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Multi-factor identification and modelling analyses for managing large river algal blooms☆

Rui Xia [a, b], Yuan Zhang [a, b, *], Gangsheng Wang [c], Yongyong Zhang [d], Ming Dou [e], Xikang Hou [a, b], Yunfeng Qiao [e, f], Qiang Wang [g], Zhongwen Yang [a, h]

[a] *State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China*
[b] *Laboratory of aquatic ecological conservation and restoration, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China*
[c] *Institute for Environmental Genomics, and Department of Microbiology and Plant Biology, and School of Civil Engineering and Environmental Sciences, University of Oklahoma, Norman, OK, 73019, USA*
[d] *Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing, 100101, China*
[e] *College of Water Conservancy and Environment, Zhengzhou University, Zhengzhou, Henan, 450001, China*
[f] *Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100012, China*
[g] *State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, No. 8 Donghu South Road, Wuhan, 430072, China*
[h] *Laboratory of Aquatic Ecological Conservation and Restoration, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China*

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ABSTRACT

River algal blooms have become a newly emerging global environmental issue in recent decades. Compared with water eutrophication in lakes and reservoirs, algal blooms in large river systems can cause more severe consequences to watershed ecosystems at the watershed scale. However, reveal the causes of river algal blooms remains challenging in the interdisciplinary of hydrological-ecological-environmental research, due to its complex interaction mechanisms impacted by multiple factors. In addition, there were still considerable uncertainties on the characteristics, impacts, driving factors, as well as the applicable water system models for river algal blooms. In this paper, we reviewed existing literature to elaborate the definition and negative effects of river algal blooms. We analyzed sensitive factors including nutrient, hydrological and climatic elements. We also discussed the application of ecohydrological models under complicated hydrological conditions. Finally, we explored the essence of the river algal bloom by the interaction effects of physical and biogeochemical process impacted by of climate change and human activities. The model-data integration accounting for multi-factor effects was expected to provide scientific guidance for the prevent and control of algal blooms in large river systems.

1. Introduction

With the rapid socioeconomic development and urbanization since the 21st century, algal blooms have grown frequently in numerous rivers and their tributaries all over the world. Their growth has drawn extensive worldwide attention. Many European countries have listed the water eutrophication issues influenced by large-scale human activities as the primary pollution pressure in the EU Water Framework Directive (Hilton et al., 2006). Eutrophication in aquatic systems is a global problem that could pose a threat to water-ecological-environmental security. To this end, a series of scientific research plans has been carried out to accommodate knowledge from multiple disciplines, such as hydrology, ecology, socioeconomic development, climate change, and human activities (Zhang et al., 2017). The International Geosphere–Biosphere Programme (IGBP) proposed by the International Council for Science in the late 1980s (IGBP, 1987–2015) was centered on biological studies of the hydrological cycle. In 2004, the Earth System Science Program initiated the “Global Water System Program” (GWSP , 2005) (Fig. 1). Its core task was to study the interaction and feedback mechanisms between social humanity

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* Corresponding author. State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China.

E-mail address: zhangyuan@craes.org.cn (Y. Zhang).

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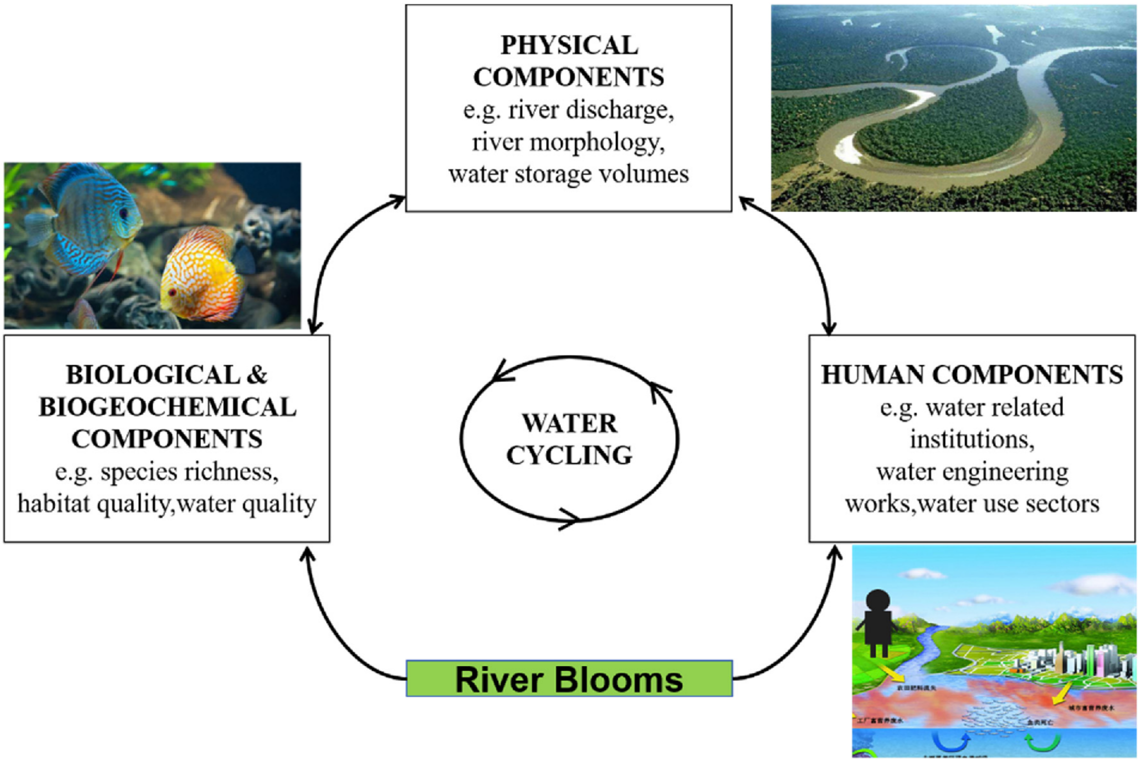

