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Characteristics of streamflow in the main stream of Changjiang River and the impact of the Three Gorges Dam

Hong Wang[a,*], Fubao Sun[a,b,c,d,e,*], Wenbin Liu[a]

[a] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[b] State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
[c] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, 100049, China
[d] Akesu National Station of Observation and Research for Oasis Agro-ecosystem, Akesu 843017, Xinjiang, China
[e] Center for Water Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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ABSTRACT

The assumption that natural system changes in a constant range runs through the practice of water resources application. However, under the changing environment, whether hydrological characteristics have changed is a crucial and important foundation for flood control and drought resistance. Based on daily water level, discharge, and precipitation for the last 100 or 60 years, this study analyzed the hydrological characteristics and their changes as results of the operation of the Three Gorges Dam (TGD) in the Changjiang (Yangtze) River. Results showed that the monthly precipitation did not significantly change for the longer period and the annual precipitation remained stationary during 1959–2018. However, the water level and discharge significantly increased during most months from January to March and significantly decreased from August to November. Yichang station, the nearest station to the TGD, changed the most, which annual runoff and water level series (1959–2018) showed obvious non-stationarity behavior. The same results were showed in period 1890–2018, while the process remained stationary for the period 1890–1970. 50.15% of the discharge at Yichang station decrease from June to November was attributed to water storage of the TGD and 57.57% of its increase during other months was attributed to recharge of the TGD. The TGD had a greater impact on the discharge, while the water level was affected by both the TGD and Gezhouba Dam. The trends of the water level and discharge were in perfect synchronization prior to 1980, but went out of sync in terms of a different direction or rate after 1980 given the operation of Gezhouba Dam. The non-stationarity behavior of discharge and water level and the change of their laws make it difficult to directly apply the relationship among precipitation-discharge-water level in the past, which brings great challenges to the planning and management of water resources.

1. Introduction

About 2/3 of rivers longer than 1000 km are no longer free-flowing (Grill et al., 2019). Alteration of the water cycle in the form of dams is deeply embedded within the modern global water cycle (NRC, 2012). During the past century, dams have been built to meet social and economic development demands, such as irrigation, electricity, flood control, and water supply (Asmal et al., 2000; Meybeck, 2003; Munoz et al., 2018). Opponents point out large dams on trunk rivers and tributaries triggering massive hydrophysical and biotic disturbances (Asmal et al., 2000; Latrubesse et al., 2017), destroying riverine ecosystems (Humborg et al., 1997), adversely affecting biodiversity and critically important fisheries (Winemiller et al., 2016; Wu et al., 2003), leading to large-scale degradation of floodplain and coastal environments (Latrubesse et al., 2017), and even increasing flood hazard levels or droughts (Lu et al., 2011; Munoz et al., 2018). The conflict and balance between the advantages and disadvantages of dams in terms of their social, economic, and ecological impact have been the subject of intense debate (Fu et al., 2010). Combined with the impact of climate change (Koster et al., 2010; Milly et al., 2005; Milly et al., 2006), the rapidly changing hydrological regime of rivers has resulted in pressures and challenges in terms of the safety of water resources, ecological environment, and aquatic organisms.

Hydrological regimes undergo remarkable changes in worldwide

* Corresponding authors at: Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China (H. Wang & F. Sun).
E-mail addresses: wanghong@igsnrr.ac.cn (H. Wang), sunfb@igsnrr.ac.cn (F. Sun).

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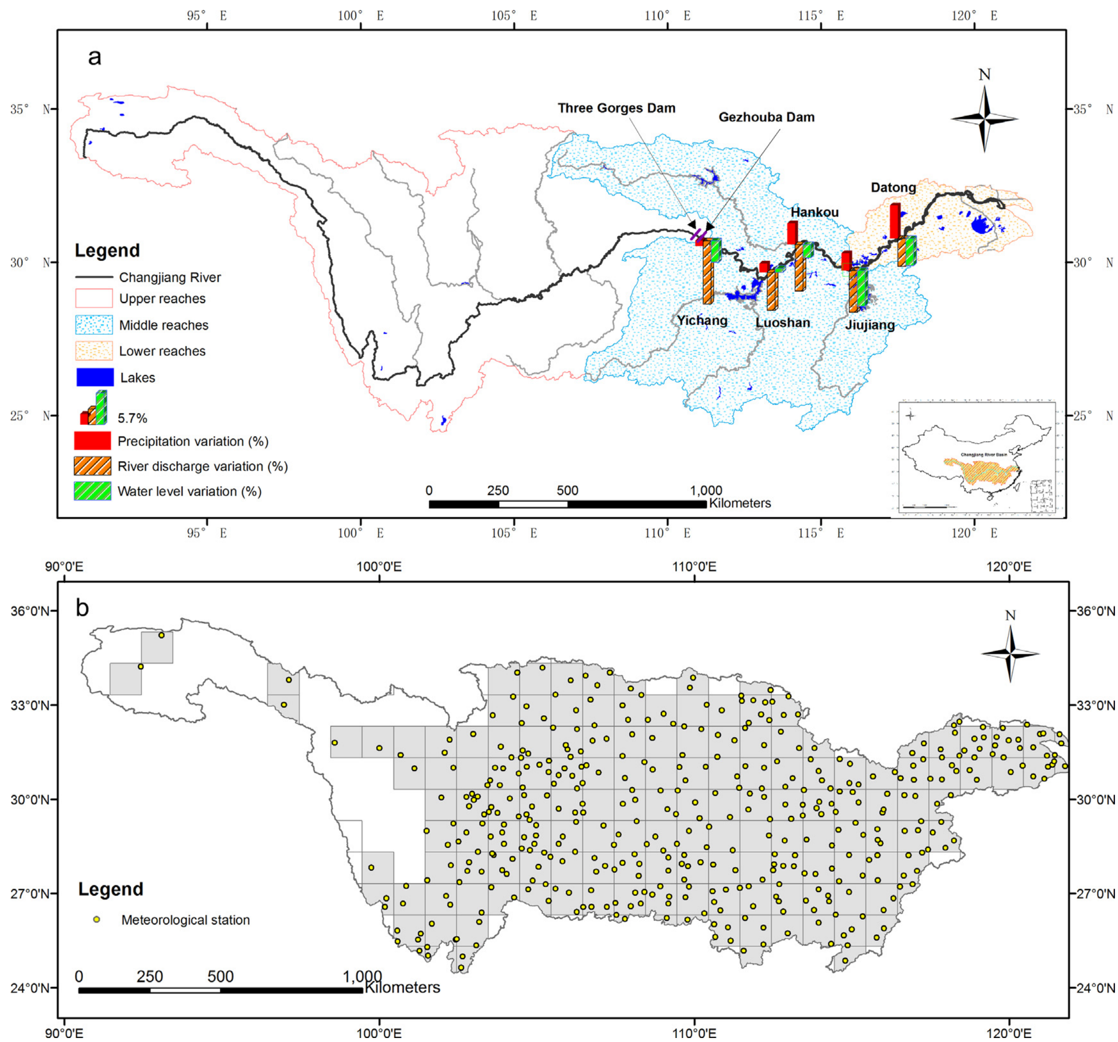

Fig. 1. study area. (a) Location of the study area and hydrological stations. The column chart shows a comparison of annual average precipitation, discharge, and water level after operation of the Three Gorges Dam (TGD) (2003–2018) compared to that before operation (before 2003). (b) The meteorological stations with daily date from 1959 to 2018 and selected grids with at least one station (spatial resolution of $1^{\circ} \times 1^{\circ}$).

rivers in response to human interferences (Humborg et al., 2002). Total of ~10,800 cubic kilometers of water has been impounded on land by the world's artificial reservoirs since ~1900 (Chao et al., 2008) and over one-half of large river systems have been affected by dams (Nilsson et al., 2005). Alterations in the timing, magnitude, frequency, duration, and rate of change of flows (Adam et al., 2007; Burke et al., 2009); water temperatures and environmental flows (Olden and Naiman, 2010); water levels (Tanny et al., 2011; Zhang et al., 2006a); and sediment load (CWRC, 2018; Guo et al., 2018; Yang et al., 2011; Zhang et al., 2006b) have been profoundly altered, resulting in a series of consequences. For example, the construction and operation of large reservoirs results in a shift in streamflow seasonality that reduces peak flows and increases low flows (Adam et al., 2007). Results show that river engineering has increased flood hazard levels on the lower Mississippi River to levels that are unprecedented (Munoz et al., 2018). The world's most biodiverse river basins - the Amazonian, Congo, and Mekong - are being subject to an unprecedented boom in the construction of hydropower dams, which overestimate economic benefits and underestimate far-reaching effects on biodiversity and critically important fisheries (Winemiller et al., 2016). More than 100 hydropower dams have already been built and numerous proposals for further dam construction are under consideration in the Amazonian basin, which will affect the basin's floodplains, estuary, and sediment plume (Latrubesse et al., 2017). The world's two largest river discharges, the Amazonas-Orinoco and Congo, are moderately affected by their large river systems, and the third largest discharge, the Changjiang River, is strongly affected (Nilsson et al., 2005).

More than 50,000 dams of different types have been built in the Changjiang River basin (Kehui et al., 2009; Yang et al., 2011), of which the Three Gorges Dam (TGD) is the largest hydroelectric power project in the world. Results have showed that TGD operation has altered the hydrological regime of the Changjiang River (Guo et al., 2012; Zhang et al., 2006b; Zhao et al., 2015). The discharge has been reduced during flood peaks and the wet-to-dry transition period, with an abrupt decrease during October; a marked increase during the low discharge months of from January to March began abruptly in 2003 (Chen et al., 2016; Guo et al., 2018). The change in the water level was not only influenced by discharge, but also by the change of sediment regime which has been altered by dam construction during the past several decades (Lou et al., 2018; Wang et al., 2018; Yang et al., 2007). The riverbed has changed from depositional before dam construction to erosional afterwards (Dai and Liu, 2013; Lai et al., 2017). The impoundment of the TGD significantly altered the flow regimes in Poyang and Dongting lakes, the two largest freshwater lakes in China, in the Changjiang River basin by reducing river discharge (Lai et al., 2014). A major consequence of such changes has been a weakening in the river forcing on the lake, allowing more lake flow to the river from July to March (Guo et al., 2012).

