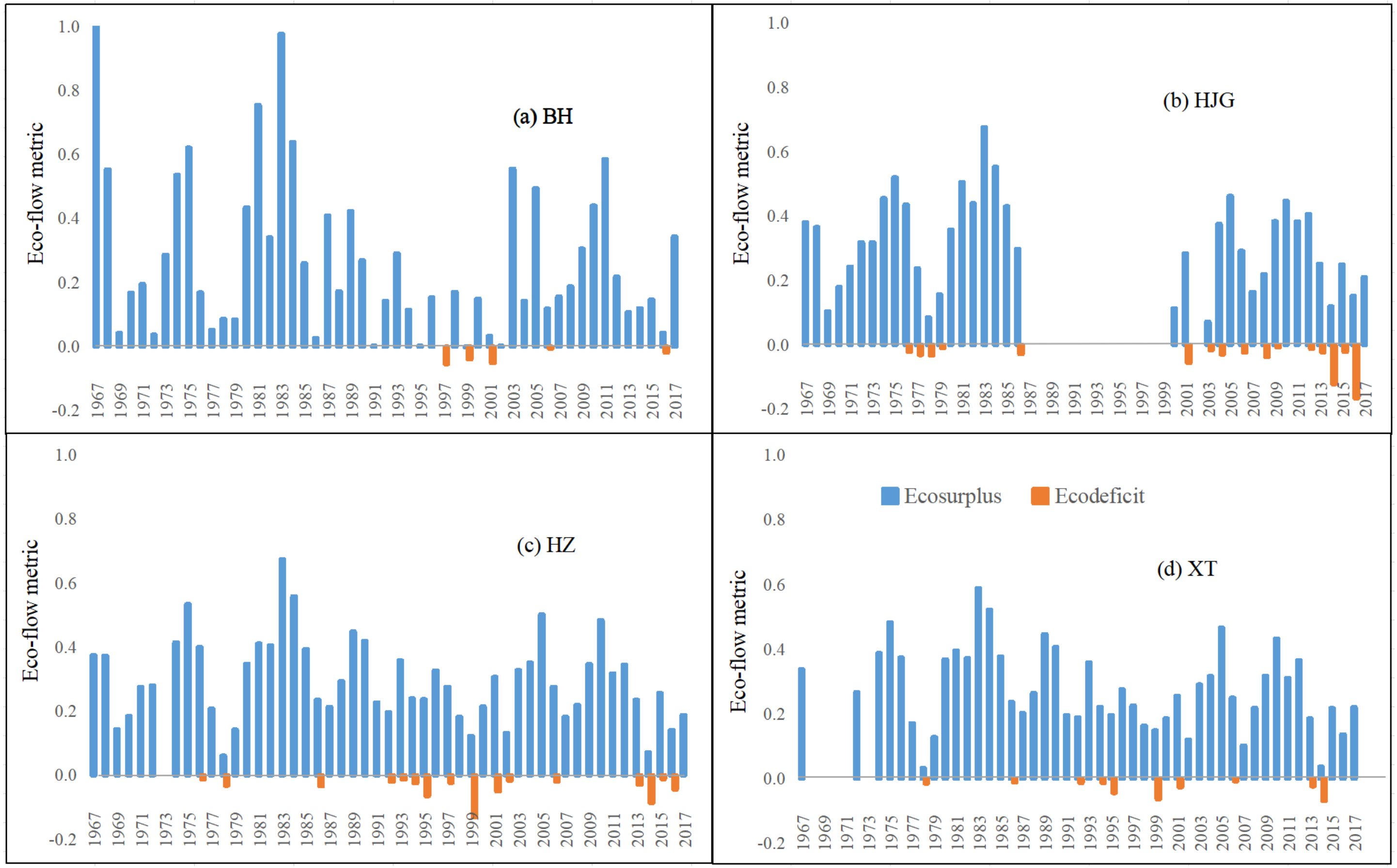

Figure 3. Temporal variations of annual ecosurplus and ecodeficit