Fig. 1. Water system based on the multi-impact process on river blooms (GWSP , 2005; Xia et al., 2018).

and biogeochemical processes, which were closely related to the hydrological processes in the drainage basin. To cope with global water security and water ecological environmental risks under complicated conditions in the future, the International Association of Hydrological Science (IAHS) formally launched a scientific program in 2013, which aims to study the interaction between natural hydrological processes and human activities and social development (Montanari et al., 2013). In 2014, IAHS further proposed a program to solve the water-ecological-environmental security problem influenced by multi-factors under changing environment, where the relationship among human activities, natural environment, socioeconomic development, and politics was emphasized (Savenije, 2015).

Compared the lake eutrophication problem, river algal blooms are more easily influenced by multi-factors including climate change and human activities at multi-scales (Descy et al., 2014; Kim et al., 2014; Chen, 2016; Zhang et al., 2017). At the watershed scale, the influence of human activities is usually reflected by the construction of dams, sluices, and water conservancy projects, land use and land cover change, agricultural non-point source, as well as industrial and domestic point source sewage discharges. Climate change impacts mainly refer to regional effect of rainfall, temperature and wind (Xia et al., 2018; Kaspersen et al., 2016; Yang et al., 2017). Meanwhile, previous studies have corroborated that algal blooms were usually accompanied by intense disturbance from human activities (Dodds et al., 2009; Finlay et al., 2013; Zhang et al., 2017). For instance, algal blooms have grown frequently in several tributaries of the Three Gorges Reservoir Region in China in recent years, including Daning River, Xiangxi River, Wujiang River, Daxi River, and Jialing River. (Zheng et al., 2009a, 2009b; Yi, 2011; Liu et al., 2016a, 2016b; Holbach et al., 2013). Furthermore, algal bloom incidents have also been found in the downstream of the Hanjiang River, the largest tributary of the Yangtze river, as well as in the water source of the middle route of the South-to-North Water Diversion Project (SNWDP) (Dou et al., 2002; Yi, 2011; Xia et al., 2012a, 2012b; Yin et al., 2017). Compared to the lake eutrophication issues, river algal blooms usually exhibit longer and broader influence because of larger impact scale, therefore causing more serious consequences.

Owing to the complexity and effects of human activities, the formation mechanisms of river algal blooms are still unclear in the field of hydro-ecology. Most simulation and prediction methods for large-scale river algal blooms have been developed on the basis of lake and reservoir. Only a few studies have focused on river algal blooms and their ecological mechanism under complicated hydrological conditions (Liu et al., 2012; Zhang et al., 2017). In recent years, a large amount of hydraulic engineering development and application, as well as pollution loads from industrial and domestic point and agricultural non-point sources, climate change, and socioeconomic development, has resulted in changing hydrological regime (Xia and Zhang, 2008; Ji et al., 2017). In near future, rapid socioeconomic development will be sustained in China and many other developing countries. With the continued operation of the Three Gorges Dam and the completion of the middle route of the SNWDP, hydrological cycle will be significantly changed in the river basins (Zhang et al., 2017). Such effects will certainly provide high requirements and challenges for the environmental and ecological protection of rivers. Algal blooms in large river system have become a world-widely discussed hydrological–ecological interdisciplinary research topic. Thus, it is urgently needed to conduct multiple impact factor identification and cause analysis on large-scale river algal blooms.