Hydrological regime changes have affected biodiversity and ecological processes in the area through both the immediate loss of habitat area and increased isolation of remaining habitat patches (Wu et al., 2003). Worse, more than 80% of the remaining lakes are no longer connected with the river, seriously limiting their capacity for buffering the water supply (Lu et al., 2011). Some results have showed that the adjustment of TGD and the replenishment from tributaries and lakes have resulted in “no drought in the drought season” (Dai et al., 2008), while some researchers have noted that although the dam is not the sole cause of Chinese drought, extensive land reclamation along the middle and lower reaches of the Changjiang River has exacerbated the drought by removing or shrinking many natural lakes across the river basin (Lu et al., 2011). The TGD and the South-to-North Water Transfer Project will also affect the frequency and intensity of severe floods in the Poyang Lake region of the middle Changjiang and will increase the flood risk during the early summer monsoon, in contrast to the original justifications for building the dam (Nakayama and Shankman, 2013). The Three Gorges Project provides opportunities for grand-scale experiments of environmental, ecological, and socio-economic impacts of large dams (Fu et al., 2010; Wu et al., 2003).

The Changjiang River basin covers an area that includes approximately 400 million people, and guarantees water to the populations of other basins via water diversion projects; thus, its hydrological regime is of vital importance. Here, we used daily water level, discharge, and precipitation data from three stations with more than 100 years and two stations with approximately 60 years of record along the lower reaches of the TGD to analyze the hydrological regime of the Changjiang River and the change resulting from operation of the TGD. In Section 2, we describe the study area and data. Section 3 reports the results of the changes hydrological characteristics and the impact of the TGD in the upstream, midstream, and downstream, respectively, and attempts to explain the results quantitatively. Section 4 is the conclusion.

2. Data and methods

Fig. 1 shows the location of the study area. The Changjiang River is approximately 6300 km long; it is the third longest river in the world. The watershed covers an area of 1.8 million km^2, accounting for approximately one-fifth of China's total land area. The total annual water resources of the Changjiang River are 961.6 billion m^3, accounting for 36% of the total river streamflow in China. The TGD is the largest hydroelectric power project in the world. Its total length of the dam axis is approximately 2309.5 m and its height is 185 m. The Three Gorges Reservoir (TGR) is an artificial lake formed after completion of the TGD, with a total area of 1084 km^2 and a total reservoir capacity of 39.3 billion m^3. In June 2003, the TGR first impounded water; thus, the influences of the reservoir on the hydrological process were analyzed by comparing data from periods before and after 2003.

TGD is in the upstream and its nearest downstream hydrological station is Yichang station, which is along the control section of the upstream. Gezhouba Dam is 37 km downstream of the TGD and 6.4 km upstream of Yichang hydrological station. It first impounded water in 1981. Luoshan, Hankou and Jiujiang station are in the midstream; Jiujiang station is the control station of the midstream. Datong station is in the downstream. These hydrological stations are used from the upstream to midstream to downstream in this study (Fig. 1(a)). Yichang, Hankou, and Jiujiang stations have data going back more than 100 years, and Luoshan and Datong stations have data for the last approximately 60 years. The daily data of water level and discharge from the five hydrological stations were obtained from the Hydrological Yearbooks of China. The daily precipitation data before 1951 were obtained from the Hydrological Yearbooks of China. Daily data during the period 1951–2018 were obtained from meteorological stations associated with the China Meteorological Data Service Center (CMDC) (http://data.cma.cn/).

Fig. 1(b) shows 420 meteorological stations without missing daily date from 1959 to 2018, which are selected to analyze the stationary characteristics of watershed precipitation. In order to minimize the statistical deviation caused by the non-uniformity of the stations distribution, we select the grids according to the spatial resolution of $1^{\circ} \times 1^{\circ}$, and identify the effective grids containing at least one station. 154 effective grids are selected and the average value is taken in the calculation for a grid containing more than one station. The method of stationarity analysis for precipitation, water level and discharge was developed by Sun et al. (2018). Traditional statistical analyses were performed using SPSS (version 22) and matlab (version R2015b). SigmaPlot 10 and ArcGIS 9.3 were used to perform geostatistical analyses and produce figures.

3. Results and discussion

3.1. The stationarity of annual precipitation, water level and river discharge in the Changjiang River basin

Fig. 1 compares the annual average precipitation, water level, and discharge between the periods before (before 2003) and after (2003–2018) operation of the TGD. The annual precipitation of the five stations increased by 37.44 mm on average. Linear trend analysis shows that there is no statistically significant change in annual precipitation at each station. Based on the precipitation observation data of 420 meteorological stations (Fig. 2) over the Changjiang River Basin from 1959 to 2018, the stationarity characteristics of annual precipitation were analyzed. Autocorrelation from lag 1 to lag 4 for the annual precipitation time series are showed in Fig. 2(a–d) and lag 5 to lag 8 are showed in Fig. s1 of the supplemental material. The 90% confidence level for the autocorrelation is used as a threshold to distinguish grid boxes that have lags autocorrelation indistinguishable from zero (blue in Fig. 2) from those showing positive (yellow) and negative (red) lags autocorrelation. 92.21–99.35% grid boxes show no significant lag 1–8 autocorrelation within the 90% confidence level. At the same time, considering 30-years historical averages as “climate normal” recommend by WMO and a climatic timescale widely used (Arguez et al., 2012; Sun et al., 2018; WMO, 2019), the stationarity of 30-year average precipitation is further analyzed. Fig. 2 (e) and (f) are the results of the 30-year average precipitation within the 90% confidence level during period 1959–1988 and 1989–2018 respectively. 95.45% grid boxes show no significant for 30-year average precipitation within the 90% confidence level. Results of the autocorrelation and average show that the annual precipitation process remained stationary and indistinguishable from a random process. Meanwhile, the annual precipitation after operation of the TGD (2003–2018) has not changed significantly compared with the precipitation during the past 60 years (1959–2018) (Fig. 3).

However, the discharge of the five hydrological stations decreased, with an average annual decrease of 51.45 billion m^3. The average water level of the five stations decreased by 0.66 m, of which the level at Yichang, Hankou, Jiujiang and Datong stations decreased by 1.71, 0.46, 0.89, and 0.42 m, respectively. In contrast, it increased by 0.18 m at Luoshan station because of the siltation in its upper reach. Yichang station has the largest proportion of discharge and water level reduction, which annual runoff and water level series (1890–2018) show obvious non-stationarity behavior, especially the annual average water level (Fig. 4). The same results are showed in period 1959–2018 (Supplemental material, Fig. s2) and before the operation of the TGD (1890–2002) (Supplemental material, Fig. s3). For the period before the operation of the Gezhouba Dam (1890–1981) (Supplemental material, Fig. s4), its autocorrelation coefficients are indistinguishable from zero overall. The 30-year average water levels and discharges within the 90% confidence level, while the last 10-year average values fell outside the 90% limits. Fig. 5 shows that the annual precipitation process remained stationary and indistinguishable from a random process for the

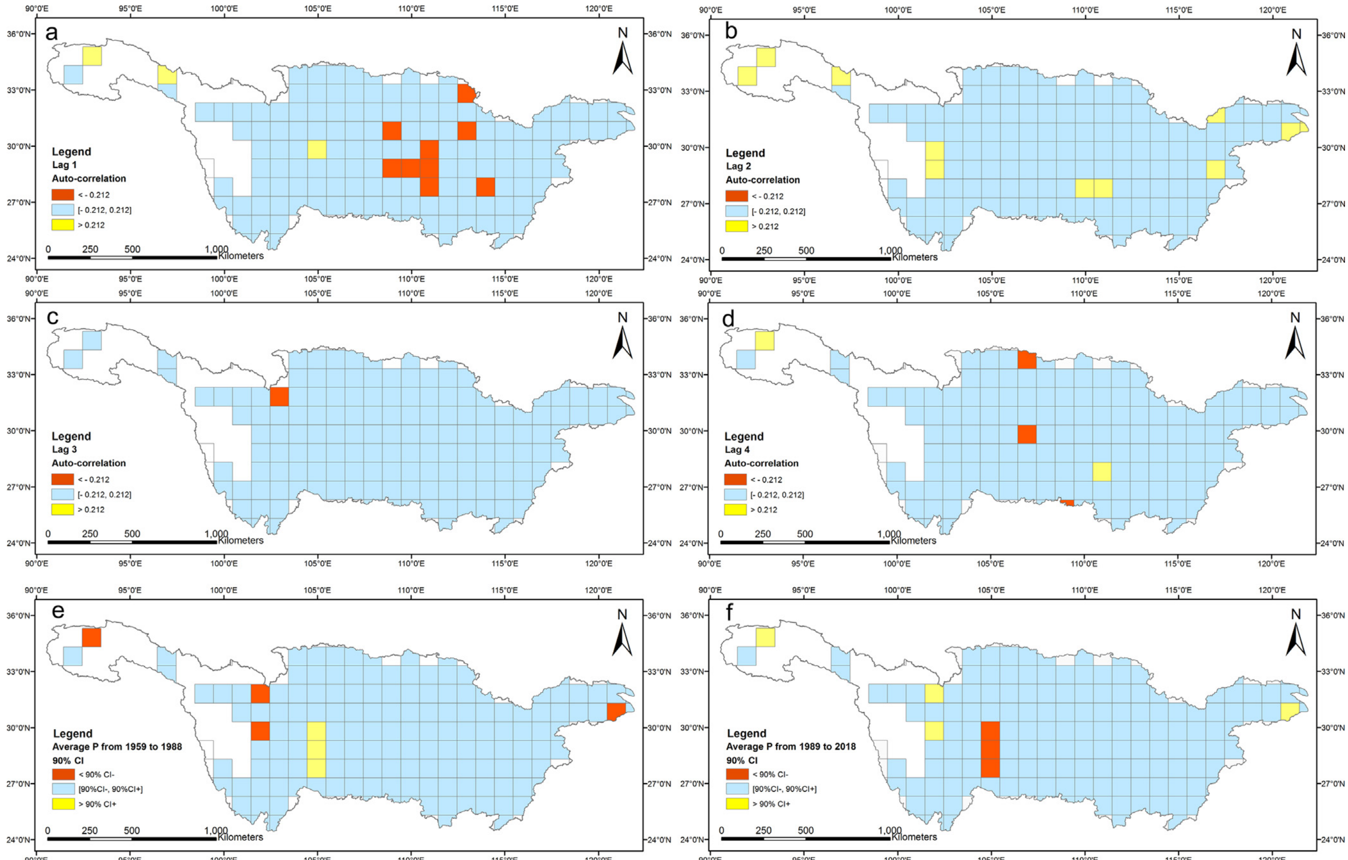

Fig. 2. Analysis of the stationarity for 60 years (1959–2018) precipitation in the Changjiang River Basin. Autocorrelation from lag 1 (a) to lag 4 (d) for the annual precipitation (1959–2018). Significance (± 0.212) is for the 90% confidence level (Cl in the subfigures). (e) and (f) are the results of the 30-year average precipitation within the 90% confidence level during period 1959–1988 and 1989–2018 respectively.

