Environmental Science and Pollution Research (2021) 28:19851–19865
https://doi.org/10.1007/s11356-020-11756-2

RESEARCH ARTICLE

Effects of hydrological change on the risk of riverine algal blooms: case study in the mid-downstream of the Han River in China

Lisha Shen [1,2] · Ming Dou [1,2] · Rui Xia [3] · Guiqiu Li [1,2] · Baiheng Yang [1,2]

Received: 10 July 2020 / Accepted: 18 November 2020 / Published online: 6 January 2021

Abstract
Algal blooms usually occur in semi-closed water bodies such as lakes or estuaries; however, it has occurred frequently in the mid-downstream of the Han River (MSHR) in China since the 1990s. We made a comparative analysis of the hydrological conditions and identified the hydrological condition thresholds that induce algal blooms. From the hydrodynamic point of view, the changes and characteristics of the hydrological conditions in the MSHR were analyzed. Furthermore, the influence on the risk of algal blooms under different design water transfer schemes for the middle route of the South-to-North Water Diversion Project (SNWDP) was studied. The results indicated that (1) the flow in the MSHR less than 900 m^3/s and water level in the Yangtze River higher than 14 m provided a suitable hydrological environment for diatoms multiply. (2) The flow of the MSHR showed a downtrend, while the water level of the Yangtze River showed an uptrend. There were variations in hydrological processes. Through specific IHA index analysis, the fact of flow reduction in the MSHR was demonstrated, and further indicated that algal bloom outbreak was in low flow period. (3) The water transfer in the middle route of SNWDP affected the risk probability of algal blooms. The more the amount of water transfer, the greater the risk probability of algal blooms. It was the Water Diversion Project from Yangtze River to Han River (WDPYHR) that replenished flow of the MSHR and was conducive to the prevention and control of algal bloom risk.

Keywords River algal blooms · Hydrological inducement of bloom outbreak · The limiting thresholds of hydrological factors · Hydrological condition change · Hydrological condition characteristics · Risk of river algal blooms

Introduction

As an important manifestation of water eutrophication, algal blooms are a natural phenomenon wherein algae propagate, grow, and accumulate in freshwaters such as rivers, lakes, and reservoirs (Yang et al. 2012). Algal blooms usually occur in lakes, reservoirs, and other water with low flow (Zhang et al. 2019; Palagama et al. 2020; Zou et al. 2020). Large-scale algal blooms have occurred in Taihu Lake (Zhang et al. 2019), Dianchi Lake (Zhang et al. 2020), and Florida Lakes (Havens et al. 2019) in the USA, as well as in The Three Gorges Reservoir (Chuo et al. 2019) and Miyun Reservoir (Li et al. 2020) in China, which have caused serious impacts on water quality. However, in recent years, algal blooms have frequently appeared in rivers, such as the Nakdong River in Korea (Jeong et al. 2007), the Thames River in the UK (Bowes et al. 2012), the St. Lawrence River in Canada (Cattaneo et al. 2013), and the Han River (Yang et al. 2017), Xiangxi River (Li et al. 2014), Daning River, and Jialing River in China (Holbach et al. 2013; Kaspersen et al. 2016). Considerable research has claimed that the accumulation of nutrients in water promotes algal growth and reproduction. Conversely, nutrient concentrations exceeding a threshold value will inhibit algal growth (Elmgren and Larsson 2001; Finlay et al. 2013). Jung et al. (2009) studied the influencing factors of diatom blooms in the lower Han River in South Korea and found that the growth of diatoms in eutrophic rivers was mainly limited by water temperature and

Responsible Editor: Vitor Manuel Oliveira Vasconcelos

✉ Ming Dou
douming@zzu.edu.cn

1 School of Water Conservancy Science and Engineering, Zhengzhou University, Zhengzhou 450001, China

2 School of Ecology and Environment, Zhengzhou University, Zhengzhou 450001, China

3 State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China

silicate concentration. When the water temperature is low (5 ~ 10 °C), the diatom density reaches its peak, resulting in the decrease of the silicate concentration in the water while other nutrients remain at the eutrophication level. Compared with the blooms in closed water areas, the problem of river algal blooms mainly lies in the multiple influencing factors and scales under complex conditions, which have more extensive impacts and more severe consequences (Xia et al. 2019). Kiss (1994), Hilton et al. (2006), and Bowes et al. (2012) analyzed the Danube River in Hungary and Kennet River in Australia and found that the relationship between nitrogen, phosphorus, and other nutrients in the water and chlorophyll-*a* concentration of algae was not unique, but showed different correlation characteristics under different hydrological conditions. Due to the unique hydrologic environment and regional particularity of different rivers, the effect and mechanism of algal growth are more complicated. The occurrence of river blooms is not only restricted by nutrient and climatic conditions, but also significantly influenced by hydrological situation (Whitehead et al. 2009). Experiments (Lucas et al. 2009; McKiver et al. 2009) have shown that algae growth had a strong response to changes in hydrological conditions, and flow affected the spatial and temporal distribution of algae. Slow hydrology (low water level, low flow rate, slow flow rate) will reduce water exchange rate and prolong the residence time of algae in the river, thus affecting the migration, diffusion, and accumulation of algae (Neal et al. 2006). The anthropogenic regulation of rivers, such as dam construction and water extraction, can greatly change the hydrological conditions in the rivers, causing severe environmental loss of river connectivity (Zhou et al. 2013; Maavara et al. 2015). With the development of water conservancy projects, the construction of dams made the trend to "lake and reservoir" of rivers obvious, resulting in the consequences of slower flow velocity and decreased river runoff, as well as reduction of self-purification capacity. Consequently, hydrodynamic conditions in the impoundment area and the backwater area of tributaries become a crucial driving factor for algal blooms. Fornarelli et al. (2011) demonstrated that there was a significant correlation between the number of diatom cells and the water transfer in the upstream reservoir of Yarrunga Lake in Australia through the observation of long sequence data. For hydrological condition influence on river algal blooms, the algal density of *Stephanodiscus hantzschii* and *Microcystis aeruginosa* was correlated with precipitation and dam flow by cross-correlation analysis (Jeong et al. 2007). The results indicated that river algal blooms were related to precipitation and dam flow. Yang et al. (2017) confirmed that when the nutrient concentration in the Pearl River tended to be stable, the key factors controlling the growth and population composition of the downstream algae were the fluctuation of water level in the upstream and downstream. It is generally believed that the occurrence of algal blooms is attributed to low flow or water level, high nutrient concentrations, and appropriate temperature. There is currently no authoritative standard and definition of thresholds for river algal blooms, and research on river algal blooms under the influence of large water conservancy projects is extremely limited.

As the largest tributary of China's Yangtze River, the Han River is the core water source of the middle route of the SNWDP. Since the first algal bloom event appeared in 1992, there have been over 10 occurrences in less than 30 years. All these bloom events have had negative impacts on river ecosystem health and drinking water safety (Pretty et al. 2003; Dodds et al. 2009). When the blooms broke out, the water was cloudy and emitted foul odor, which seriously affected the ecological landscape function of the river. The nutrient (total nitrogen (TN) and total phosphorus (TP)) concentrations in the mid-downstream of the Han River in the spring were usually far above the eutrophication thresholds (i.e., TN = 0.2 mg/L, TP = 0.02 mg/L) as per China's National Water Quality Standard (GB3838-2002), and showed an increasing trend (Liang et al. 2012). In the years of blooms, the flow, water level, and flow velocity of mid-downstream were generally lower than those of the same period without bloom years. Bloom outbreaks have been common in relatively stationary bodies, but large river algal blooms were extremely rare all over the world (Xia and Zhang 2008; Xia et al. 2012). By the end of 2014, after the middle route of SNWDP was officially put into operation, the water transfer of the Danjiangkou Reservoir had a tremendous impact on flow changes. Yang et al. (2012) found that water quality factors and climate factors were not the key factors that restricted the occurrence of algal blooms in the Han River, but hydrological factors, such as flow and flow rate under the influence of water transfer projects, were the driving ones. It is urgent to identify the elements affecting the algal blooms in the MSHR, and how to maintain the ecological environment and water resources management in the future.

Our research analyzed the inherent relationships between hydrological regime change and algal blooms in the MSHR and identified the threshold range of hydrological driving factors that were easy to induce the algal blooms. In addition, the change process of the hydrological regime in the MSHR and the flow characteristics during were analyzed. Finally, we studied the actual inflow of the MSHR and the impact of different design water transfer schemes for the middle route of the SNWDP on the algal blooms. Our study aims to developed reference values for the middle route of SNWDP's operation and dispatchment and water environment protection of the MSHR.

Study area

As the largest tributary of the Yangtze River, the Han River originates in the southern foothills of the Qinling mountains, and main stream flows through Shaanxi and Hubei provinces, and finally runs into the Yangtze River in Wuhan City. The length of the main river is about 1577 km, and its total drainage area covers 168,400 km^2 (Xia et al. 2020a, b). The middle stream of the Han River is defined from Danjiangkou Reservoir to Zhongxiang (270 km) and the downstream is defined from Zhongxiang to the mouth of the Han River (406 km) where it joins the Yangtze River (Fig. 1). The total drainage area of the mid-downstream of the Han River is 64,000 km^2, with an elevation from 500 m at Danjiangkou Reservoir to 110 m at Wuhan City (Li et al. 2008). The Han River basin is located in the subtropical monsoon climate distribution area, with distinct seasons and abundant rainfall. The perennial average temperature is 15-17 °C. Annual precipitations range from 700 to 1300 mm from the middle stream to the downstream of the Han River, and 80% of precipitation concentrates in the period from May to October. The Danjiangkou Reservoir, located in the middle reaches of the Han River, is the core source of water for the middle route of SNWDP in China. The lower reaches have high population density and rich land resources. Downstream flows through areas with high population density and rapid industrial development, and the Jianghan Plain is an important commodity grain base and the core industrial base of economic development in Hubei Province. In the past two decades, the rapid development of agriculture and social economy has resulted in the discharge of organic pollutants and nutrients, which has increased the pollution load of the mid-downstream of the Han River, resulting in deterioration of the water environment. There are frequent algal blooms in the middle and lower reaches. During the algal bloom period, the algal density increased gradually from the Danjiangkou Reservoir to the Yangtze River estuary.