The cause analysis on algal blooms in large river systems can be very important not only for sustainable water resource and ecosystem management, but also for the implementation and optimization of mega water project operations. This study reviews the possible causes of large river algal blooms based on the latest literature and research, key factors and their interaction mechanisms that may cause river eutrophication. Lastly, future trends and key scientific issues with regard to river ecological issues under multiple impact factors are proposed in order to provide theoretical support to reveal the formation of river blooms.

2. Research progress on the causes of large river algal blooms

2.1. Definition of river algal blooms and their consequences

2.1.1. Definition of river algal blooms

River algal blooms refer to the thick algal film that forms at the surface layer of river water due to massive algae (diatom, blue–green algae, and green algae) growth under the comprehensive effects of the afflux of domestic and industrial wastewater, as well as agricultural non-point-source pollutants and the input of rich nutritive salts, such as N, P, K, Si and other nutrients. Usually, the grade of algal density and quantity can express algal content in the water body and outbreak intensity of "algal blooms" (Yu et al., 2009). Meanwhile, related studies have affirmed that blue and green algae are dominant species in the lake eutrophication (Jung et al., 2009; Bowes et al., 2008; Domingues et al., 2008). Complicated and dramatic hydrological conditions are formed in river water than in lakes and reservoirs due to water exchange, generally centering on diatom blooms applicable to rapid water flow and low-temperature condition. Therefore, river algal blooms usually tend to occur with a low temperature between 15 °C and 20 °C during late winter and early spring (Chen et al., 2014). By contrast, lake and reservoir eutrophication likely occurs in summer and autumn when temperature is high (Yang et al., 2011; Fabbro and Duivenvoorden, 1996; Reynolds and Reynolds, 2011). Under healthy water ecosystem conditions, algae growth and reproduction in freshwater will maintain a proper dynamic equilibrium. When nutrient concentration in the water body tends to be saturated because of changes in meteorological and hydrological conditions, mass propagation and the growth of algal cells give rise to remarkable changes in water color and properties. Therefore, the nature of water eutrophication is an extreme manifestation of an imbalance in water ecosystem. River algal bloom is a manifestation of an aggravated river water environment and an unhealthy water ecosystem.

2.1.2. Key features between river algal blooms and Lake eutrophication

The influence factors of river algal blooms are complicated and diversified with great algal individual differences, as well as certain regional differences. Currently, the existing literatures have not formed recognized standards and definition of the threshold value of river algal blooms (Xia et al., 2012a, 2012b; Zhang et al., 2017). Under most circumstances, judging the occurrence of river blooms should be done according to actual conditions (Zheng et al., 2006). According to the investigation of large-scale river algal blooms in China, the direct basis to identify the outbreak intensity of river algal blooms is algal density (algal cell concentration) (Lu et al., 2000; Dou et al., 2002; Yin et al., 2017). In addition, algal density thresholds during river algal blooms present the differences of physical environmental characteristics in different regions. For instance, Lu et al. (2000) and Dou et al. (2002) initially identified that the direct cause for the outbreak of algal blooms in the downstream of Hanjiang River in 1992–2000 was rapid Cyclotella reproduction. Their study corroborated that the algal blooms in Hanjiang River were notable when algal density reaches 1.0×10^7/L. On the basis of *Guidelines on Freshwater and Seawater Quality*, Li et al. (2014) highlighted that human contact is not recommended when blue–green algae density in the water body exceeds 1.5×10^7/L and that algal density exceeding 2.0×10^7/L poses serious threat to human health (Warne et al., 2014). In general, according to the definition of megascopic severe algal blooms, most of the present research takes 1.0×10^7/L as the critical value for the outbreak of diatom blooms in rivers. From year 1992–2014, algal density monitoring of evaluation results during algal blooms in the downstream of Hanjiang River verified this conclusion.