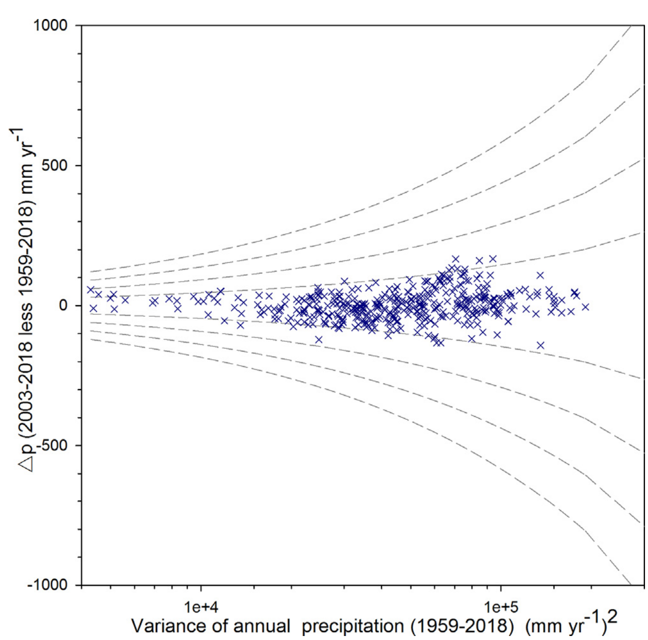

Fig. 3. Testing the annual precipitation after operation of the TGD (2003–2018) for significant changes compared with precipitation during the past 60 years (1959–2018). The ordinate shows △P (calculated as average annual precipitation for 2003–2018 less that for 1959–2018) as a function of the variance of the annual time series (1959–2018) for the observations.

period before 1970. These results indicate that the change of hydrological characteristics of the Changjiang River is closely related to human activities. Therefore, the daily and monthly hydrological characteristics in the upstream, midstream, and downstream of the Changjiang River and the impacts of the TGD were analyzed in detail.

3.2. Hydrological characteristics in the upstream and the impact of the Three Gorges Dam

Yichang hydrological station is the control station of the upstream of the Changjiang River and the first hydrological station in downstream of the TGD. Based on the discharge data from 1878 to 2018, water level data from 1890 to 2018, and precipitation data from 1891 to 2018 at Yichang station, the hydrological characteristics in the upstream and their changes before and after the operation of the TGD were analyzed.

3.2.1. Time process of water level and discharge

The daily water level and discharge data at Yichang hydrological station were divided into seven periods according to age. Data before 1900 are considered period 1. The data are divided into one period approximately every 20 years from 1901 to 2002, periods 2–6 in chronological order. The data after the operation of the TGD (2003–2018) are considered period 7. In addition, the daily average level and discharge of all years were calculated for comparison. The average daily water level and discharge data for each period were calculated and compared as shown in Fig. 6.

Results show that the average daily water level most significantly declined during the period 2003–2018 (period 7). Compared to the period before the operation of the TGD (1890–2002), the average water

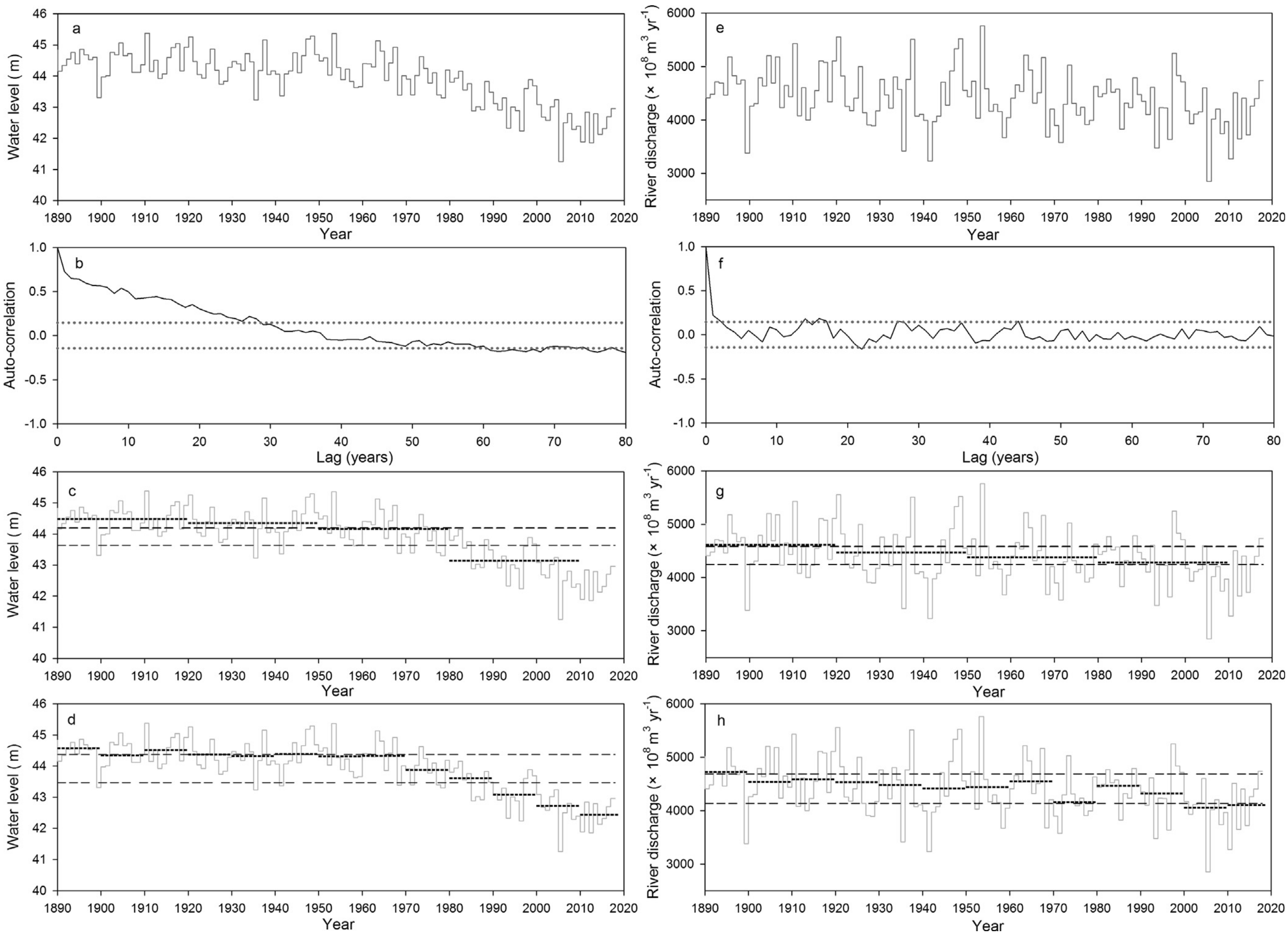

Fig. 4. Annual water level and river discharge at the Yichang hydrological station during 1890–2018. (a) Water level. (e) River discharge. (b) and (f) Autocorrelation of wate r level and river discharge with 90% confidence level (dashed). Averages (dotted line) over (c, g) 30-year and (d, h) 10-year time periods with 90% confidence level (dashed).

level of Yichang station decreased by 1.71 m on average, with 2.46 m during flood season (May-October) and 1.21 m during non-flood season (November-April). Meanwhile, the average water level during the period 1981–2002 (period 6) also significantly decreased. The annual average water level decreased by 0.86 m; the average water level during the non-flood season decreased by 1.06 m.

Compared to the period before the operation of the TGD (1890–2002), the average daily discharge of period 7 decreased by 1,643.26 m^3/s, accounting for 11.54% of the daily average discharge. The discharge, which decreased from May to November and increased from January to April and December, decreased by 17.39% during the flood season and increased by 10.57% during the non-flood season. There was no significant difference among the periods before 1960 for daily water level and discharge. Compared to the period 1878–2002, the average discharge of period 1981–2002 decreased by 3.52%, decreasing by 4.06% during June-November and 1.50% during January-May and December.

Linear trend analysis showed that the annual water level for the period 1890–2018 and discharge for the period 1878–2018 quite significantly decreased ($P < 0.01$). The water level quite significantly decreased ($P < 0.01$) every month and the fastest rate was during October, with a 3.09 cm/year on average decreasing rate. River discharge significantly increased ($P < 0.05$) during January and February, while it quite significantly decreased ($P < 0.01$) from September to November and the fastest rate was also during October, with a 49.49 $m^3/s/yr$ on average decreasing rate.