Because of the unique hydrologic environment and regional particularity of the river, the formation mechanism and influence of the blooms are more complicated. In our study, we mainly focus on the effect of hydrological regime changes on the algal blooms in the mid-downstream of the Han River. The hydrological data of Huangzhuang station, Xiantao station, and Hankou station respectively represent the hydrological conditions of the middle reaches of the Han River, and the lower reaches of the Han River and the Yangtze River. The hydrological data (flow and water level) in the study were from the Yangtze River Hydrology Bureau, and the data series was from the years 1971 to 2017. In addition, the 10-day water quality data and water temperature data involved in the study were obtained from Zongguan station and Baihezui station,

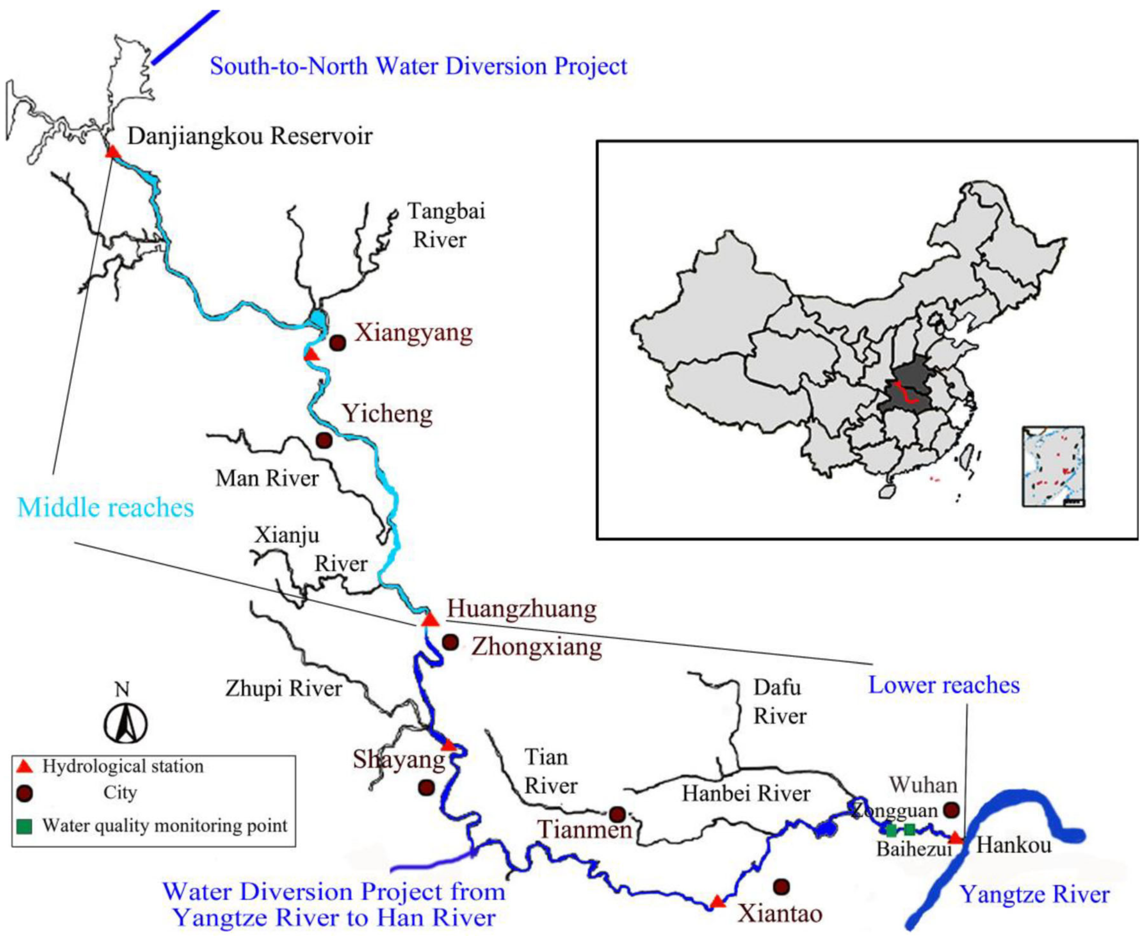

Fig. 1 Distribution of water system and main hydrological and water quality monitoring stations in the mid-downstream of the Han River

representative stations of water quality monitoring in the lower reaches of the Han River, and the data sequence was from the years 1992 to 2014. For the flow sequence of Xiantao station under different design water transfer schemes for the middle route of the SNWDP, based on the 10-day scale flow data of Danjiangkou Reservoir of the years 1956 to 2013 provided by Department of Yangtze River Water Resources Commission, we established the regression relationship between the released flow from Danjiangkou Reservoir and the flow of the Xiantao station to calculate the flow of Xiantao station under the design water transfer schemes. To meet the research needs, the data sequence was extended to the year of 2017 through interpolation.

Methods

The main research ideas of this paper are as follows: First, summarize and analyze the previous bloom events in the mid-downstream of the Han River, qualitatively identify the key hydrological elements that induce the blooms in combination with existing studies, and divide the numerical interval of key hydrological elements with different degrees of algal blooms. Secondly, the hydrological variables of Huangzhuang station, Xiantao station, and Hankou station were analyzed to identify the hydrological variation points on different scales by the hydrological variation diagnosis. After comprehensive consideration of various influencing factors, different periods of hydrological situation were divided. Then, based on the IHA method, the hydrologic indexes of the mid-downstream of the Han River were selected to analyze and compare the hydrologic regime characteristics of different periods. Finally, according to different design water transfer schemes of SNWDP, copula joint probability distribution function for hydrological regimes of the Han River and the Yangtze River in different hydrological conditions was built to quantify the algal bloom risk under actual inflow situation and different water transfer schemes. The research framework was shown in Fig. 2.

Hydrological alteration diagnosis

In the long-term development process, with the change of climate conditions, human activities, and the construction of large-scale water conservancy projects, the hydrological regime may have changed. The hydrological alteration diagnosis (HAD) (Xie et al. 2010) can identify variation point of hydrological variables. We complete the analysis of hydrologic alteration through the following three steps:

(1) Preliminary diagnosis. The process line method, the sliding average method, and the Hurst coefficient method were considered to determine whether the series exhibits alteration.

(2) Detailed diagnosis. The Spearman rank correlation test method and the Kendall rank correlation test method were chosen to identify trends in alteration. Four methods were selected to identify jump diagnosis, and statistical experiments and vector similarity principles were utilized to determine the weight of each method (Table A.1 in the Supplementary information). If the significant alteration is determined, the significance is recorded as + 1; otherwise, it is − 1.

(3) Comprehensive diagnosis. If the comprehensive significance value is > 1, the alteration is determined significant.

The indicator of hydrologic alteration

The HAD can only judge the change trend and time of the flow process over a long time. However, it cannot analyze the flow of specific characteristics. The indicator of hydrologic alteration (IHA) (Richter et al. 1998) is an effective method to evaluate river hydrological and ecological variation; currently, it has been successfully applied to evaluate hydrological alterations in a suite of watersheds located in arid, semi-arid, and humid regions (Belmar et al. 2013; Puig et al. 2016). Therefore, with the help of the IHA method, we further explored the hydrological and ecological conditions in the MSHR. Considering that growth and reproduction of algae are faster under low flow conditions, and algae are more easily to agglomerate under the condition of low flow rate, 18 hydrological indicators, including the mean flow of each calendar month, 1-day minimum, 3-day minimum, 7-day minimum, date of minimum, low pulse count, and low pulse duration, were selected to analyze the characteristics of hydrological driving factors in algae growth and propagation.

The risk probability analysis for algal blooms

Copula function does not limit the marginal distribution of variables and can describe the non-linear and asymmetric correlation between variables (Schweizer 2007), so it is an excellent tool to analyze multivariate probability problems. In this study, the copula joint probability distribution function was constructed for the flow of the Xiantao station and the water level of Hankou station to calculate the joint probability. Combining with the threshold value of hydrological conditions under different degrees of bloom risk, the hydrological encounter probability was classified into different levels of algal bloom risk.