2.1.3. Consequences of river algal blooms

As hydrological regime change in rivers is more violent with respect to lakes and reservoirs, algal blooms generally will not easily occur in a flowing river water. Therefore, the occurrence of river algal bloom indicates deteriorating water eco-environmental condition. The direct influence of river algal blooms is algal toxin generation and algal aggregation to aquatic animals and plants. Generally, river algal blooms are dominated by diatoms due to high water flow rate. However, blue and green algae blooms have also been found in some tributaries because of the hydrological conditions similar to lakes (Zheng et al., 2006; Yin et al., 2017). Algal toxins include cyclic peptides, alkaloids, and lipopolysaccharides, which can directly affect the metabolism of aquatic organisms and even cause their death due to large-area hepatic hemorrhage (Paerl and Otten, 2013). In addition, a large quantity of growing algae will block the filter units of peripheral eater works and affect water quality. Algal blooms could lower river water transparency and DO content, which will directly exert negative influences on aquatic products like fishes and the health and daily lives of residents on the riverside (Carpenter et al., 1998). Algal bloom events can lead to negative impacts and serious consequences to the river ecosystem health, as well as the drinking water safety (Dodds et al., 2009; Pretty et al., 2003; Whitehead and Read, 2013). In 2008, over 100-km (out of 1577 km) algal blooms occurred in the downstream of the Hanjiang River, the largest tributary of the Yangtze River, which severely affected the drinking water of approximately 200,000 people. Consequently, multiple peripheral public water works were shut down due to water intake blocking along the Hanjiang River.

Large river algal blooms not only exert a negative influence on river ecosystem, but also have extensive social and political effects (Gao and Gao, 2010). Most of river algal blooms are closely related to water conservancy project construction and implementation (Ha et al., 2002). For example, many large-scale hydraulic projects in China have been completed or in construction, including the Three Gorges Dam, the Gezhou Dam, SNWDP and etc. These rivers are generally located in the backwater areas of reservoirs (e.g., Xiangxi River and Daning River) or water source areas (Hanjiang River). Mega water transfer projects are also found in large rivers in the world, such as the Nile River in Africa, the Amazon River in South America, the Danube River in Europe and etc. Among them, some famous cross-basin water transfer projects have been built and implemented for a nearly half century, include the Snow Mountain Water Diversion Project in Australia, the Grand Artificial Canal project in Libya, the California Water Diversion Project, the West Water Diversion Project in Egypt, as well as the North Water Diversion Project in Israel (Whitehead et al., 2015; Zhang et al., 2017). These water diversion projects usually cause major eco-environmental problems in both upstream and downstream of the water diversion channels, including changes in river morphology caused by siltation, runoff changes caused by uneven distribution of water resources, and soil salinization due to reduction of water runoff (Mitrovic et al., 2011; Oliver et al., 2014; Reynolds and Reynolds, 2011; Yang et al., 2017; Kim et al., 2014). Once algal blooms occur in these sensitive areas with large population, the consequence can be grave compared to water eutrophication in lakes and reservoirs, such as unsafe drinking water and considerable pressure from the international community. Algal blooms have become a major problem faced by governments at all levels, water conservancy, and environmental protection departments.

2.2. Possible driving factors of river algal blooms

2.2.1. Impact of nutrient loads on river algal blooms

Usually nutrients are one of the most important factors for freshwater eutrophication in lake and reservoirs. However, recent research has affirmed that nutrients may not be the limiting factor for most algal blooms in river system (Yang et al., 2011; Chen et al., 2014; Kirkwood et al., 2007; Lewis and Mccutchan, 2010; Bowes et al., 2012). Generally, the excessive input of nutrients, such as nitrogen (N) and phosphorus (P), was usually considered as the main source of limiting factor of blue and green algae eutrophication in lakes and reservoirs (Lynam et al., 2010; Pasztaleniec and Poniewozik, 2010). Eutrophication was formed in the water body by accumulating a large quantity of N and P, which cause the excessive reproduction of dominant algal species and the outbreak of algal blooms. However, owing to the large river basin, pressures from human activities like agricultural non-point and industrial and domestic point sources is considerable, and pollution load from river basin was increasing. With the changes in dominant algal species during the river algal blooms, the limiting factors and reaction mechanism of nutrients become increasingly complicated in river ecosystems. No unified conclusion is available yet over the limiting factors, and their influence degrees are somehow weakened in lake eutrophication (Bowes et al., 2011; Desortová and Punčochář, 2011; Istvánovics and Honti, 2012; Oliver et al., 2014; Zhang et al., 2017). Based on the samples from the outbreak of diatom blooms in Hanjiang River of China in year of 2003, Zheng et al. (2009a, 2009b) and Yin et al. (2017) analyzed the maximum concentration range of nutrients applicable to diatom growth. The results contended that the concentrations of nutrients such as N, P, and Si in the Hanjiang River already satisfied the basic conditions for algal growth but not the main limiting factors of the outbreak of algal blooms. Essential elements for diatom growth include C, Si, N, and P. However, Si is not taken as the main limiting factor in freshwater ecosystems (Reynolds and Reynolds, 2011; Yang et al., 2011). 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 et al., 2001; Paerl, 2009; Finlay et al., 2013).