The monthly water level and discharge processes at the Yichang hydrological station are shown in Fig. 7. It can be seen that the change trend in the water level and discharge were in perfect synchronization prior to 1980. After 1980, the water level continued to decrease, but the discharge increased or did not significantly change during the non-flood season and the discharge decreased or did not significantly change during the flood season. As a result, the water level and discharge processes showed an apparent out of sync relationship during the non-flood season and May-June during the flood season. Both the water level and discharge decreased during the period July-October, but the rates were not the same.

3.2.2. *Relationship between water level and discharge*

According to the previous seven periods, the relationships between daily, monthly, and annual water level and discharge from 1890 to 2018 were analyzed. Fig. 8(a) shows the daily relation from 1890 to 1980. It can be seen that there was a good relationship between daily water level and discharge. Fig. 8(b) supplements the relationship during the periods 1981–2002 and 2003–2016. It can be seen that the water level gradually decreased under the same discharge, and the higher discharge and water level significantly decrease. Fig. 8(c) and (d) show monthly and annual relationships between water level and discharge, respectively. The results for the months and years also showed that the water level under the same discharge decreased and the higher water level and discharge decreased since 1980.

The monthly water level and discharge data were divided into

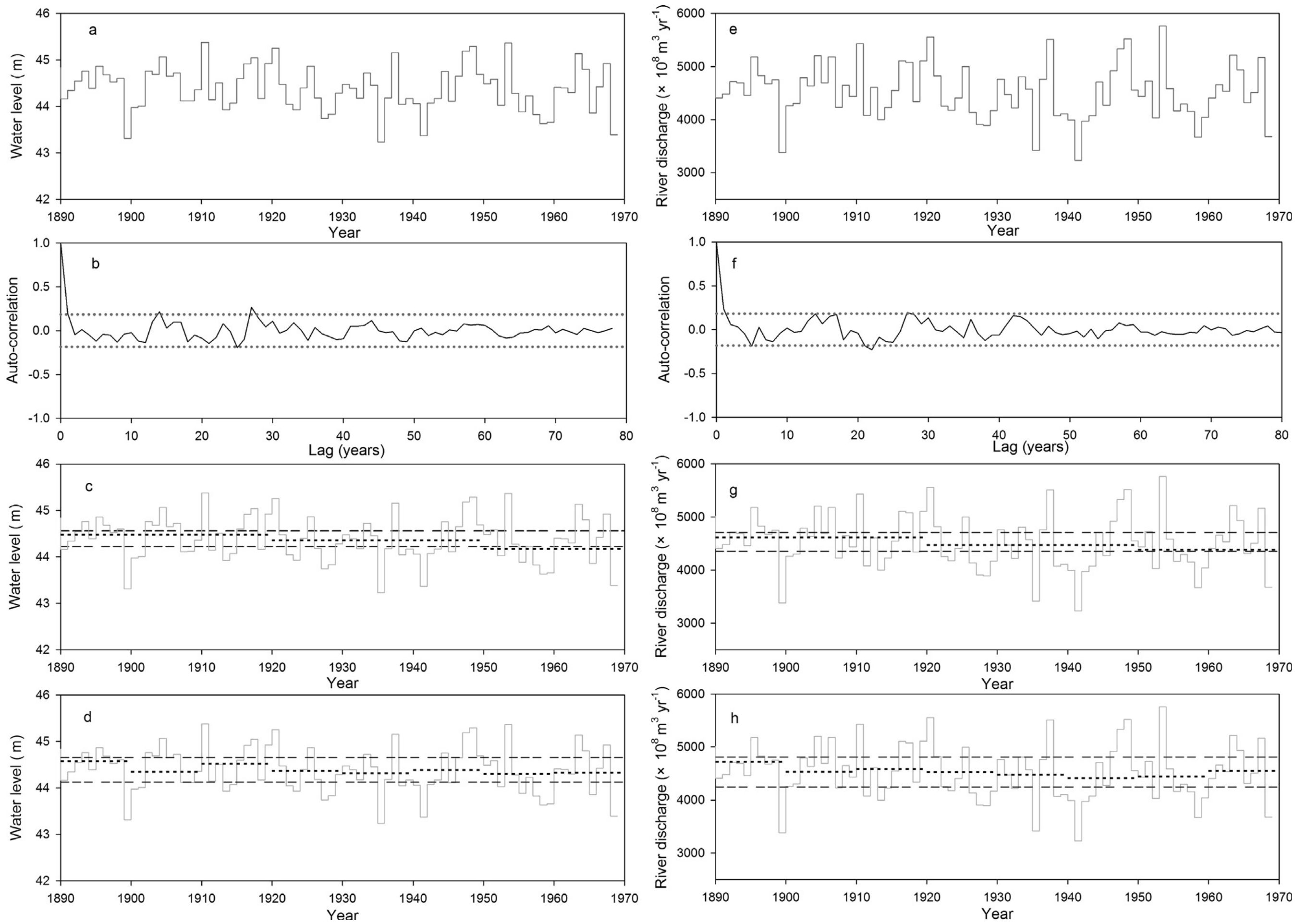

Fig. 5. Annual water level and river discharge at the Yichang hydrological before 1970. (a) Water level. (e) River discharge. (b) and (f) Autocorrelation of water level and river discharge with 90% confidence level (dashed). Averages (dotted line) over (c, g) 30-year and (d, h) 10-year time periods with 90% confidence level (dashed).

periods before and after 2003. Compared to the period before 2003, the 95% and 5% quantile of water level decreased by 1.77 and 0.48 m, respectively, and the data range narrowed to 83.19% during the period 2003–2018. The data of discharge at 95% quantile decreased to 87.65%, the data at 5% quantile increased to 123.28%, and the data range narrowed to 72.23% during the period 2003–2018.

Because the water level and discharge processes varied greatly during each month, the relationship between daily water level and discharge was further analyzed monthly (Fig. 9). The daily relationship during each month was very good prior to 1980, and can be used to supplement each's data. However, since 1980, particularly after 2003, the relationship during the non-flood season has been marginal. This

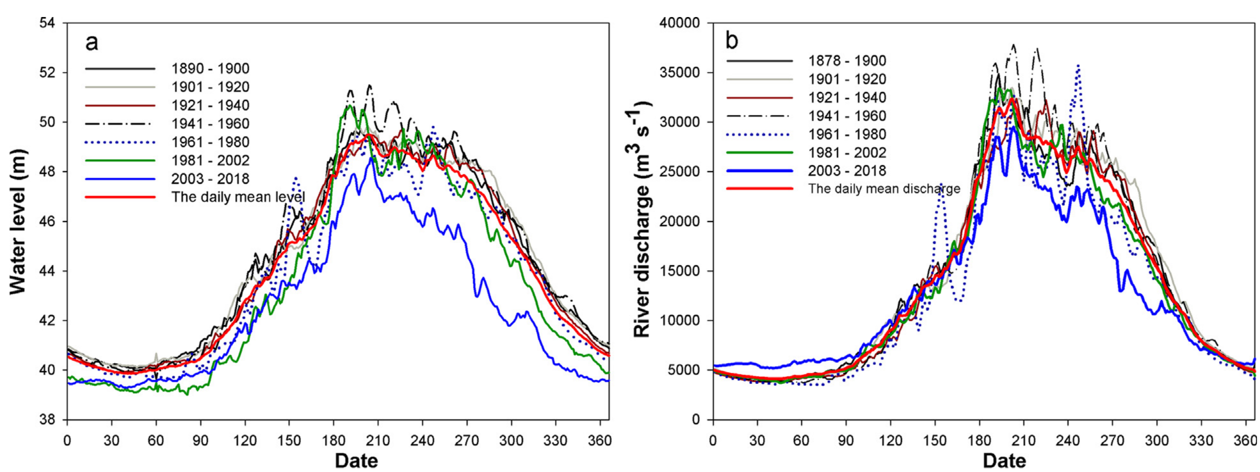

Fig. 6. Average daily water level and discharge for each period at the Yichang hydrological station. The daily water level from 1890 to 2018 and discharge from 1878 to 2018 are divided into seven periods by age. Data before 1900 are considered period 1. Data are divided into five periods each of approximately 20 years from 1901 to 2002. The data after the operation of the TGD (2003–2018) are considered period 7.

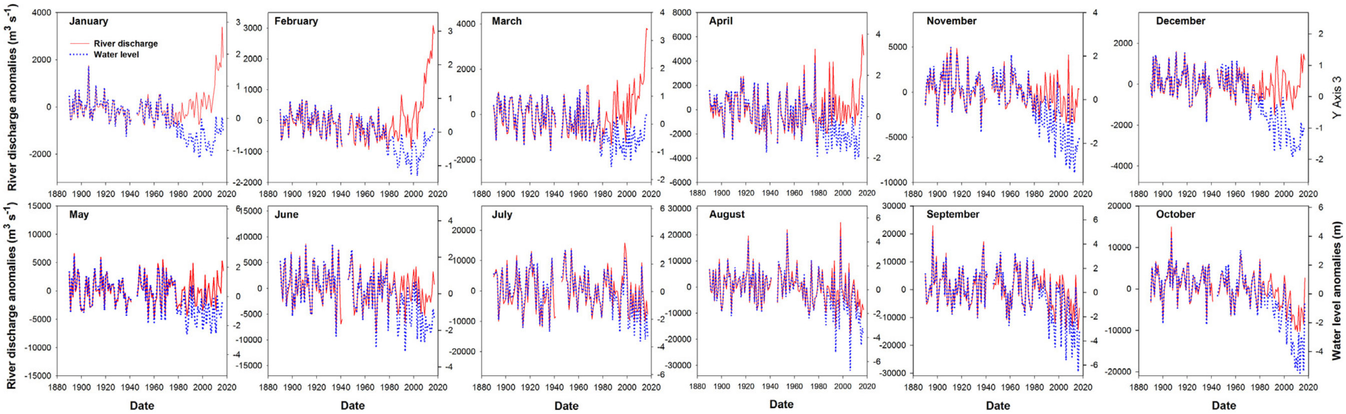

Fig. 7. Monthly water level and discharge processes at Yichang hydrological station. The red solid line is the discharge value and the blue dotted line is the water level value. The six subfigures above are results for the non-flood season, and the six subfigures below are results for the flood season. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

showed that the relationship at the Yichang hydrological station has significantly changed since 1980. Considering that the water level and discharge processes present obviously became out of sync during the non-flood season, considerable attention should be paid to the period after 1980, particularly after 2003, in the hydrological analysis and calculation.