The marginal distribution of n-dimensional random variables $(X_1, X_2, \ldots, X_N)$ is $F_{X_i}(x) = P_{X_i}(X_i \leq x_i)$, in which

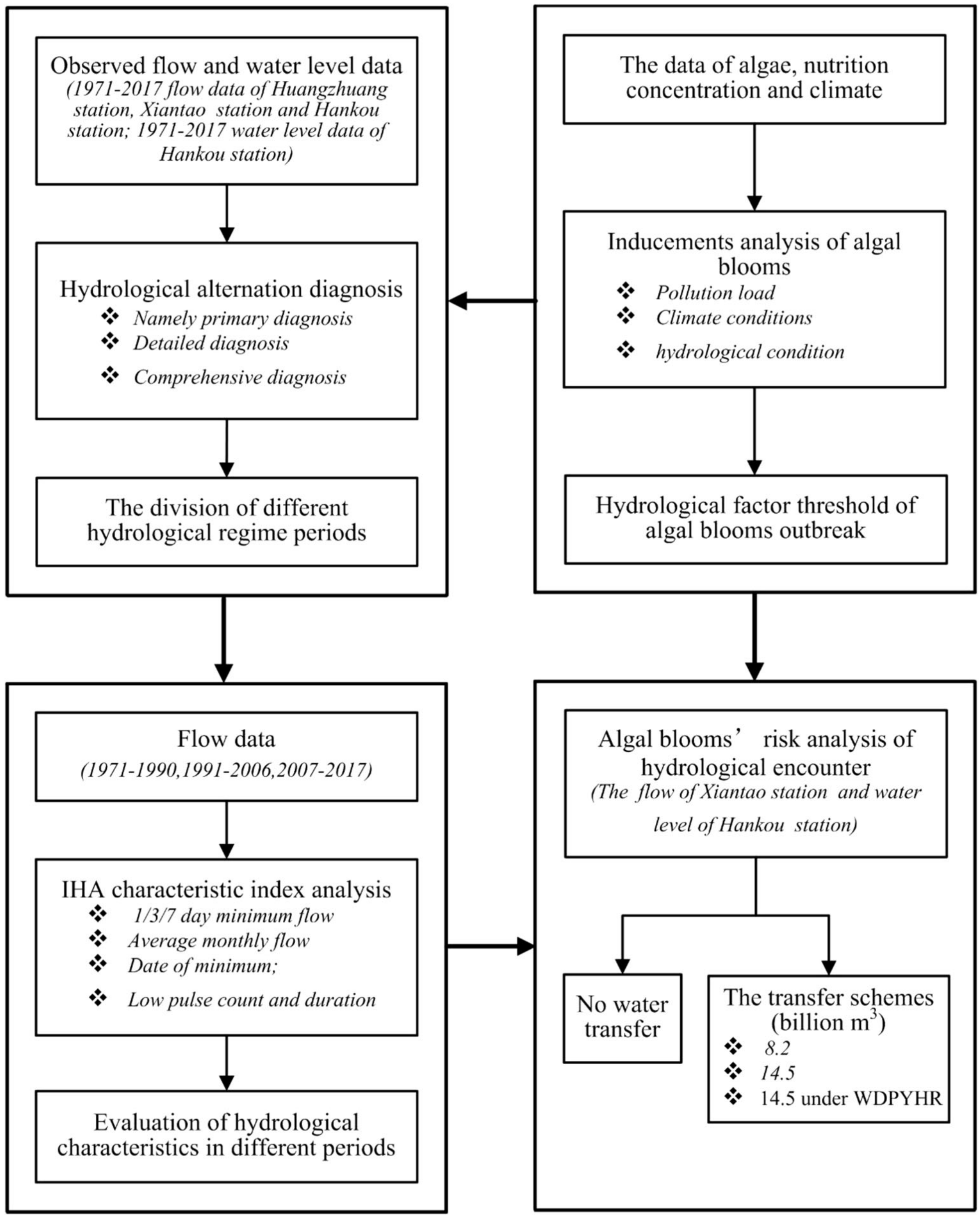

Fig. 2 Research framework

N represents the number of random variables and X_i represents the value of the random variable $(X_1, X_2, \ldots, X_N)$. The function is expressed as follow:

$$H_{X_1,X_2,\ldots,X_N}(X_1, X_2, \ldots, X_N) = P\{X_1 \le x_1, X_2 \le x_2, \ldots, X_N \le x_N\} \quad (1)$$

The multivariate joint distribution function H can be expressed as:

$$H_{X_1,\ldots,X_N}(x_1, x_2, \ldots, x_N) = C(F_{X_1}(x_1), F_{X_2}(x_2), \ldots, F_{X_N}(x_N)) \quad (2)$$

where $C(\bullet)$ represents the copula joint probability distribution function of random variables $(X_1, X_2, \ldots, X_N)$, which corresponds to marginal distribution $F_{X_1}(X_1), F_{X_2}(X_2), \ldots, F_{X_N}(X_N)$.

The construction of the copula function mainly includes the fitting of marginal distribution and the determination of unknown parameters of the copula function. In this paper, the marginal distribution function selected for flow and water level was kernel density estimation, whose mathematical expression is as follows:

$$f_n(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - X_i}{h}\right) \quad (3)$$

where $K(\bullet)$ is the kernel function; h is the window width.

In hydrological research, meta-Gaussian copula, Clayton copula, Gumbel copula, and Frank copula are widely used (Table A.2 in the Supplementary information). In our research, these 4 types of copula function were selected. The unknown parameters of the meta-Gaussian copula function are determined by the maximum likelihood method.

For the goodness of fit evaluation of copula function, ordinary least squares (OLS) (Simo 2010) and Akaike's information criterion (AIC) (Pei et al. 2019) were used. The construction of copula function systematically quantifies the risk probability of different degrees of algal blooms under different water transfer schemes.

Results

Inducement analysis of algal blooms in the MSHR

River algal blooms are closely related to climate, hydrology, and the composition and distribution of nutrients in rivers. At present, a recognized standard and definition of algal blooms threshold has not been developed (Xia et al. 2012; Zhang et al. 2017). In most studies, 1.0×10^7 cells/L was considered the critical value for the occurrence of river algal blooms. According to our analysis of the monitoring results, it was also preliminarily confirmed that when the algal cell density reached 1.0×10^7 cells/L, algal blooms were more likely to appear.

Based on the summary of the main features of all the algal bloom events in the MSHR, it was found that the occurrence time of algal blooms was concentrated from January to March (we called the prone period of algal blooms PPAB). When algal blooms occurred, the total nitrogen (TN) density was over 1.0 mg/L; total phosphorus (TP) density usually was above 0.1 mg/L (Table 1). Both TN and TP were higher than the critical eutrophication thresholds of 0.2 mg/L for TN and 0.02 mg/L for TP. Xin et al. (2020) showed that TN and TP in the Wuhan section of the Han River have reached the medium eutrophication level, and the water has the conditions for algae to grow and reproduce. This means that the occurrence of algal blooms is not limited by nutrient conditions. For the water temperature of algal growth and reproduction, previous studies (Zheng et al. 2017) have shown that diatom reproduction would be active above 9 °C, and 10-17 °C was the optimum range. In the PPAB, the temperature was about 10 °C, meeting the needs of diatom growth and reproduction, indicating that algal blooms were not limited by temperature.

As there is no limitation of nutrients and water temperature of the Han River, hydrological conditions are the more prominent function. Early studies indicated that during the algal blooms, the hydrological conditions of the Han River and the Yangtze River showed differences (Dou et al. 2002). Under the joint action of the reduction for flow in the MSHR and increasing water level in the Yangtze River, the flow rate of the MSHR slowed down. The capacity of receiving pollution and self-purification was reduced and the flow dilution of the water body weakened, resulting in the accumulation of nutrients, which provided a suitable environment for the growth and reproduction of phytoplankton. Wu et al. (2017) found that from November to the following March, the flow of the mainstream and the water level was reduced, and the cross section velocity was low, which were the factors for the occurrence of algal blooms. In our study, the average flow and water level in the years with algal blooms and the years without algal blooms in the PPAB were analyzed. It also showed the flow of the MSHR in the years with algal blooms was less than that of the years without algal blooms (Fig. 3(a)). The difference of mean value was 303 m^3/s, while the water level was slightly higher about 0.5 m. Therefore, hydrological factors were one of the key factors to induce algal blooms. During the PPAB, the lower flow of the MSHR and higher water level of the Yangtze River were the hydrological conditions that promoted algal blooms.

Our study found that the flow of less than 900 m^3/s and water level higher than 14 m provided a suitable hydrological environment for algae reproduction (Fig. 3(b)). Further study found that there were no blooms when the water level of the Yangtze River was less than 14 m or more than 18 m. Considered comprehensively, when the flow was over 900 m^3/s, and the water level was more than 18 m or less than 14 m, it could be regarded as a risk-free range. When the flow was 600 ~ 900 m^3/s, and the water level was 14 ~ 15 m, there was a light risk. When the flow was 400 ~ 600 m^3/s and the water level was 15 ~ 16 m, there existed a moderate risk. If the flow was less than 400 m^3/s, and the water level was 16 ~ 18 m, it was considered a heavy risk.

Identification of hydrological variation in the MSHR

In our research, the variation of hydrological series was identified synthetically in the PPAB, wet season, and annual series of flow in the Han River and flow and water level in the Yangtze River. Based on the analysis of hydrological processes in different scales, our research focused on the changes in hydrological processes in the PPAB.

In the PPAB (Fig. 4), the change of flow in the Huangzhuang and Xiantao stations was synchronous. The flow process fluctuated around the multi-year average flow. Both the 5-year sliding average and 10-year sliding average showed downtrend. The flow of Hankou station was abnormally large in the year of 2000. Not taking into account the extreme flow conditions in 2000, there is no significant change in the flow process. Both the 5-year sliding average and 10-year sliding average showed slight uptrend. The 5-year

Table 1 Summary of main characteristics of algal bloom events

Years	Months	Peak algal density (10^6 cell/L)	Dominant species	Chl-*a* (ug/L)	TP/TN (mg/L)	Temperature (°C)
1992	2-3	16	Diatom	12.82	0.09/1.22	10.0
1998	2-3	26	Diatom	——	0.2/1.65	11.4
2000	2-3	73	Diatom	——	0.13/1.35	11
2003	1-3	17	Diatom	33.97	0.18/2.08	13.5
2008	2-3	53	Diatom	30.93	0.16/2.02	9.09
2009	1-4	28	Diatom	67.83	0.12/1.85	8.76
2010	2-3	22	Diatom	29.00	0.11/1.84	9.80
2011	2-3	38	Diatom	35.33	0.17/2.20	11.66
2015	2-3	45	Diatom	——	0.07/1.28	11.05
2016	3	34	Diatom	70.6	0.1/1.38	13.27
2018	2-3	32	Diatom	——	0.06/1.70	11.96

sliding average and 10-year sliding average of water level in the Hankou station had an obvious uptrend. The preliminary diagnosis of the flow and water level in the PPAB showed that the flow in the three representative stations and the water level in the Hankou station may have trend or jump variation. For the wet season and annual series, the results also showed so.