In addition, studies have showed that lake and reservoir eutrophication was manifested by algal density and nutritive elements like N and P presenting considerable positive correlations with Chl-a concentrations. Nevertheless, limited studies have covered the obvious of positive correlations between algae density and nutrients during river algal blooms. Meanwhile, Zeng (2006) analyzed sample data from Xiangxi River in the Three Gorges Dam Region during the rainy season. The results verified that phytoplankton and Chl-a concentrations had no significant positive correlations with the main nutrient loads in the river water. Instead, they presented negative correlations in some time periods. Even though water nutrient concentrations remained unchanged, changing external environmental factors (light intensity, flow velocity, and hydrological conditions) could cause apparent diatom blooms. The result confirms that the nutrient levels of the water body was saturated already during the spring. A recent study has proven that nutrients are not the main limiting factor of river algal blooms (Yin et al., 2017). Similar studies also have claimed that when total phosphorus (TP) content in the river exceeds 30 μg/L, nutrients will not be the main limiting factors (Hilton et al., 2006; Sivapragasam et al., 2010), but other physical factors (e.g., water flow, water temperature, etc.) can exert evident and direct gain effects on the formation of river algal blooms.

2.2.2. Impact of hydrological factors on river algal blooms

The influences of hydrodynamic conditions on algal blooms in large rivers have always been disputed. In recent years, there are increasing number of ecologists proposing that hydrological regime will be the most sensitive driving factor to affect the formation of river algal blooms (Zhang et al., 2017; Yang et al., 2017). Laboratory experiments showed that algal absorption kinetics responded strongly to changes in hydrological conditions (e.g., water velocity and water level), where the influence of water fluctuation and agitation on algal growth manifested certain spatial–temporal patterns (Lucas et al., 2009; Mckiver et al., 2009; Yang et al., 2017). First of all, hydrological conditions can affect water retention time by changing water exchange rate. Slow hydrological regime include low water level, less water volume and slow flow rate could reduce the water exchange rate, as well as lengthen the retention time of algae in river, thereby influencing algal migration, diffusion, and accumulation (Soballe and Kimmel, 1987; Neal et al., 2006; Lucas et al., 2009; Mckiver et al., 2009). In addition, different hydrological regimes may result in considerable differences in the spatial distribution of nutrients in water body. Hydrological regime was able to change the net growth rate of algal populations by directly influencing its absorption of nutrients, resulting in an evident spatial heterogeneity of algal density (Cózar and Echevarría, 2005; Arin et al., 2002). Diatom was usually found as the dominant species of river algal blooms due to its adaptation to the rapid river water flow (Dou et al., 2002; Xia et al., 2012a, 2012b). Blue–green algae was commonly found in lake and reservoir eutrophication as dominant species, and it was highly sensitive to hydrodynamic conditions (Harris and Baxter, 2010). In the backwater areas of reservoir tributaries influenced by large-scale water conservancy project, related studies have corroborated that changes in nutrients and temperatures during the outbreak of most river algal blooms are not remarkable. However, river hydrological regime and water cycle process affected by human activities (e.g., impounding reservoirs) are more prominent than those of lakes. For example, the characteristics of algal blooms in Daning River in the Three Gorges Reservoir Region were studied by using isotope tracer technique. The results corroborated that water level jacking caused main stream backflow and elevated nutrient concentration in the backwater area, further leading to river algal blooms (Zheng et al., 2009a, 2009b). Moreover, Liu et al. (2016a, 2016b) confirmed that layered density currents in river water may cause eutrophication in the Three Gorges Reservoir Region and algal blooms could be alleviated through reservoir tide scheduling.

In addition, increasing river water quantity and flow velocity can accelerate pollutant dispersion and degradation by changing horizontal and vertical water exchange rates, which ultimately decreased the algal reproduction rate in rivers (Chung et al., 2008; Zheng et al., 2011; Yin et al., 2017). The low flow improves water transparency and creates an environment with proper light and temperature conditions for algal growth and reproduction. By contrast, rapid water flow rate will generate large shear stress that inhibits algal growth due to the accelerated internal cycle. Therefore, interval hydrodynamic thresholds do exist and usually have significant impact on the formation of river algal blooms (Mitrovic et al., 2011). For instance, previous studies proposed that threshold value of flow velocity for the proper growth of most phytoplanktons was usually 0.04 m/s (Long et al., 2011). By studying river algal blooms on the lower reaches of Nakdong River in Korea, Jeong et al. (2007) affirmed that the retention time of diatom growth in the water body was significantly correlated to water discharged from the upstream reservoir and rainfall in the drainage basin. Yang et al. (2011) put forward that water agitation directly acted upon algal growth by influencing light condition, algal nutrients absorption, and motion status in the water body. Besides the influences of water quantity and flow velocity in the river, water level has also recently attracted attention from ecologists. Yang et al. (2012) have found Chl-a was very sensitive to the variation of water level, and novel flushing strategy for diatom bloom prevention was proposed in the lower-middle Hanjiang River in China. Kong and Song (2011) pointed out that water disturbance caused changes in physical and chemical factors like underwater light density distribution, thereby influencing algal growth. Yang et al. (2017) affirmed that when nutrient concentration tends to be stable in the Zhu River of China, the main factor controlling downstream algal growth and the population composition was the upstream and downstream water level fluctuations. The above studies fully contend that, compared with lake and reservoir eutrophication, hydrological regime changes can exert a direct influence on algal blooms in rivers.