3.2.3. *Relationship between precipitation and water level - discharge*

The variation trend in monthly precipitation at Yichang station was analyzed based on daily precipitation data from 1891 to 2018. The results show that through the precipitation during November, which significantly increased ($P < 0.05$) with a rate of increase of 0.16 mm/yr, there was no significant change during the other months. The average monthly precipitation ranges from 17.20 mm to 219.33 mm.

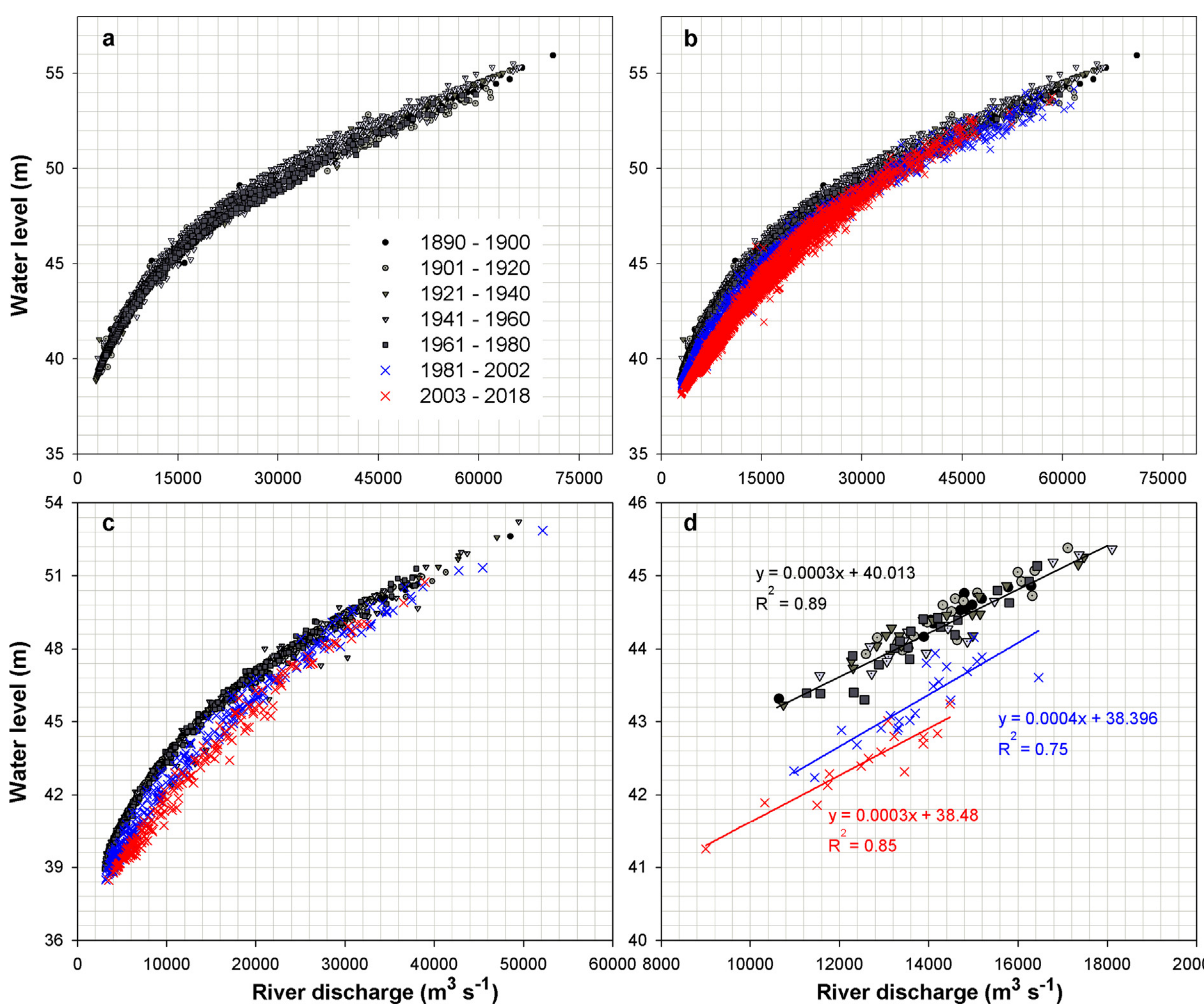

Fig. 8. Relationships between daily, monthly, and annual water level and discharge from 1890 to 2018. (a) Relation of daily water level and discharge from 1890 to 1980. (b) Daily relation from 1890 to 2018. (c) Monthly relation. (d) Annual relation.

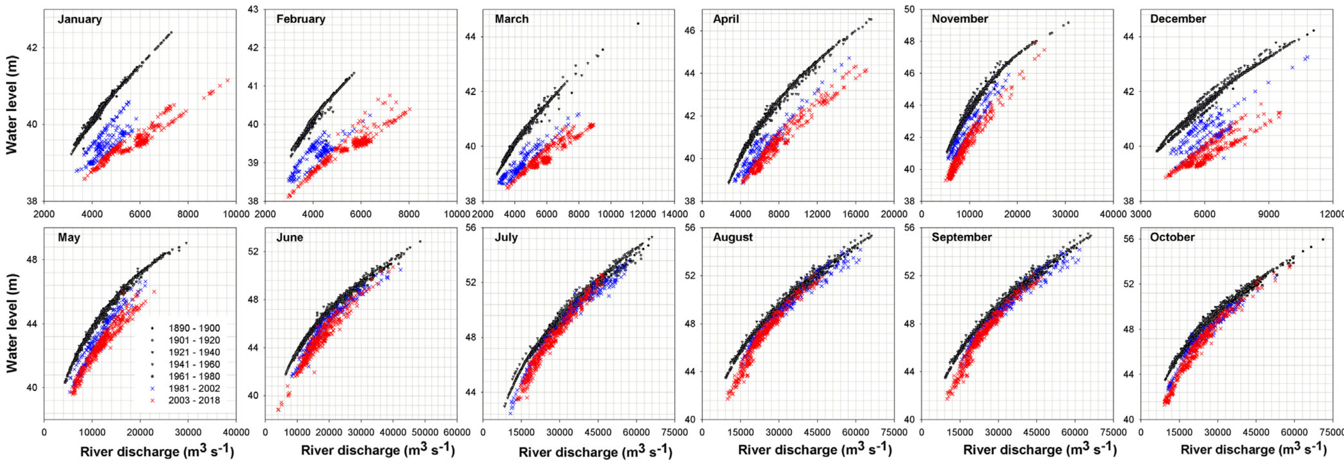

Fig. 9. Relationships between daily water level and discharge from 1890 to 2018 for each month. The six subfigures above are for the non-flood season, and the six subfigures below are for the flood season.

The annual precipitation also showed no significant change (Fig. 10(a). The annual average precipitation was 1137.16 mm, the maximum and minimum precipitation were 1,827.60 and 642.20 mm.

From 1890 to 2018, the discharge at the Yichang station most rapidly increased during January, while the water level decreased, and the difference between the water level and discharge was the most significant. Both the water level and discharge most rapidly decreased during October. Fig. 10(b) and (c) show the comparison of water level, discharge, and precipitation at the Yichang station during January and October from 1890 to 2018, respectively. Although there was no statistically significant change in precipitation, there were significant changes in discharge and water level.

3.2.4. Impact of Three Gorges Dam on discharge at the Yichang station

Fig. 11(a) compares the daily average water inflow and outflow of the TGR, outflow of the Gezhouba Dam, and discharge of the Yichang station from 2009 to 2017. It can be seen that the outflow values of the TGR and Gezhouba Dam and Yichang station are nearly equal at the same time. There is a good correlation (1:1 line, R^2 = 0.99) between the outflow of the TGR and Gezhouba Dam and the discharge at the Yichang station (Fig. 11(c), (d)). This showed that the TGD has a significant impact on the discharge at Yichang station, while the Gezhouba Dam has a limited impact. This is mainly because the Gezhouba Dam is a low-head water conservancy project with a reservoir capacity of 1.58 billion m^3, which accounted for approximately 0.36% of the average annual runoff at Yichang station (441.44 billion m^3). The Gezhouba reservoir has a limited capacity to retain and regulate floods. There is a good correlation between the daily water level of the downstream of the Gezhouba Dam and Yichang station (Fig. 11(e)), while the daily average upstream water level of the Gezhouba Dam is much higher than that in downstream and Yichang station (Fig. 11(f)). Therefore, the TGD has a greater impact on the discharge at Yichang station and the water level was affected by both the TGD and Gezhouba Dam, which is consistent with the results shown in Fig. 1.

From 2009 to 2017, the average water inflow and outflow of the TGR was 391.70 billion m^3 and 368.04 billion m^3, respectively. Approximately 6.04% of the average annual volume of inflow was blocked by the TGR. The daily and monthly average inflow and outflow for the TGR and the percentage change in outflow compared to the inflow from 2009 to 2017 are shown in Fig. 11(a) and (b), respectively. It can be seen that the reservoir retained discharge from June to November and replenishes water to the river from January to May. The inflow and outflow during December did not obviously change. The average amount of water retained by the TGR from June to November was 8.25% of the average annual inflow. The monthly maximum amount of water retained occurred during October, accounting for 26.68% of its monthly water inflow. From January to May, the average recharge from the reservoir to the river was 2.22% of the average annual inflow. The monthly maximum amount of water recharge occurred during February, accounting for 19.23% of its monthly water inflow.

Compared to the period 1878–2002, the average discharge for the period 2009–2017 decreased by 11.03%, decreasing by 14.41% during the period June-November and increasing by 3.38% during January-May and December. The decrease of 47.95% from 2003 to 2018 from the previous average discharge was because of water storage in the TGR. From June to November, the decrease of 50.15% from the previous average discharge was because of the water storage in the TGR, while 57.57% of the increase in discharge from January to May and December was because of the recharge of the reservoir. The reservoir caused significant alterations of natural river regimes (Vicente-Serrano, et al., 2014).