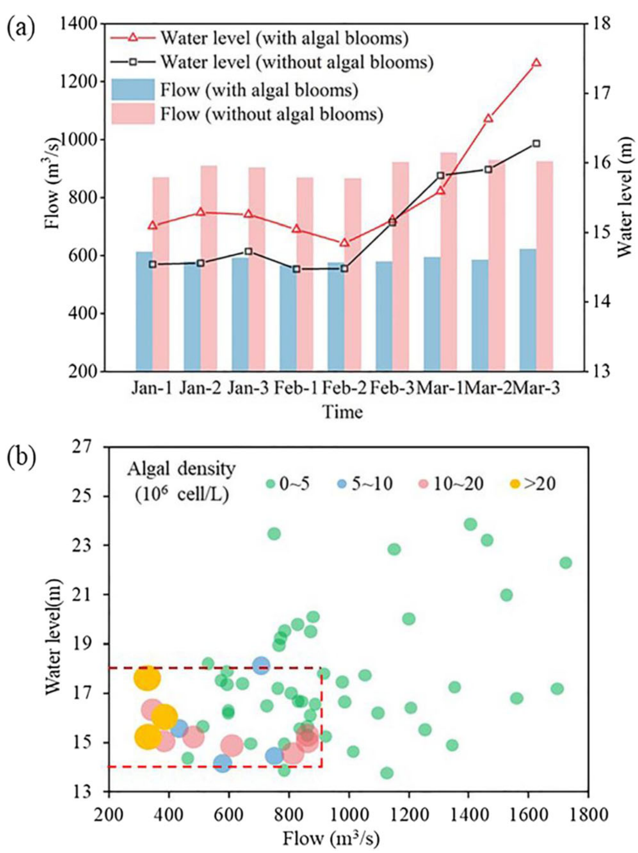

Fig. 3 The relationship between the hydrological conditions and algal density in the PPAB. **a** Average flow of the Xiantao station and water level of the Hankou station for the years with algal blooms and the years without algal blooms. **b** Relationship between flow, water level, and algal density

The detailed diagnosis showed that the results of different methods were not identical (Table A.3 in the Supplementary information). It was difficult to determine the specific years of the variation point and variation trend. Based on the comprehensive diagnosis of hydrological sequence variation, the possible variation points of the MSHR the Yangtze River were shown in Table 2. According to relevant research (Ban et al. 2018), the annual runoff depth in the upper reaches of the Han River changed in 1990 and 2012, and the slope of the double mass curve of rainfall and runoff in the upper reaches and the whole basin began to have an obvious downward trend after 1990. Through the analysis of hydrological characteristics in the lower reaches of the Han River, Xia et al. (2020a, b) found that the runoff process of the lower reaches of the Han River changed significantly around 1990 and 2009, and the downstream flow showed a significant downward trend after 1990. Besides, the variation point of the water level of the Yangtze River in wet season and the PPAB was 2006. In May 2006, the Three Gorges Dam (the largest concrete gravity dam in the world) on the Yangtze River was completed. The operation of the Three Gorges Project in the later period had been influencing the hydrological regime of the Yangtze River. Considering that the low flow in the Han River and the high water level in the Yangtze River were favorable hydrological condition for algal bloom outbreak, the year 2006 was taken as the second variation point. The hydrological time series was divided into 3 different hydrological situation periods, which were period I (1971-1990), period II (1991-2006), and period III (2007-2017).

The flow characteristics under different hydrological conditions

By the IHA method, it was found that compared with period I, the monthly average flow in periods II and III decreased. The variation of monthly average flow in different periods further confirmed the decreasing trend of flow (Fig. 5). On the one

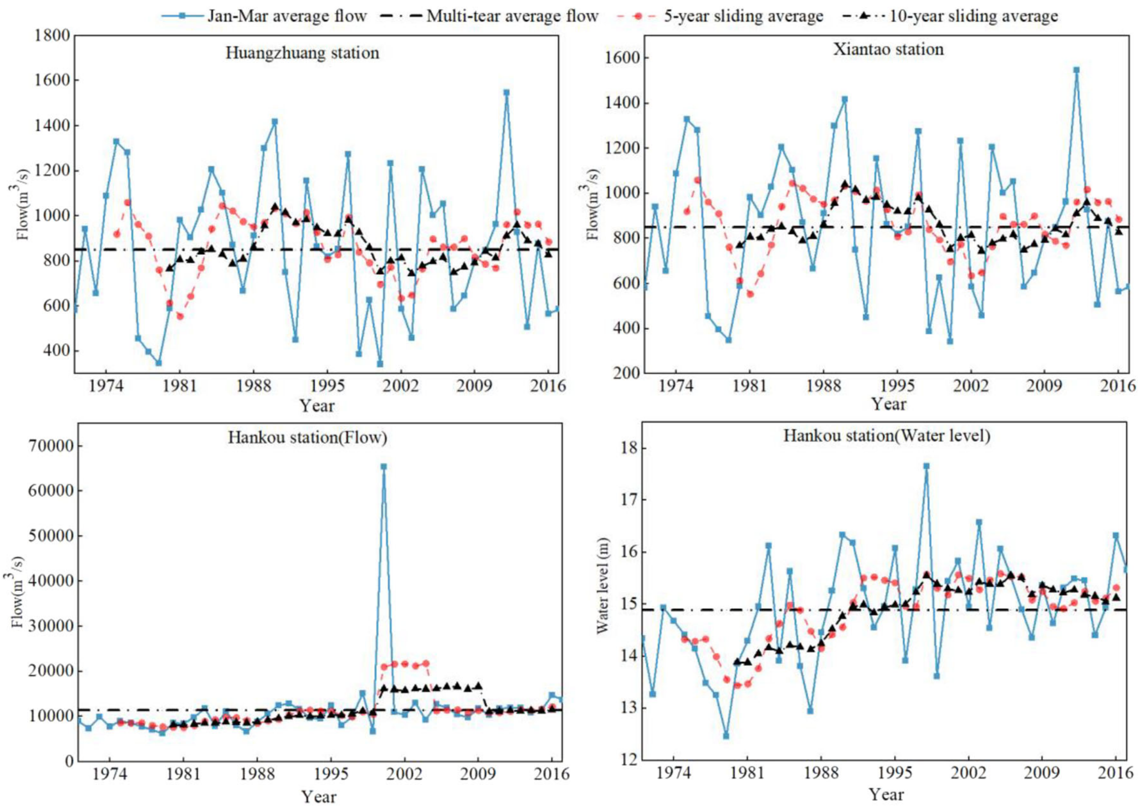

Fig. 4 The results of the preliminary diagnosis

hand, the reduction of flow in the MSHR is caused by the decrease of natural runoff. On the other hand, it is influenced by human activities. The initial project of the Danjiangkou water control project on the upper reaches of the Han River was completed in 1974. In 2005, the SNWDP was started to construct, and the Danjiangkou dam was upgraded. The project was fully completed on April 19, 2012, which means that the retention capacity of the Danjiangkou Reservoir was further improved. On December 12, 2014, the middle route of the SNWDP was officially opened to supply water, further reducing the flow of the MSHR.

The minimum 1-day, 3-day, and 7-day flow decreased from periods I to II, then increased from periods II to III (Fig. 6(a)-(c)). The minimum flow occurred mainly in January to April (Fig. 6(d)). The occurrence time of algal blooms coincided with that of the minimum flow, which indicated that the algal blooms occurred in a low-flow hydrological condition. The low pulse count increased, while the low pulse duration gradually decreased (Fig. 6(e)-(f)). The operation of Danjiangkou Reservoir and the water supply in the middle route of the SNWDP have effect on the flow of the MSHR.

Risk analysis of algal blooms under different hydrological conditions

According to the principle of the optimum fitting, the best fitting function types of the actual inflow and different design water transfer schemes of the middle route of SNWDP were shown in Table 3. The theoretical distribution has a good fit

Table 2 Comprehensive diagnosis results of different stations

Stations	Comprehensive diagnosis of jumping year			Trend comprehensive significance			Jump comprehensive significance		
	Y	W	P	Y	W	P	Y	W	P
Huangzhuang	1990	1990	——	2	2	− 2	0	2	2
Xiantao	1990	1990	2013	0	− 2	− 2	2	2	− 4
Hankou (flow)	——	——	1999	− 2	− 2	2	− 2	− 1	− 2
Hankou (water level)	1979	2006	2006	− 2	− 2	2	2	4	− 2

Y means year; *W* means wet season; *P* means the prone period of algal bloom

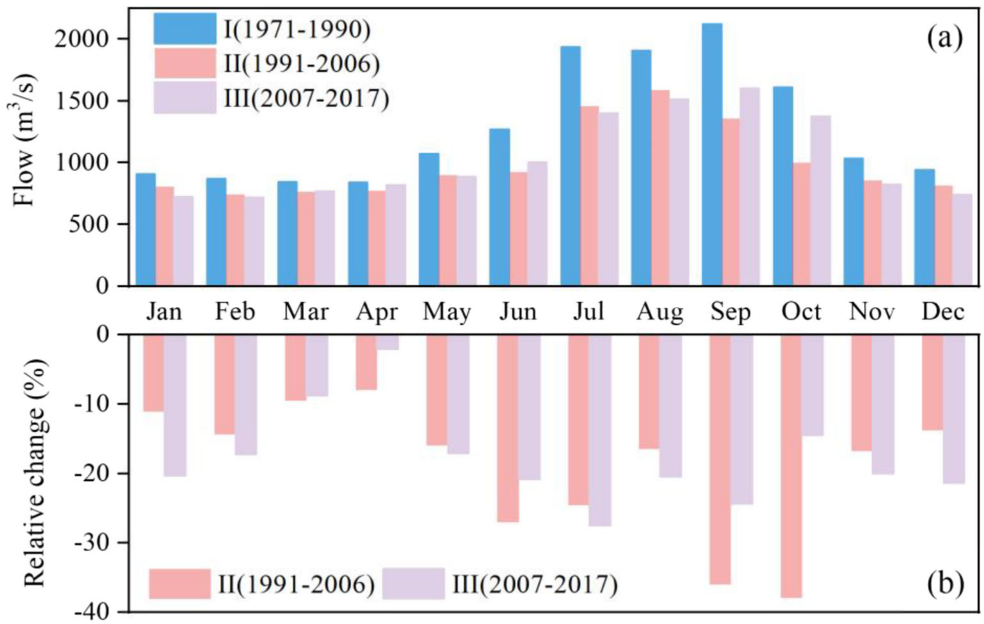

Fig. 5 Monthly average flow and change rate. **a** Monthly average flow in different periods. **b** Change rate of monthly average vagrancy in periods II to III compared with period I

for the empirical distribution (Fig. A.1 and Fig. A.2 in the Supplementary information).