2.2.3. Impact of climatic factors on river algal blooms

Changes in air temperature, light and rainfall intensity directly affect river algal blooms. Rainfall intensity directly impacts river runoff (Yang et al., 2017), whereas air temperature impacts algal growth, death, and metabolism rate by changing physical and chemical reaction rates in the water, then increasing the risk of river algal blooms (Larroude et al., 2013; Zhang et al., 2017; Abonyi et al., 2018). Climate change impacts are always critical in lakes and reservoirs with a small area of water body (Su et al., 2012). Water eutrophication caused by blue−green algae normally occurs in high temperature during summer, but large-scale river algal blooms commonly occur toward the end of winter or the beginning of spring when water temperature is low. Suitable water temperatures for the growth of blue algae, green algae, and blue−green algae are approximately 30−35 °C, 20−25 °C, and 15−20 °C, respectively (Chen et al., 2014). By contrast, diatom blooms in rivers usually has strong tolerance to the low temperature. Their growth peak was in spring and autumn. Meanwhile, Jiang et al. (2008) asserted that the bacteria population in the water body increases dramatically when water temperature is within 25−35 °C. Bacteria stimulated visible algal growth by increasing P release from sediments to overlying water (Jiang et al., 2008). Light is also a direct factor that affects aquatic organisms' photosynthesis (Xia et al., 2012a, 2012b). On the basis of the analysis of water samples during the outbreak of algal blooms in Hanjiang River, Kuang et al. (2000) affirmed that the growth rate of diatoms notably increased under light intensity of 2000−5000 lx. Rainfall influences streamflow in two ways. First, changes in rainfall frequency and intensity affect the hydrodynamic conditions of rivers (Hao et al., 2010). Such change disturbs algal distribution and growth by altering scouring and dilution of surface pollutants along the riverbank (Jeppesen et al., 2009). Second, changes in rainfall pattern and process can increase extreme regional hydrological events and affect the transport and transformation of nutrients and pollutants in the river. Additionally, riverbank scouring by rainfall changes the geomorphology of river channels, which causes the degradation of the assimilative capacity of the water body (Jeppesen et al., 2011). Beside rainfall and water temperature, wind effect on river algal blooms has also been studied in recent years (Xia et al., 2018). For example, some research indicated wind will accelerate the release of nutrients from sediments in the bottom water by changing the river water hydrodynamic conditions and enhancing the mixture of nutrients (Reynolds and Reynolds, 2011). Recent studies also proposed that a high intensity of wind waves could break up the aggregation of algae from the surface river water, therefore to decrease the probability of the occurrence of algal blooms (George et al., 2007; Su et al., 2012; Xia et al., 2018). However, only a few studies have been conducted on the influence of climate change on the river eco-environment, particularly on the outbreak of river algal blooms. Recent simulation studies on water quality and water ecosystem have been primarily carried out in terms of water temperature change in a single watercourse or under experimental conditions (please insert citations). However, the mechanism of the formation process of large-scale river algal blooms under complicated climate conditions remains unexplored.

3. Nature analysis of river algal blooms

Based on the above literature reviews, it is recognized that the comprehensive understanding of large river algal blooms requires hydrological−ecological interdisciplinary research accounting for multi-factor influences. In the complicated high-order and multi-factor influencing process of a large-scale river system, key factors driving the formation of river algal bloom usually include changing runoff process and the direct influence of rising temperature on algal growth (Jiang et al., 2014). Under the intense disturbance from human activities, the construction of upstream water conservancy project and the operation of sluice-dam affect the downstream runoff. Moreover, industrial and domestic pollution discharges increase the nutrient load and the deterioration of water quality. Therefore, river algal blooms are a result of combined effects of meteorology, hydrology, and water quality (Viney et al., 2010; Yang et al., 2017).