3.3. Hydrological characteristics in the midstream and downstream and the impact of the Three Gorges Dam

The hydrological characteristics in the midstream and downstream of the Changjiang River were analyzed and their changes before and after the operation of the TGD were compared, based on the discharge, water level, and precipitation data at Luoshan station from 1954 to 2018, Hankou station from 1865 to 2018, and Jiujiang station from 1904 to 2018 in the midstream, and Datong station from 1951 to 2018 in the downstream.

3.3.1. Variation in the daily average water level and discharge after operation of the Three Gorges Dam

The daily water level and discharge data at the Luoshan, Hankou, Jiujiang, and Datong hydrological stations were divided into two periods according to the operation year of the TGR (2003). Data before 2003 are considered period 1 and data from 2003 to 2018 are considered period 2. The average daily water level and discharge data for the two periods were calculated, respectively, for the four stations and the results were compared as shown in Fig. 12. One can see that the water level and discharge in the midstream and downstream increased from January to April; significantly decreased from July to November; and changed relatively little during May, June, and December.

From January to April, the daily water level of the four hydrological stations increased by 0.75 m on average, with an average increase of 0.91 m in the midstream and 0.29 m in the downstream. From July to November, the daily water level decreased by an average of 1.28 m, with an average decrease of 1.38 m in the midstream and 0.99 m in the

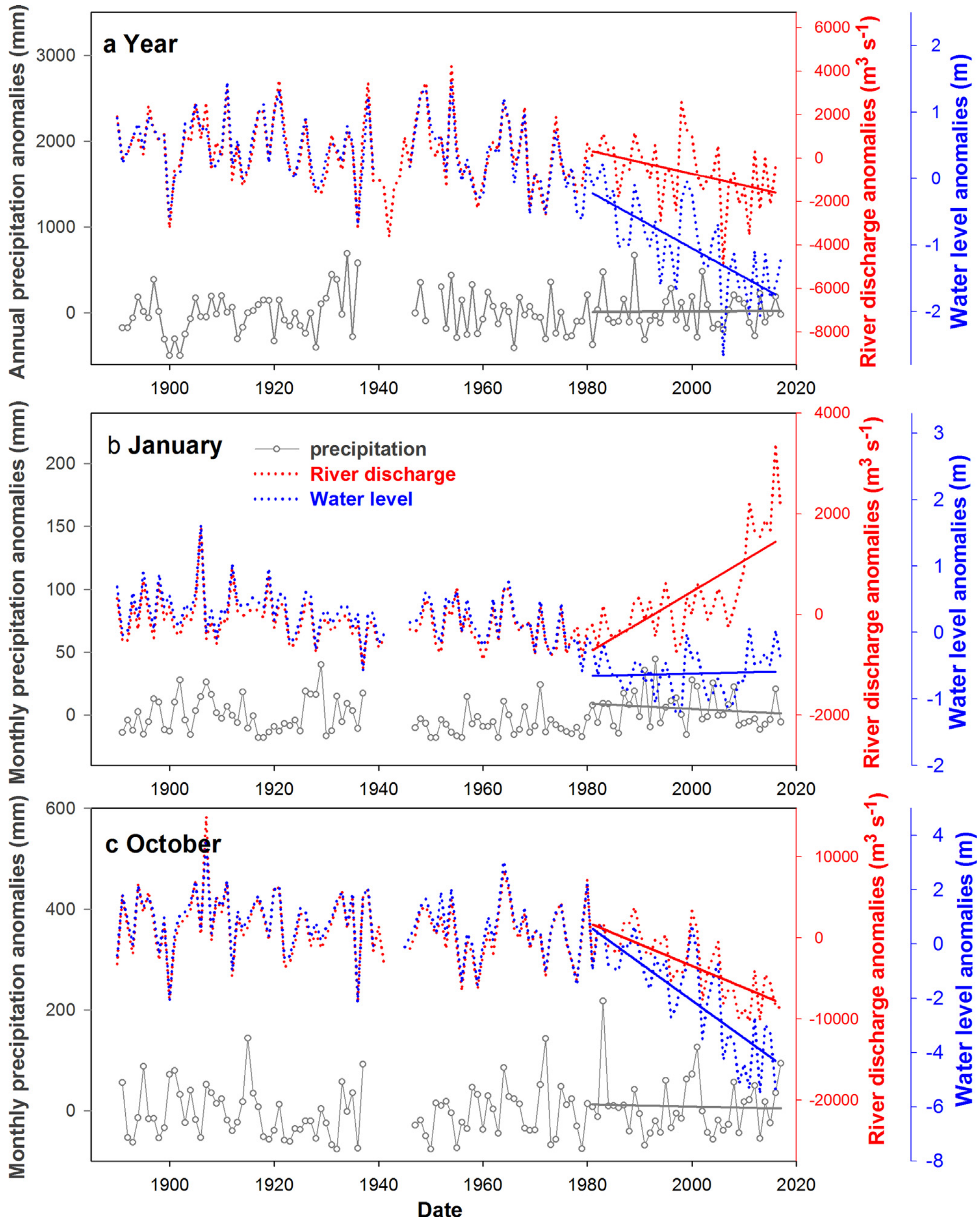

Fig. 10. Comparison of water level, discharge, and precipitation at Yichang hydrological station by year, during January, and during October from 1890 to 2018. (a) Results by year. (b) Results during January. (c) Results during October. The gray Y-axis, line with the circle, and solid line are the axis, values and trend line for precipitation. The blue Y-axis, dotted line, and solid line are the axis, values, and trend line for water level. The red Y-axis, dotted line, and solid line are the axis, values, and trend line for discharge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

downstream. Comparing the results of the four stations, the daily average water level at Luoshan station increased the most during January-April, decreased the least during July-November, increasing by 1.49 m and decreasing by 0.44 m, respectively. From January to April, the daily discharge increased by 1,976.34 m^3/s on average, with an average increase of 1,917 m^3/s in the midstream and 2,154 m^3/s in the downstream. From July to November, the average daily discharge decreased by 6,132.22 m^3/s, 6,622.61 m^3/s in the midstream, and 4,661.05 m^3/s in the downstream. These results were consistent with changes between inflow and outflow at the TGR.

3.3.2. Relationship between precipitation and water level - discharge

Linear trend analysis showed that the annual discharge at Hankou station and the water level at Jiujiang station quite significantly decreased ($P < 0.01$) and the water level at Luoshan station quite significantly increased ($P < 0.01$). There was no statistically significant change in discharge and water level for the remaining stations and no statistically significant change in annual precipitation at the four stations.

The monthly water level increased significantly in 50% (8/16) of the months from January to April, and others have no statistically significant change. From August to November, the water level in 11/16 of the months decreased significantly. The monthly discharge increased significantly in 9/12 of the months from January to March, and decreased significantly in 11/16 of the months from August to November. Others have no statistically significant change. The monthly precipitation of the four stations showed no significant change in 83% of the monthly precipitation, only 6/48 of the monthly precipitation increased

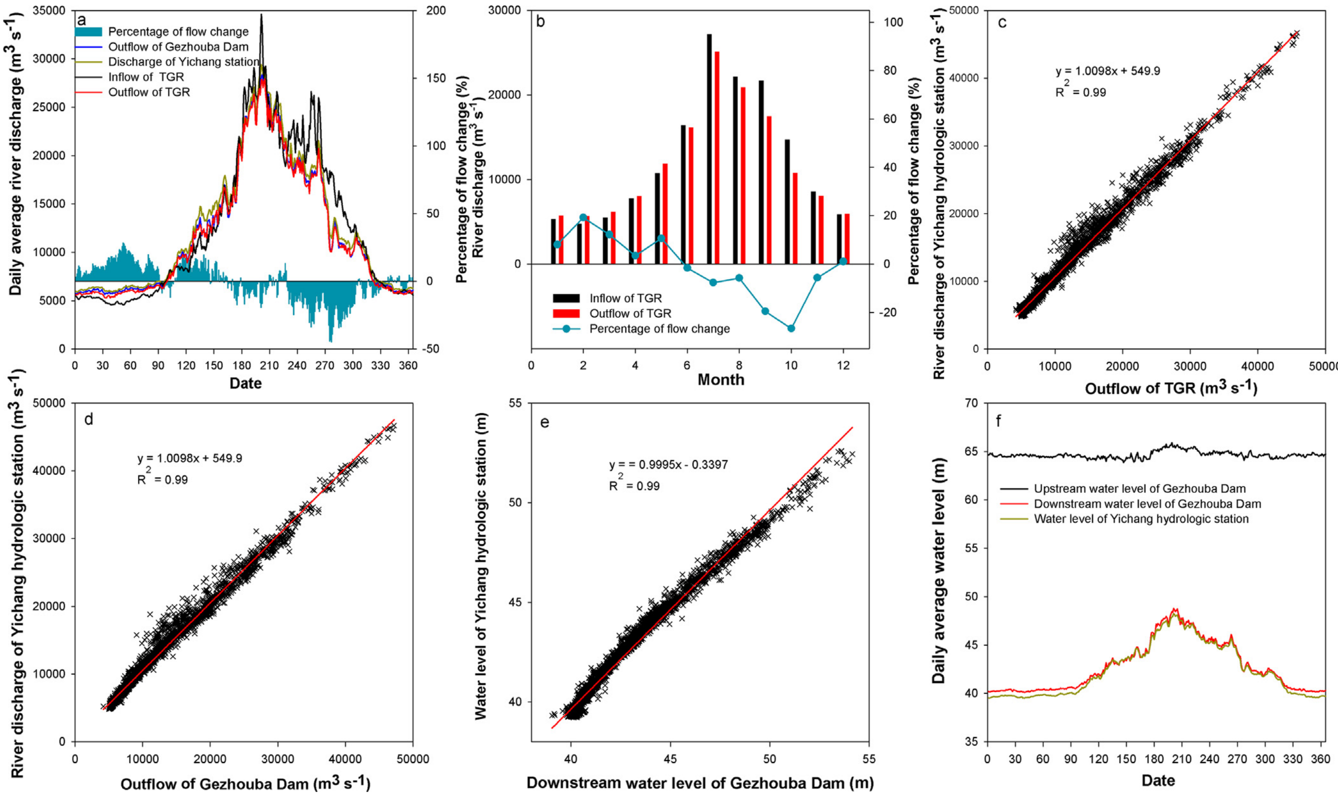

Fig. 11. Comparison of water flow and level of the Three Gorges Reservoir (TGR) and Gezhouba Dam and the discharge at the Yichang hydrological station from 2009 to 2017. (a) The daily average water inflow and outflow of the TGR and the percentage change of outflow compared with inflow, the outflow of the Gezhouba Dam and the discharge at the Yichang station. (b) The monthly average water inflow and outflow of the TGR and the percentage change. (c) The scatter plot between the daily outflow of the TGR and the discharge at the Yichang station. (d) The scatter plot between the daily outflow of the Gezhouba Dam and the discharge at the Yichang station. (e) The scatter plot between the daily water level of the downstream of the Gezhouba Dam and Yichang station. (f) The daily average water level of the upstream and downstream of the Gezhouba Dam and the water level at the Yichang hydrological station.