In the case of actual inflow, the risk probability of algal blooms gradually increased. The total risk probability in 3 periods was 13.64%, 16.02%, and 20.09%, respectively (Fig. 7). For different degrees of algal bloom risk probability, the light risk probability was the largest, the moderate risk probability followed, and the heavy risk probability was the smallest. The light risk probability accounted for about 63% of the total risk probability, the moderate risk probability accounted for about 31%, and the heavy risk probability accounted for about 6%. Although the heavy risk probability was low, it increased rapidly, so the occurrence of heavy risk cannot be ignored. In addition, the occurrence of heavy risk will bring more severe impacts on river water quality, livelihood, and economy of coastal residents. The results showed that the risk probability of algal blooms increased as time went on, and the influence of algal blooms became more and more serious.

There are differences in the risk probability of algal blooms under different design water transfer schemes. The risk probability of algal blooms under the design scheme of 14.5 billion m^3 (scheme 2) was highest, followed by design scheme of 8.2 billion m^3 (scheme 1), and the design scheme of 14.5 billion m^3 water transfer under WDPYHR (scheme 3) was the smallest. The greater the amount of water transfer, the higher

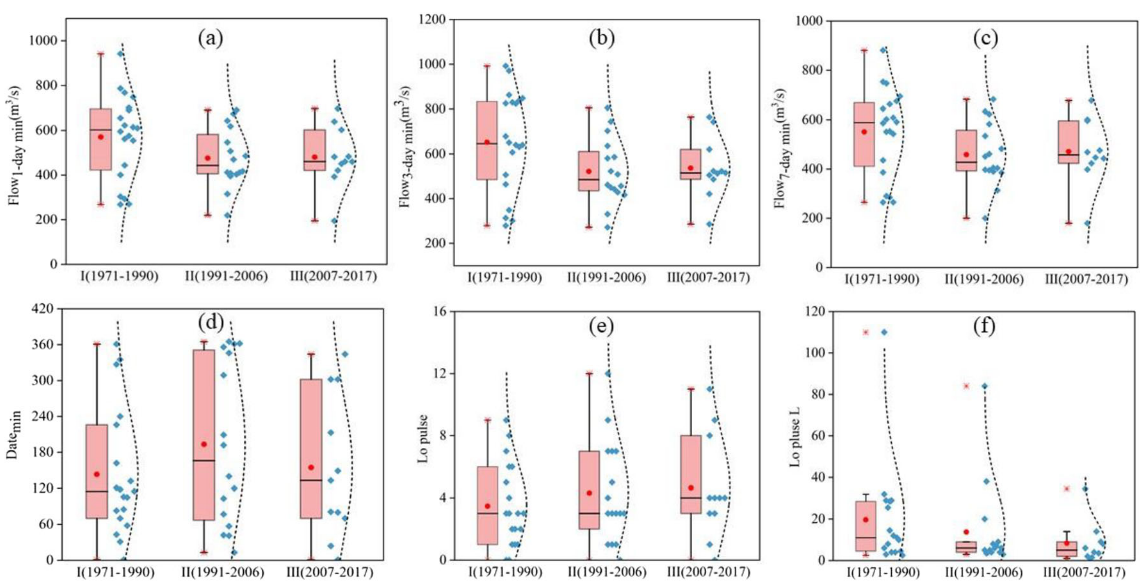

Fig. 6 The results of related IHA indicators. **a**-**c** The minimum 1-day, 3-day, and 7-day flow in different periods. **d** Time distribution of the minimum flow in different periods. **e** Low pulse count in different periods. **f** Low pulse flow duration in different periods

Table 3 The best copula function types of actual inflow and different design water transfer schemes in different periods

Schemes	Period I (1971-1990)	Period II (1991-2006)	Period III (2007-2017)
Actual inflow	Clayton copula	Gaussian copula	Clayton copula
Scheme 1	Gumbel copula	Frank copula	Gumbel copula
Scheme 2	Frank copula	Clayton copula	Frank copula
Scheme 3	Frank copula	Gumbel copula	Clayton copula

Scheme 1 means the design scheme of 8.2 billion m^3; scheme 2 means the design scheme of 14.5 billion m^3; scheme 3 means the design scheme of 14.5 billion m^3 water transfer under WDPYHR

the risk probability of algal blooms. The algal bloom risk probability of three different design water transfer schemes from periods I to III all had varying degrees of increase (Fig. 8). Scheme 2 had the largest increase, which was about 6%. The increase in scheme 1 was about 4% and that in scheme 3 was about 3%. The analysis of the flow process in the MSHR showed that the flow had a downtrend in the PPAB. The flow reduced from periods I to III, and the risk probability of algal blooms continued to increase, which further showed that the low flow provided favorable hydrological conditions for diatom. For the different degrees risk of algal blooms, the probability of light risk was the highest, followed by moderate risk, and the probability of heavy risk was the smallest.

The contribution rate (CR) refers to the ratio of the number of effective or useful achievements to the consumption and occupation of resources, that is, the ratio of output to input. We used CR to characterize the discrepancies of risk probability between different designed water transfer schemes and the actual situation of water inflow. The expression is as follows:

$$\gamma = \frac{(C_r - C_\omega)}{C_\omega} \times 100\% \tag{4}$$

where γ represents the CR; C_r is the algal bloom risk probability of the design water transfer schemes, and C_ω is the risk probability of the actual inflow.

There were significant differences in CR of risk probability of algal blooms under different design water transfer schemes. The CR of total risk probability and different degree risk probability in scheme 1 and scheme 2 were positive, while in scheme 3, it was negative (Fig. 9). Scheme 1 and scheme 2 would increase algal blooms in the MSHR, but scheme 3 alleviated algal bloom risk probability.

The CR for dissimilar degrees of risk probability was different. For scheme 1, the CR of total risk probability and light risk probability in 3 periods were about 35.5% and 25.5%, and the CR of moderate risk probability and the heavy risk probability were both high. For scheme 2, the CR of total risk probability in 3 periods was about 63%. The low risk probability was over 85% in period II, and the moderate risk probability exceeded 85% in period I. For the CR of heavy risk probability, it was all over 100% in the three periods, even reached to 166.3% in period II and more than 390% in period III. The heavy risk probability increased sharply during period II. The CR under total risk probability, light risk probability, and moderate risk