The formation of river algal blooms is usually affected by multiple processes, including physical and biogeochemical processes and human activities. The physical processes mainly refer to the hydrological processes of the drainage basin, including water cycle among atmosphere, ocean and land surface, rainfall-runoff process, and changing of river landform and sediments. The biogeochemical processes mainly include interaction between terrestrial and river ecosystems. Human activities mainly include land use change, sluice-dam operation, urbanization and human water intake (Xia et al., 2018). Other water-related organizations, water conservancy projects, and water supply departments constitute the important carrier and the main driving force for the change of the river ecosystem. The above processes do not occur independently but interact with each other. Substance circulation and energy flowing in the land-surface processes influence the biogeochemical cycles. Biogeochemical cycles feed back to underlying land surface processes, including runoff changes caused by changing of vegetation and evapotranspiration. In addition, human activities affect the physical, hydrological, and biogeochemical processes (Zhang et al., 2017).

Water cycle usually acted as the most important pathway, it links the "geosphere - biosphere − atmosphere" in the Earth system, which has become one of the core issues of global change. Water cycle could be influenced by both natural changes and human activities, which determines the formation of river algal blooms by changing hydrodynamic process (Zhang et al., 2017). Because of the high intensity of human activities and the impact of global climate change, the actual watershed water cycle is no longer a pure natural hydrological process (Whitehead et al., 2015). It was accompanied by human-induced impacts, including interaction between rivers and lakes (reservoirs), water regulation and storage, water withdrawal by various industries and sectors, inter-basin water transfer, as well as agricultural and ecological water consumption (Xia et al., 2018). Therefore, a comprehensive framework to integrate both natural and human-induced eco-hydrological cycle is required to understand the underlying mechanisms for river algal blooms, in which the interactions among multi-factors should be considered for the outbreak of large-scale river algal blooms (Fig. 2).

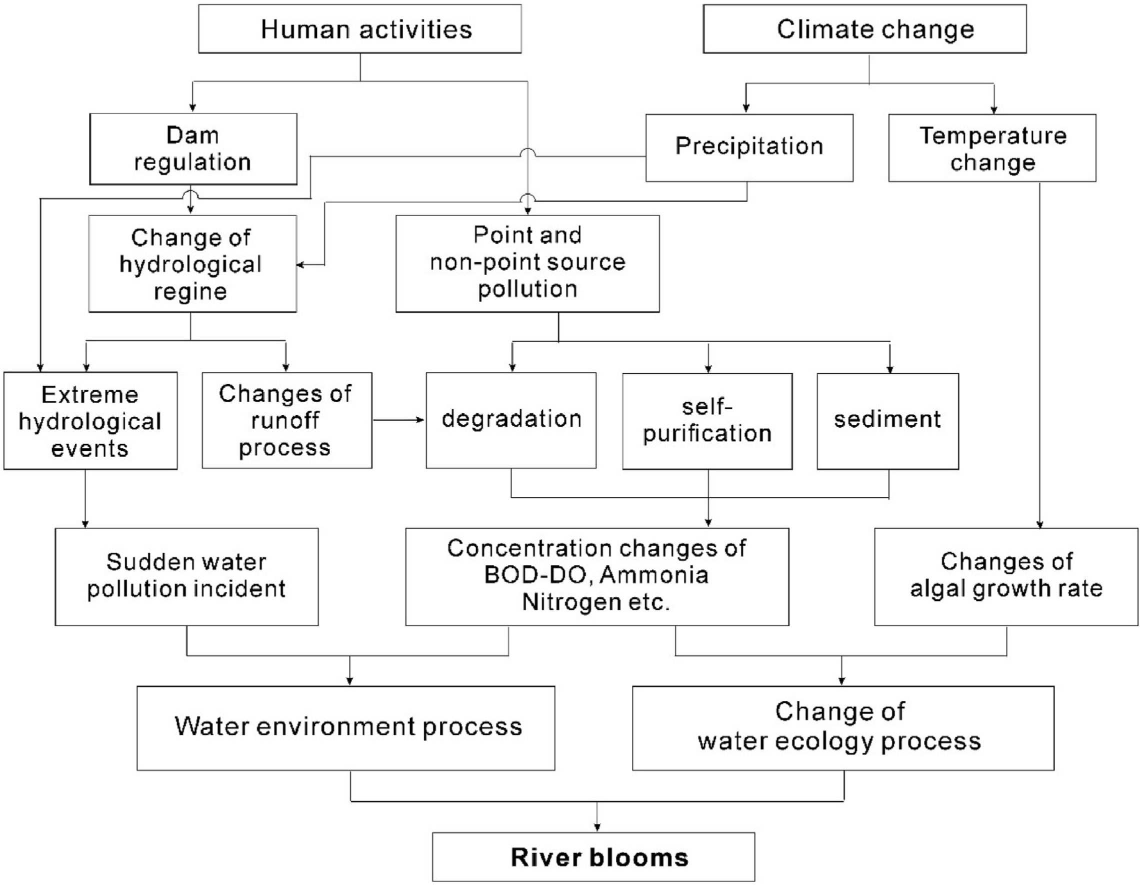

Fig. 2. Interaction of multiple factors in large river systems.