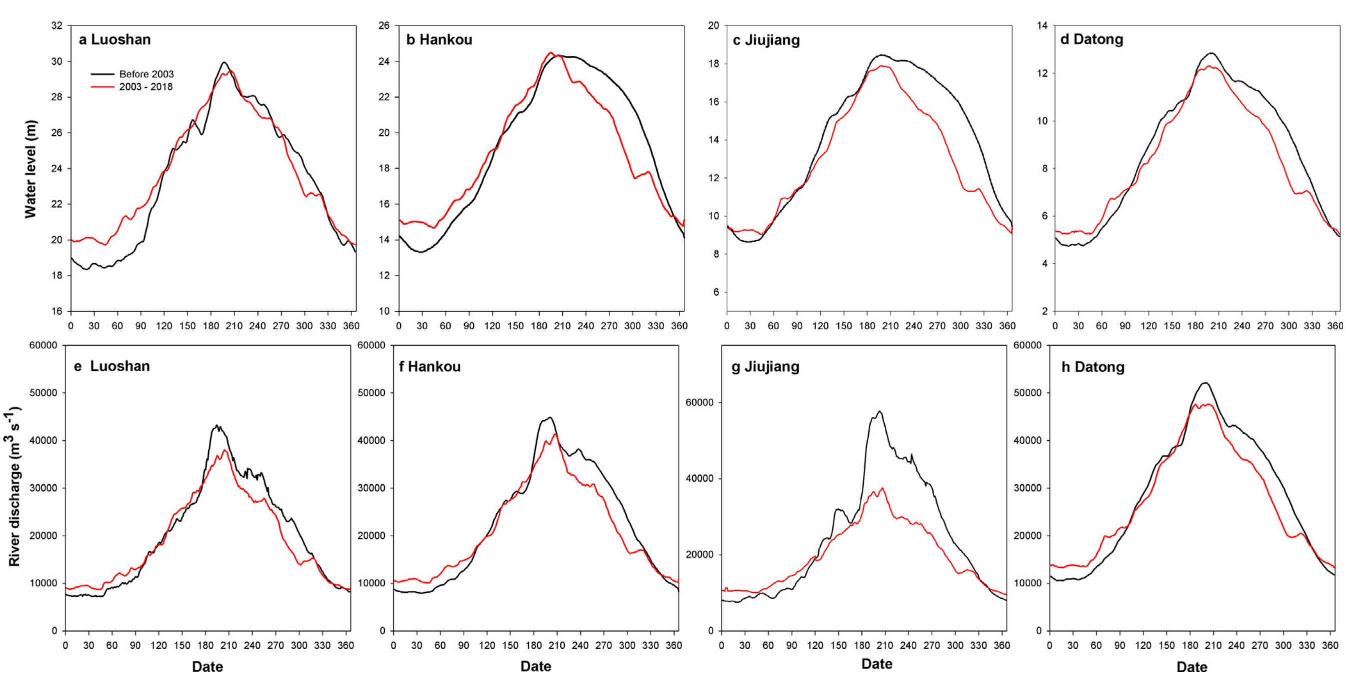

Fig. 12. Average daily water level and discharge data before and after TGD operation at the Yichang, Luoshan, Hankou, Jiujiang, and Datong hydrological stations. The black solid line is the period before TGD operation (before 2003); the red solid line is the period after TGD operation (2003–2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

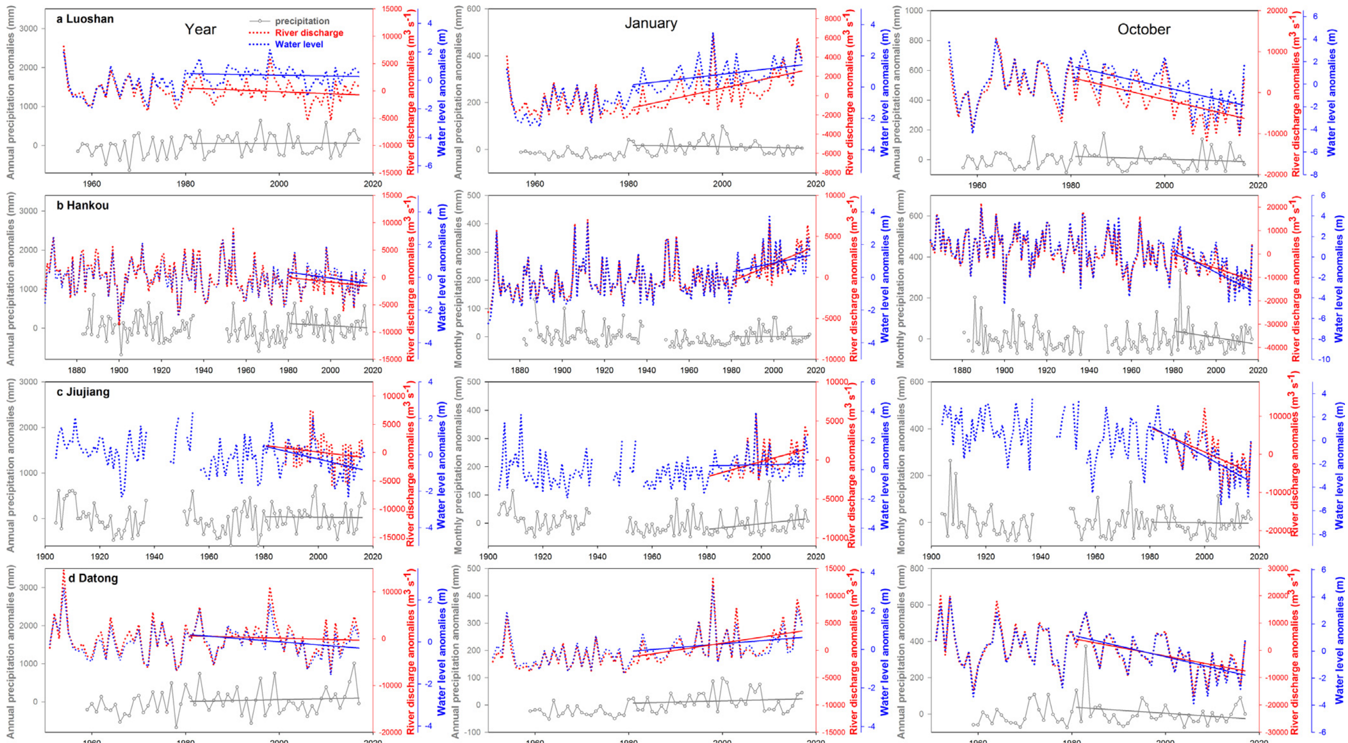

Fig. 13. Comparison of water level, discharge and precipitation at Luoshan, Hankou, Jiujiang and Datong hydrological stations in year, January and October from 1890 to 2018. (a) The results of Luoshan station. (b) The results of Hankou station. (c) The results of Jiujiang station. (d) The results of Datong station. The gray Y-axis, line with circle and solid line are the axis, values and trend line of precipitation. The blue Y-axis, dotted line and solid line are the axis, values and trend line for water level. The red Y-axis, dotted line and solid line are the axis, values and trend line for discharge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

significantly and 2/48 decreased significantly. The precipitation of the four stations in October did not change significantly in statistics, while their discharge and water level decreased extremely significantly ($P < 0.01$).

The discharge of each station increased significantly during January and decreased significantly in October. Therefore, the time processes of precipitation, water level and discharge for year, January and October are showed in Fig. 13. Similar to the trend of water level and discharge at Yichang station, the changes trends were with perfect synchronization before 1980 and got out of sync after 1980. Though the trend of water level and discharge at Hankou and Datong stations were well fitted, the increase rate of discharge during January was greater than that of water level, and the decrease rate of water level in October was greater than that of discharge from 1981 to 2018.

3.3.3. Relationship between water level and discharge

Fig. 14 shows the relationships between daily, monthly, and annual water level and discharge at the four hydrological stations. Daily and monthly results showed that the water level and discharge began to reach a median after 2003; the higher value significantly decreased and the lower value significantly increased.

The monthly water level and discharge data were divided into periods before and after 2003. Compared to the period before 2003, the water level at 95% quantile decreased by 0.82 m on average at the four stations, increased by 0.90 m at the 5% quantile, and the data range narrowed to 78.25% during the period 2003–2018. The range of water level in the midstream narrowed to 76.09% and that in the downstream narrowed to 84.72%. Compared to the period before 2003, the 95% quantile of discharge at the four stations decreased by 3,425.89 m^3/s on average, the 5% quantile increased by 2443.63 m^3/s, and the data range narrowed to 69.29% during the period 2003–2018. The range of discharge in the midstream narrowed to 67.31% and that in the downstream narrowed to 73.23%.