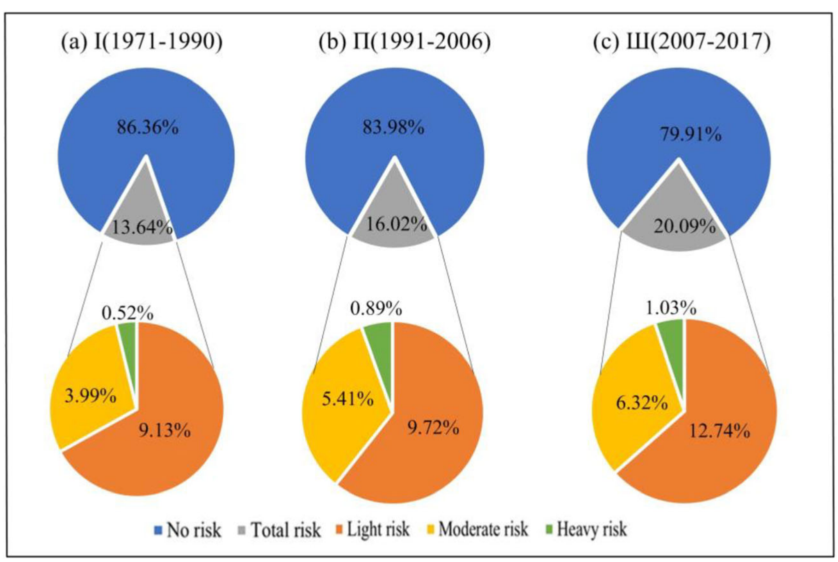

Fig. 7 Risk probability of algal blooms in different periods of actual inflow

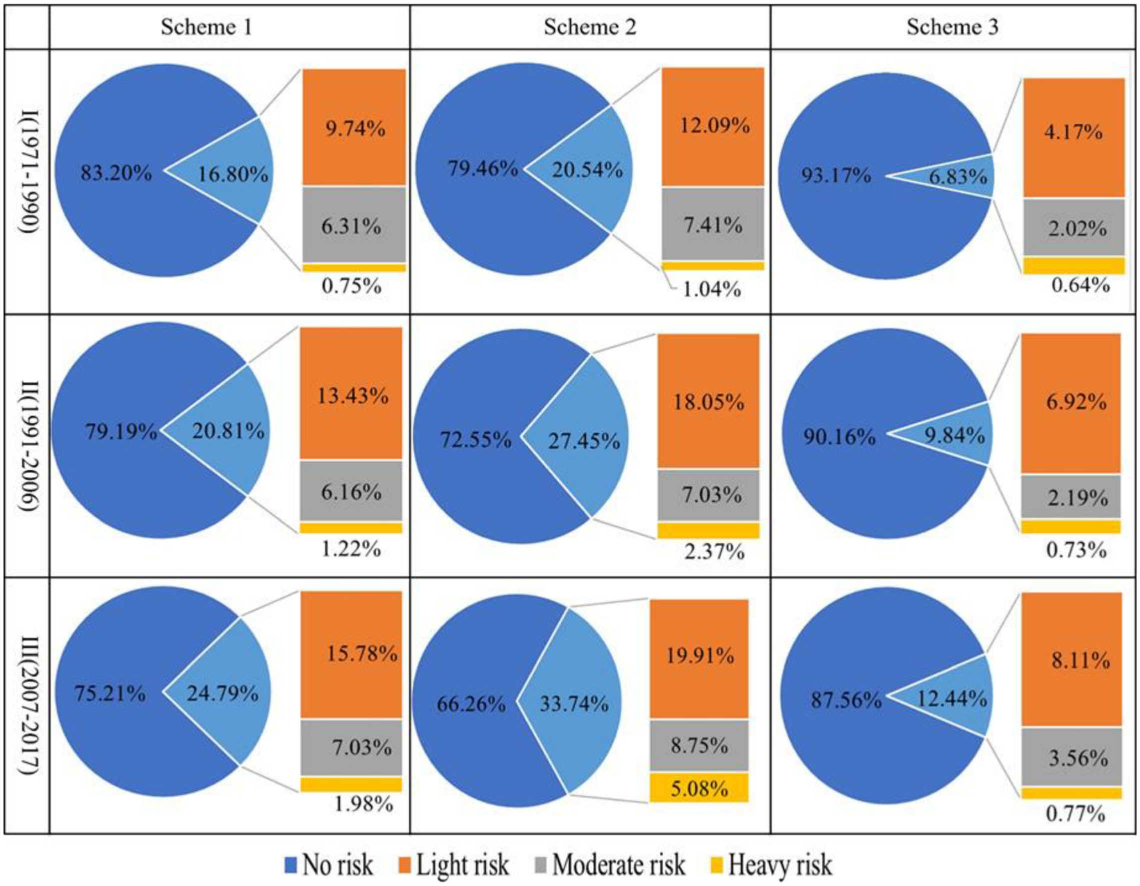

Fig. 8 Risk probability of algal blooms in different water transfer schemes under different periods

probability were all negative for scheme 3, and only the heavy risk probability was a slight increase.

From different periods, the CR of the total risk probability, the moderate risk probability, and the heavy risk probability in three schemes were smaller in period I and larger in periods II and III. The CR of the heavy risk probability increased significantly during periods II and III. For the moderate risk probability, it was larger in period I, similar in periods II and III.

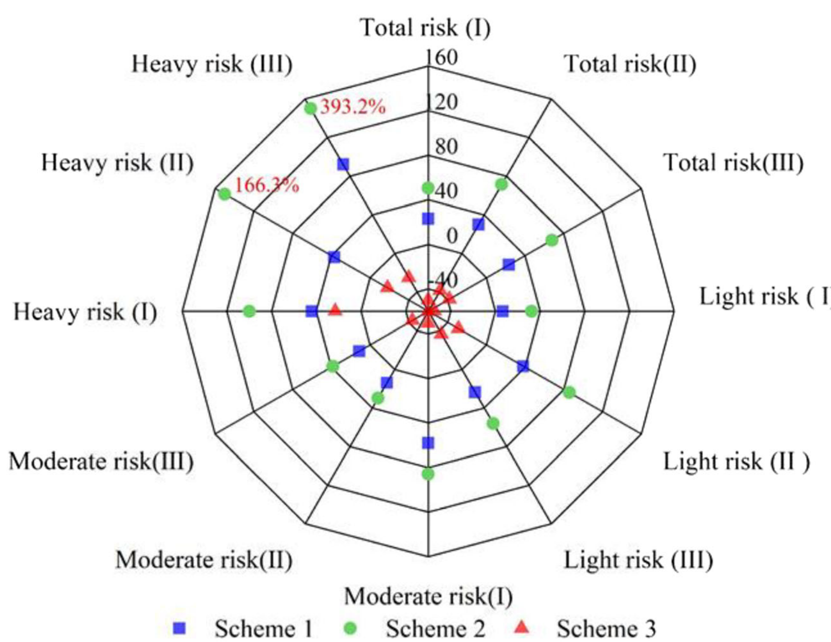

Fig. 9 Risk contribution rate in different periods under different design water transfer schemes

Furthermore, the risk probability of algal blooms under scheme 3 was lower than other schemes in each period, and algal blooms in the MSHR had been slowed down by WDPYHR. It was the water transfer scheme that had a negative impact on the occurrence of algal blooms. The larger the water transfer, the less the flow as well as the slower the flow velocity, so the higher the risk of algal blooms. The scheme of WDPYHR is beneficial to alleviate the adverse impact of water transfer on the ecological environment and play a positive role in the protection of the water environment of the MSHR.

Discussion

Influencing factors of algal bloom outbreak and hydrologic factor thresholds in the MSHR

Algal bloom outbreak is a complicated interdisciplinary research problem of environment, ecology, and hydrology. Currently, the most widely accepted factors affecting eutrophication are pollution load, hydrological conditions, and climate change (Padisak et al. 2010). From the ecological point of view, water quality, climate, and hydrological factors are equally important for the occurrence of algal blooms. However, in the future, it is undoubtedly the hydrological conditions that will have the greatest variation and the greatest impact in the MSHR. Through comparative analysis, our study found that during bloom events in the MSHR, changes in pollution load and temperature are relatively weak compared with hydrological conditions. The water level of the Yangtze River was higher and the flow of the Han River was lower during prone periods of algal blooms, which is consistent with the special hydrological situation during algal blooms in the Han River elucidated by earlier studies (Wu et al. 2017).

Excessive or slow flow rate affects the occurrence of river algal blooms, so there is an interval threshold for the hydrological conditions affecting the occurrence of algal blooms. During algal blooms of the Han River from 1992 to 2000, 350-500 m^3/s is the threshold flow suggested by most studies to prevent algal blooms (Xie et al. 2004). The analysis of the algal bloom events after 2005 showed that the critical value for preventing algal blooms in the PPAB was 500 m^3/s, and the minimum flow value for preventing blooms after 2009 increased to 800 m^3/s (Ying et al. 2017). Our study comprehensively analyzed and summarized the algal bloom events of the Han River from 1992 to 2018. Flows less than 900 m^3/s in the MSHR and water levels of the Yangtze River during 14-18 m are the suitable hydrological environment for algal bloom outbreak, which is consistent with the effect section of the water level of the Yangtze River (Xia et al. 2020a, b). Studies by many researchers on the hydrological conditions affecting the algal bloom in the mid-downstream of the Han River indicates that the threshold of hydrological conditions for the occurrence of algal blooms is also changing constantly under the influence of human activities and climate change, and the flow threshold of the Han River to prevent bloom outbreak has an increasing trend. Different from previous studies, this study considers not only the limit of the flow of the Han River but also the limit of the water level of the Yangtze River in determining the hydrological conditions affecting bloom outbreak in the mid-downstream of the Han River. The hydrological threshold values of the flow in the Han River and the water level of the Yangtze River under different degrees of bloom severity were presented in this paper, which is a new breakthrough in the study of blooms in the mid-downstream of the Han River. The flow and water level threshold proposed in this study is more in line with the requirements of blooms threshold under the new hydrological situation in the MSHR.

Analysis of hydrological condition change and flow characteristics in the MSHR

To some extent, the change of the hydrological situation affects the structure and stability of river ecosystems. The hydrological regime of the mid-downstream in the Han River changed significantly in the 1990s, while the hydrological regime of the Yangtze River changed under the interference of the Three Gorges Water Conservancy Project. The gradual warming of the climate and the continuous strengthening of human activities have changed the hydrological situation of the Han River, showing different characteristics in different periods. According to the analysis of monthly average flow, the minimum flow of 1, 3, and 7 days is also concentrated in the prone period of the algal blooms, which coincided with the occurrence time of algal bloom outbreaks. It is further confirmed that the low flow period is suitable for algal bloom outbreaks in the MSHR. As discussed earlier, the key hydrological driving factor for bloom outbreak in the MSHR is the occurrence of low flow in the MSHR and higher water level of the Yangtze River, forming a "static" water body like lakes and reservoirs. In the PPAB, the monthly mean flow of the MSHR decreased from periods I to III, and the total risk increased from periods I to III. Low pulse count increases continuously and low pulse duration decreases, which is because the operation of many water conservancy projects in periods II and III had reduced flow during high flow periods and increasing flow in the PPAB. Based on the comprehensive analysis of hydrological condition change, representative IHA index characteristics, and the risk of algal bloom outbreaks in the MSHR, the algal blooms in the MSHR are the result of the interaction of two hydrological conditions: the low flow of the Han River and high water level of the Yangtze River. Therefore, it is reasonable for us to choose the flow of the Han River and the water level of the Yangtze River as the hydrological conditions to study the joint risk of algal blooms in the MSHR.

Risk analysis of algal blooms in the MSHR under different hydrological conditions

Although much attention has been paid to the formation mechanisms of blooms in lake ecosystems (Paerl et al. 2011; Carey et al. 2012; Su et al. 2019), little work has been done to investigate the causes of harmful algal blooms taking place in the highly regulated and low-flow rivers in China, let alone the practice of prevention (Xin et al. 2020). In a previous study (Xie et al. 2005), based on algal bloom events from 1992 to 2000, the probability of algal bloom occurrence in the MSHR without water transfer, the design scheme of 8.2 billion m^3 water transfer, and the design scheme of 14.5 billion m^3 water transfer was calculated quantitatively as 9.2%, 10.2%, and 13.6%, respectively. In our study, the algal bloom risk under the actual inflow and different design water transfer schemes showed that the total risk probability means value of the algal blooms under the schemes of actual inflow, the design scheme of 8.2 billion m^3 water transfer, the design scheme of 14.5 billion m^3 water transfer, and the design scheme of 14.5 billion m^3 water transfer under WDPYHR was 16.58%, 20.8%, 27.2%, and 9.7%, respectively. Both studies showed that the higher the designed water transfer volume, the higher algal bloom risk in the mid-downstream of the Han River. The implementation of the middle route of SNWDP has a great effect on the increase of the probability of algal blooms and changes the water environment capacity in the MSHR (Xie et al. 2007). By comparing the risk of blooms from 1992 to 2000, it can be found that the algal bloom risk has nearly doubled in the past less than 20 years. The increase of algal bloom risk is due to the high intensity of human activity over the past 20 years. The discharge of a large number of pollutants further makes the river water environment deteriorated, and climate change and water conservancy project change the original hydrological situation of the Han River.

It is challenging to reduce the pollution loads to the Han River in the near future due to large populations and rapid economic development. Hydrological regulation is feasible and efficient to implement to reduce the risk of river algal blooms (Mitrovic et al. 2008; Xin et al. 2020). The risk of algal blooms for the design scheme of 14.5 billion m^3 water transfer under WDPYHR was lower than that without the WDPYHR. The implementation of the scheme of WDPYHR has a positive effect on alleviating the algal bloom risk. Based on the two key hydrological conditions (the flow of the Han River and water level of the Yangtze River), and considering the difficulty of controlling river algal blooms by changing the water level of the Yangtze River, a simple method of preventing algal blooms by adjusting the flow in the Han River is proposed. In the PPAB, when the flow is lower than 900 m^3/s, algae growth in rivers should be observed and analyzed in time. When the flow is less than 600 m^3/s, monitoring of water conditions and quality needs to be further strengthened. On the premise of guaranteeing the amount of SNWDP, consideration also should be given to increasing appropriately release of the Danjiangkou Reservoir and the diversion of the water supply of the WDPYHR to the Han River should be increased.

Conclusions

In this study, we have made a detailed analysis of the hydrological conditions during the PPAB, and have proposed the range of flow in the MSHR and water level of the Yangtze River with different degrees of algal blooms. Based on the copula function, a method was proposed to characterize the risk probability of algal blooms by the association of flow in the MSHR and the water level in the Yangtze River. This method can easily and quickly obtain the risk level and risk probability of algal blooms and provide a simple and effective method for the identification and prevention of algal blooms. The main results were as follows:

(1) In the PPAB, the main hydrological driving factors were the low flow in the MSHR and the high water level of the Yangtze River. Moreover, the risk ranges for the flow of the Han River and water level of the Yangtze River corresponding to different algal bloom degrees were preliminary given: When the flow was 600 ~ 900 m^3/s, and the water level was 14 ~ 15 m, there was a light risk. When the flow was 400 ~ 600 m^3/s and the water level was 15 ~ 16 m, there existed a moderate risk. If the flow was less than 400 m^3/s, and the water level was 16 ~ 18 m, it was considered a heavy risk.

(2) The hydrological series were divided into 3 different hydrological regime periods according to hydrological variation diagnosis: I (1971-1990), II (1991-2006), and III (2007-2017). The monthly average flow decreased from periods I to III, and the minimum flow appeared in the PPAB. The decrease of flow changes the ecological conditions of the MSHR and creates a more suitable environment for the diatoms, which increases the risk probability of algal blooms.

(3) Different design water transfer schemes had dissimilar effects on the risk of algal blooms in the MSHR. The larger the design water transfer, the higher the risk probability. Fortunately, the WDPYHR can reduce the risk probability of algal blooms to some extent. Therefore, in the process of water transfer, the coordination between water transfer and residual flow should be taken into consideration to avoid the occurrence of water environmental problems such as algal blooms caused by water transfer.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-020-11756-2.

Authors' contributions Lisha Shen: resources, data curation, formal analysis, methodology, formal analysis, and writing of the original draft. Ming Dou: resources, methodology, formal analysis, and modifying the paper. Rui Xia: checking English grammar and improving English writing. Guiqiu Li: data curation and formal analysis. Baiheng Yang: data curation and formal analysis.

Funding This research was supported by the National Natural Science Foundation of China (grant numbers 51679218, 51879239, 51879252, 51709238) and the Outstanding Young Talent Research Fund of Zhengzhou University (grant number 1521323001).

Data availability Not applicable.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

Ethical approval Not applicable.

Consent to participate Consent.

Consent to publish Consent.

References

Ban X, Zhu BY, Shu P, Lv XR (2018) Trend and driving force of climate and hydrological process in Hanjiang Basin (in Chinese). Resour Environ Yangtze Basin 27(12):2817–2829

Belmar O, Bruno D, Martinez-Capel F, Barquin J, Velasco J (2013) Effects of flow regime alteration on fluvial habitats and riparian quality in a semiarid Mediterranean basin. Ecol Indic 30:52–64. https://doi.org/10.1016/j.ecolind.2013.01.042

Bowes MJ, Gozzard E, Johnson AC, Scarlett P, Roberts C, Read DS, Wickham H (2012) Spatial and temporal changes in chlorophyll-a concentrations in the River Thames basin, UK: are phosphorus concentrations beginning to limit phytoplankton biomass? Sci Total Environ 426:45–55

Carey CC, Ibelings BW, Hoffmann EP, Hamilton DP, Brookes JD (2012) Eco-physiological adaptations that favour freshwater cyanobacteria in a changing climate. Water Res 46(5):1394–1407. https://doi.org/10.1016/j.watres.2011.12.016

Cattaneo A, Hudon C, Vis C, Gagnon P (2013) Hydrological control of filamentous green algae in a large fluvial lake (Lake Saint-Pierre, St. Lawrence River, Canada). J Great Lakes Res 39(3):409–419. https://doi.org/10.1016/j.jglr.2013.06.005

Chuo M, Ma J, Liu D, Yang Z (2019) Effects of the impounding process during the flood season on algal blooms in Xiangxi Bay in the Three Gorges Reservoir, China. Ecol Model 392:236–249. https://doi.org/10.1016/j.ecolmodel.2018.11.017

Dodds WK, Bouska WW, Eitzmann JL, Pilger TJ, Pitts KL, Riley AJ, Thornbrugh DJ (2009) Eutrophication of US freshwaters: analysis of potential economic damages. Environ Sci Technol 43(1):12–19. https://doi.org/10.1021/es801217q

Dou M, Xie P, Xia J, Shen XL, Fang F (2002) Influence of the water transfer project from south to north (middle route) on algal bloom in Hanjiang River (in Chinese). Adv Water Sci 6:714–718

Elmgren R, Larsson U (2001) Nitrogen and the Baltic Sea: managing nitrogen in relation to phosphorus. Sci World J 1(Suppl 2):371–377

Finlay JC, Small GE, Sterner RW (2013) Human influences on nitrogen removal in lakes. Science 342:247–250. https://doi.org/10.1126/science.1242575

Fornarelli R, Galelli S, Antenucci JP, Castelletti A (2011) Input variable selection for ecological modelling in inter-basin water transfer management. 19th International Congress on Modelling and Simulation (MODSIM2011) 4022–4028

Havens KE, Ji G, Beaver JR, Fulton RS, Teacher CE (2019) Dynamics of cyanobacteria blooms are linked to the hydrology of shallow Florida lakes and provide insight into possible impacts of climate change. Hydrobiologia 829:43–59. https://doi.org/10.1007/s10750-017-3425-7

Hilton J, Ohare MT, Bowes MJ, Jones JI (2006) How green is my river? A new paradigm of eutrophication in rivers. Sci Total Environ 365(1):66–83. https://doi.org/10.1016/j.scitotenv.2006.02.055

Holbach A, Wang L, Chen H, Hu W, Schleicher N, Zheng B, Norra S (2013) Water mass interaction in the confluence zone of the Daning River and the Yangtze River-a driving force for algal growth in the Three Gorges Reservoir. Environ Sci Pollut Res 20(10):7027–7037. https://doi.org/10.1007/s11356-012-1373-3

Jeong K-S, Kim D-K, Joo G-J (2007) Delayed influence of dam storage and discharge on the determination of seasonal proliferations of Microcystis aeruginosa and Stephanodiscus hantzschii in a regulated river system of the lower Nakdong River (South Korea). Water Res 41(6):1269–1279. https://doi.org/10.1016/j.watres.2006.11.054

Jung SW, Kwon OY, Lee JH, Han M-S (2009) Effects of water temperature and silicate on the winter blooming diatom Stephanodiscus hantzschii (Bacillariophyceae) growing in eutrophic conditions in the lower Han River, South Korea. J Freshw Ecol 24:219–226. https://doi.org/10.1080/02705060.2009.9664286

Kaspersen BS, Christensen TB, Fredenslund AM, Moller HB, Butts MB, Jensen NH, Kjaer T (2016) Linking climate change mitigation and coastal eutrophication management through biogas technology: evidence from a new Danish bioenergy concept. Sci Total Environ 541:1124–1131. https://doi.org/10.1016/j.scitotenv.2015.10.015

Kiss KT (1994) Trophic level and eutrophication of the River Danube in Hungary. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen 25(3):1688–1691

Li S, Xu Z, Cheng X, Zhang Q (2008) Dissolved trace elements and heavy metals in the Danjiangkou Reservoir, China. Environ Geol 55:977–983. https://doi.org/10.1007/s00254-007-1047-5

Li J, Jin Z, Yang W (2014) Numerical modeling of the Xiangxi River algal bloom and sediment-related process in China. Eco Inform 22: 23–35. https://doi.org/10.1016/j.ecoinf.2014.03.002