Given the relationship between water level and discharge, it can be seen that the water level under the same discharge at Luoshan station increased after 1981 compared to the period before 1980 (Fig. 14 (a)). This was mainly because the increase in the water level during January-April was more than the decrease during July-November, leading to the increase in the annual average water level, while the average annual discharge decreased. It can be seen that the relationships between water level and discharge at the other stations during different periods were relatively stable.

Results showed that the monthly precipitation in upstream, midstream, and downstream did not significantly change during most of the months, while the water level and discharge significantly changed. This was consistent with the results over the Changjiang River Basin showing that precipitation has remained virtually unchanged over the period of record (1955–2014) based on data from 91 meteorological stations (Chen et al., 2016). Though precipitation is the main explanatory variable for discharge in the Changjiang River, explaining 89% of the variance in annual discharge (Jing et al., 2014), the hydrology of the Yangtze River is mainly controlled by the TGD and precipitation variability has a limited effect on the discharge (Mei et al., 2015). Meanwhile, because the Gezhouba Dam is a low-head water conservancy project and the reservoir capacity only accounted for approximately 0.36% of the average annual runoff at Yichang station, it has little effect on the discharge. Hence, there was an abrupt change in the water discharge that occurred in 2003 (Chen et al., 2016; Zhao et al., 2015). The effects diminish with distance downstream from the dam (Guo et al., 2012), thus the hydrological characteristics of the Yichang hydrological section, the nearest to the TGD, changed most dramatically.

Results showed that the annual, monthly, daily discharge, water level, and their synchronization and range are all significantly changed at Yichang station. The TGD has a greater impact on the discharge at Yichang station and both the TGD and Gezhouba Dam affected the

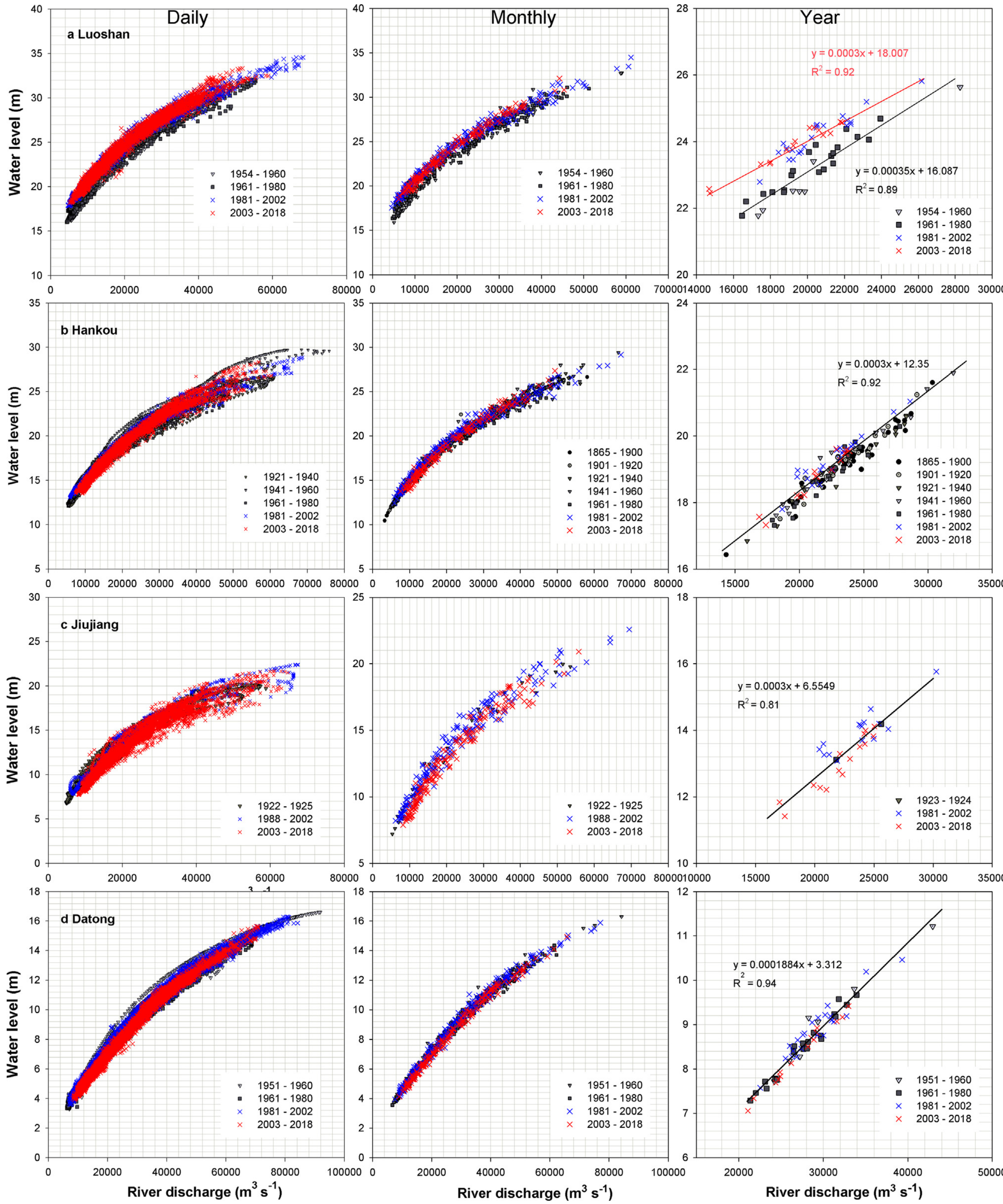

Fig. 14. Relationships between daily, monthly, and annual water level and discharge at the Luoshan, Hankou, Jiujiang, and Datong hydrological stations. (a) Luoshan station. (b) Hankou station. (c) Jiujiang station. (d) Datong station.

water level. The reservoirs exerted more influence on changes in water level than on the discharge of the Changjiang River (Zhang et al., 2006b). The feasibility study of the TGD project from 1986 to 1989 predicted that long-term and long-distance river erosion would occur downstream of the dam, the water level at the same discharge would decrease after construction of the TGD, and the mathematical model predicted that the water level at Yichang station could be reduced by 1.71 m when the erosion and deposition of the river channel were at an equilibrium (CAE, 2010). While the measured data showed that the erosion speed and scope were greater than the original predictions, the dynamic state of the river course has not dramatically changed (CAE, 2010). This was mainly attributed to the reduction in discharge and sediment from upstream, interception and regulation of the TGR, soil and water conservation measures, and artificial sand excavation.

According to measured data at the upstream hydrological station of the TGD, the annual average sediment entering into the TGR during the period 1950–1986 was 493 million tons, 377 million tons during the 1990 s, 190 million tons during the period 2003–2007, and 121 million tons during the period 2008–2018 after the operation of the TGD (CAE, 2010; CWRC, 2018). During the four years (2003–2006) after TGD impoundment, ~60% of the sediment entering the TGR was trapped (Kehui et al., 2009). The annual sediment yield at Yichang station was 502 million tons during the period 1953–1986, 414 million tons during the period 1987–2002, 66.70 million tons during the period 2003–2007, and 20.40 million tons during the period 2008–2018 after the operation of the TGD (CAE, 2010; CWRC, 2018). A significant decreasing trend was detected at the Datong station downstream at a 99% confidence level from 1953 to 2010 (Yang et al., 2007; Zhao et al., 2015). More than 50,000 water reservoirs, together with the Water and Soil Conservation Project (WSCP) in the Changjiang River basin (Kehui et al., 2009; Yang et al., 2011; Zhao et al., 2015), have changed the discharge, water level, and relationship between them.

4. Conclusions

Generally, we obtain hydrological and precipitation characteristics from the historical monitoring data of the river basin, and then serve for the planning and management of the basin. However, under the changing environment, it is urgent to know which characteristics of hydrological and precipitation have changed significantly, and even affect their direct use in river basin guidance. Based on the monitoring data since the establishment of the hydrological stations in the Changjiang River, the changes of hydrological characteristics in a century scale are analyzed.

The water level and discharge time series have significantly changed. The annual discharge decreased with a slight increase in precipitation, while the monthly and daily discharge increased during dry periods and decreased during flood season. The time series trend of water level was the same as that of the discharge change, increasing during the dry season and decreasing during the flood season, but the water level and discharge change rates were different. These leaded to different synchronization between water level and discharge in the upper, middle, and lower streams. Before 1980, the relation between water level and discharge showed perfect synchronization at all stations. After 1980, in the upstream, the water level decreased and the discharge increased during the non-flood season, thus the synchronization was completely destroyed. During the flood season, the water level reduction rate was faster than that of the discharge, and the relation became out of sync. The synchronization in the upper reach of the midstream also became out of sync after 1980. Though the synchronization in the midstream and downstream fitted well, the increase rates during the dry season and decrease rates during the flood season of the discharge and water level were also different.

Compared to the period before the operation of the TGD (before 2003), the higher water level and discharge decreased and the lower increased, which resulted in their ranges narrowing to 78.25% and 70.02% on average during the period 2003–2018, respectively. The 95% quantile of discharge decreased to 87.65% and the 5% quantile increased to 132.12% on average. Compared to the period 1878–2002, the average discharge at Yichang station during the period 2009–2017 decreased by 11.03%, decreasing by 14.41% during the period June-November and increasing by 3.38% during January-May and December. The decrease of 47.95% in the average discharge from 2003 to 2018 was because of water storage in the TGR.

The annual precipitation showed stationarity, which indicated that the future precipitation could be described by the characteristics of the past precipitation. However, the discharge and water level showed obvious non-stationarity (especially after 1970), the relationship between discharge and water level has changed significantly, and the degree of change was different in different regions of the basin. The relationship between precipitation and discharge, water level and discharge in the past are difficult to be directly applied in the current basin, which brings great challenges to flood control, drought resistance, and ecological protection. It is important to examine and explain the alteration, distinguish the positive and negative effects and then put forward reasonable measures and suggestion to avoid additive and cumulative effects and improve the protection of water resources and the ecological environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.104498.

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