Li Y, Nwankwegu AS, Huang Y, Norgbey E, Paerl HW, Acharya K (2020) Evaluating the phytoplankton, nitrate, and ammonium interactions during summer bloom in tributary of a subtropical reservoir. J Environ Manag 271:110971. https://doi.org/10.1016/j.jenvman.2020.110971

Liang KX, Wang XY, Zhang DB, Zhou YH (2012) Ecological conditions of diatom water bloom formulation in the middle and lower reach of the Hanjiang River and strategy for water bloom control (in Chinese). Environ Sci Technol 35:113–116

Lucas LV, Thompson JK, Brown LR (2009) Why are diverse relationships observed between phytoplankton biomass and transport time? Limnol Oceanogr 54:381–390. https://doi.org/10.4319/lo.2009.54.1.0381

Maavara T, Parsons CT, Ridenour C, Stojanovic S, Duerr HH, Powley HR, Van Cappellen P (2015) Global phosphorus retention by river damming. Proc Natl Acad Sci U S A 112(51):15603–15608. https://doi.org/10.1073/pnas.1511797112

McKiver W, Neufeld Z, Scheuring I (2009) Plankton bloom controlled by horizontal stirring. Nonlinear Process Geophys 16:623–630. https://doi.org/10.5194/npg-16-623-2009

Mitrovic SM, Chessman BC, Davie A, Avery EL, Ryan N (2008) Development of blooms of Cyclotella meneghiniana and Nitzschia spp. (Bacillariophyceae) in a shallow river and estimation of

effective suppression flows. Hydrobiologia 596:173–185. https://doi.org/10.1007/s10750-007-9094-1
Neal C, Hilton J, Wade AJ, Neal M, Wickham H (2006) Chlorophyll-a in the rivers of eastern England. Sci Total Environ 365:84–104. https://doi.org/10.1016/j.scitotenv.2006.02.039
Padisak J, Hajnal E, Naselliflores L, Dokulil MT, Noges P, Zohary T (2010) Convergence and divergence in organization of phytoplankton communities under various regimes of physical and biological control. Hydrobiologia 639(1):205–220
Paerl HW, Xu H, McCarthy MJ, Zhu G, Qin B, Li Y, Gardner WS (2011) Controlling harmful cyanobacterial blooms in a hyper-eutrophic lake (Lake Taihu, China): the need for a dual nutrient (N & P) management strategy. Water Res 45(5):1973–1983. https://doi.org/10.1016/j.watres.2010.09.018
Palagama DSW, Baliu-Rodriguez D, Snyder BK, Thornburg JA, Bridgeman TB, Isailovic D (2020) Identification and quantification of microcystins in western Lake Erie during 2016 and 2017 harmful algal blooms. J Great Lakes Res 46(2):289–301. https://doi.org/10.1016/j.jglr.2020.01.002
Pei H, Feng H, Yang F, Li Z, Yang G, Niu Q (2019) Estimation of leaf nitrogen content of winter wheat based on Akaike's information criterion (Conference Paper). IFIP Advances in Information and Communication Technology 546:132–240. https://doi.org/10.1007/978-3-030-06179-1_24
Pretty JN, Mason CF, Nedwell DB, Hine RE, Leaf S, Dils R (2003) Environmental costs of freshwater eutrophication in England and Wales. Environ Sci Technol 37(2):201–208. https://doi.org/10.1021/es020793k
Puig A, Olguin Salinas HF, Borus JA (2016) Recent changes (1973-2014 versus 1903-1972) in the flow regime of the Lower Parana River and current fluvial pollution warnings in its Delta Biosphere Reserve. Environ Sci Pollut Res 23(12):11471–11492. https://doi.org/10.1007/s11356-016-6501-z
Richter BD, Baumgartner JV, Braun DP, Powell J (1998) A spatial assessment of hydrologic alteration within a river network. Regul Rivers Res Manag 14(4):329–340
Schweizer B (2007) Introduction to copulas. J Hydrol Eng 12(4):346–346. https://doi.org/10.1061/(asce)1084-0699(2007)12:4(346)
Simo P (2010) Linear regression analysis: theory and computing. Int Stat Rev 78(1):144
Su H, Wu Y, Xia W, Yang L, Chen J, Han W, Xie P (2019) Stoichiometric mechanisms of regime shifts in freshwater ecosystem. Water Res 149: 302–310. https://doi.org/10.1016/j.watres.2018.11.024
Whitehead PG, Wilby RL, Battarbee RW, Kernan M, Wade AJ (2009) A review of the potential impacts of climate change on surface water quality. Hydrol Sci J 54:101–123. https://doi.org/10.1623/hysj.54.1.101
Wu XH, Ying DC, Li C, Chen L, Li Y, Zhao Y (2017) Analysis of factors influencing diatom blooms in the middle and lower Hanjiang River (in Chinese). J Ecol 6:19–28. https://doi.org/10.15928/j.1674-3075.2017.06.003
Xia J, Zhang Y (2008) Water security in north China and countermeasure to climate change and human activity. Phys Chem Earth 33(5):359–363. https://doi.org/10.1016/j.pce.2008.02.009
Xia R, Chen Z, Zhou Y (2012) Impact assessment of climate change on algal blooms by a parametric modeling study in Han River. Journal of Resources and Ecology 3(3):209–219. https://doi.org/10.5814/j.issn.1674-764x.2012.03.003
Xia R, Zhang Y, Wang G, Zhang Y, Dou M, Hou X, Yang Z (2019) Multi-factor identification and modelling analyses for managing large river algal blooms. Environ Pollut 254:113056. https://doi.org/10.1016/j.envpol.2019.113056
Xia R, Wang G, Zhang Y, Yang P, Yang Z, Ding S, Jia X, Yang C, Liu C, Ma S, Lin J, Wang X, Hou X, Zhang K, Gao X, Duan P, Qian C (2020a) River algal blooms are well predicted by antecedent environmental conditions. Water Res 185:116221–116221. https://doi.org/10.1016/j.watres.2020.116221
Xia R, Zhang Y, Wang L, Zhang YY, Dou M, Qiao YF, Zhang MH (2020b) Characteristics identification of multiple influencing factors on Hanjiang River algal bloom. Res Environ Sci 33(04):911–920
Xie P, Xia J, Dou M, Zhang WS (2004) South-to-north water transfer project on the middle and lower reaches of Hanjiang river on the influence of China and countermeasure research (II)-the Hanjiang River blooms occur probability analysis and prevention countermeasures (in Chinese). J Nat Resour 19(5):545–549
Xie P, Dou M, Xia J (2005) Effects of different water transfer schemes on the algal blooms of the Middle route of South-to-North Water Diversion Project on the South-to-North Water Diversion Project (in Chinese). South-to-North Water Transfers and Water Science & Technology
Xie P, Dou M, Xia J (2007) Scenario analysis of the occurrence probability of Hanjiang Bloom under the changing environment of South-to-North Water Diversion Project (in Chinese). Harmonious Development of Energy Conservation and Environmental Protection — Proceedings of the 2007 Annual Meeting of China Association for Science and Technology 5
Xie P, Chen GC, Lei HF, Wu FY (2010) Hydrological variation diagnostic system (in Chinese). Journal of Hydroelectric Engineering 29(1):85–91
Xin X, Zhang H, Lei P, Tang W, Yin W, Li J, Li K (2020) Algal blooms in the middle and lower Han River: characteristics, early warning and prevention. Sci Total Environ 706:135293. https://doi.org/10.1016/j.scitotenv.2019.135293
Yang Q, Xie P, Shen H, Xu J, Wang P, Zhang B (2012) A novel flushing strategy for diatom bloom prevention in the lower-middle Hanjiang River. Water Res 46(8):2525–2534. https://doi.org/10.1016/j.watres.2012.01.051
Yang JR, Lv H, Isabwe A, Liu L, Yu X, Chen H, Yang J (2017) Disturbance-induced phytoplankton regime shifts and recovery of cyanobacteria dominance in two subtropical reservoirs. Water Res 120:52–63. https://doi.org/10.1016/j.watres.2017.04.062
Ying DC, Yin ZJ, Yang CH, Wang D (2017) Key hydrological thresholds and scheduling strategies for controlling spring diatom blooms in the Middle and lower Reaches of the Han River (in Chinese). Hydrology 9:31–34
Zhang Y, Xia R, Zhang M, Jing C, Zhao X, Fan J (2017) Research progress on cause analysis and modeling of river algal blooms under background of mega water projects. Res Environ Sci 30(8):1163–1173
Zhang X, Li B, Xu H, Wells M, Tefsen B, Qin B (2019) Effect of micronutrients on algae in different regions of Taihu, a large, spatially diverse, hypereutrophic lake. Water Res 151:500–514. https://doi.org/10.1016/j.watres.2018.12.023
Zhang Y, Zuo J, Salimova A, Li A, Li L, Li D (2020) Phytoplankton distribution characteristics and its relationship with bacterioplankton in Dianchi Lake. Environ Sci Pollut Res 27:40592–40603. https://doi.org/10.1007/s11356-020-10033-6
Zheng LL, Zhang Q, Li TL, Ying DC, Song LR (2017) The effects of three different environmental factors on the growth and physiology of the dominant species Stephanodiscus sp. in Han River Diatom (in Chinese). Trans Oceanol Limnol (6):91–97
Zhou J, Zhang M, Lu P (2013) The effect of dams on phosphorus in the middle and lower Yangtze river. Water Resour Res 49(6):3659–3669. https://doi.org/10.1002/wrcr.20283
Zou R, Wu Z, Zhao L, Elser JJ, Yu Y, Chen Y, Liu Y (2020) Seasonal algal blooms support sediment release of phosphorus via positive feedback in a eutrophic lake: insights from a nutrient flux tracking modeling. Ecol Model 416:108881. https://doi.org/10.1016/j.ecolmodel.2019.108881