4. Modelling and prediction methods of river algal blooms

4.1. Regressive empirical algorithms

The occurrence of eutrophication and multi-factor interaction mechanisms are still unclear. Water eco-environment models have been developed based on hydrological, water quality, and water ecological observations. Simple correlation and regression analyses were used to empirically simulate the relationship between TP and Chl-a (Jin et al., 1990). These models had simple structure, and the correlations between species and environmental factors could be quickly identified. Therefore, the empirical models have been widely applied to qualitative studies of river algal blooms in (Elliott et al., 1999a; Elliott et al., 1999b; Leland and Porter, 2000). Most eco-hydrological models were focused on total nitrogen (TN) and TP simulations as they were the dominant nutrients in water ecosystems. For example, the TP mass balance model (Vollenweider, 1975) was developed based on the empirical relationship between phytoplankton biomass, nutrition concentrations, and hydrological conditions (like water depth and flow velocity) (Han et al., 2003). Besides the empirical models for TN and/or TP, dynamic algal growth models based on limiting factors have been developed and tested (Sterner and Grover, 1998). These models use the Michaelis–Menten equation (Chen and Orlob, 1975) or the Droop method, which are applicable to water bodies with P as the main limiting factor. Most models were developed based on the empirical relationship between algal photosynthesis and nutrient availability. Empirical models are simple and convenient to directly simulate nutrient concentrations in water bodies. However, these empirical models usually assume complete mixing of water column and a linear relationship between algal growth and nutrient availability (Dumitran, 2010). Although a single limiting nutrient (e.g., N or P) related to algal growth has been further considered, the influences of multi-factor interaction and dynamic processes of river ecosystems are difficult to be represented. Considerable research results have contended that the simulated algal densities usually did not agree well with the measurements in water bodies with strong mobility. In fact, the equilibrium between phytoplankton and nutrient concentrations are generally used as a semi-quantitative assessment method in the early-stage research of the mechanistic models in terms of lakes and reservoirs with static water flow. This equilibrium method has been rarely applied to algal bloom simulation and prediction in large rivers.

4.2. Artificial intelligence algorithms

Artificial intelligence (AI) algorithms have been widely used in many research fields. AI is thought to be more powerful in handling nonlinear problems than the regression-based empirical methods. Therefore, when solving complicated problems like large-scale river algal blooms, researchers have attempted to introduce AI algorithms to understand the changing processes of river ecosystems (Maier and Dandy, 1997; Recknagel, 1997; Whitehead et al., 1997). On the basis of grey correlation analysis, Wang (2006) built a mathematical algal growth model (logistic regression) for Jialing River in China, and the relationship between Chl-a and hydrological and water quality was identified. In addition, Hou et al. (2006) established a radial basis function neural network model to simulate the outbreak process of blue algal blooms in Darling River, Australia, and identified the contributions of the main hydrological factors. Liu et al. (2007) developed a simulation and forecasting system for river algal blooms in Beijing based on the modified back-propagation neural network. Moreover, accurately forecasted the daily change of Chl-a and algal blooms in the river by a multi-variant BP artificial neural network model. According to a high prediction accuracy AI based model of Daning River in the Three Gorges Reservoir Region in China, Wang and Zheng (2013) highlighted that algal density is correlated with hydrodynamic factors. Kim et al. (2014) simulated algal bloom dynamics in a Han River (Korea) by using the ensemble Kalman filter or assimilation of water quality variables in the framework, linking uncertainty of model simulation and observation. Cha et al. (2016) developed a Bayesian hierarchical approach to model seasonal algalvari ability along an upstream to downstream of Nakdong River in Korea, the model result was successfully captured the shift in the spatial and monthly patterns of Chl a. Shen et al. (2019) applied an approach using long-term observational data (from 1990 to 2013) and the Support vector machine (LS-SVM) for simulating algal blooms in the tributary of the Chesapeake Bay, the modelling results indicate that the data-driven model is capable of simulating interannual algal blooms with good predictive skills and is capable of forecasting algal blooms responding to the change of nutrient loadings and environmental conditions. Generally, although linear regression and mechanistic models could not effectively solve river eutrophication problems due to the simplified model structure, AI algorithms have the potential to more accurately simulate river algal blooms due to their powerful self-learning and training abilities. Although the AI-based models can accurately characterize the nonlinear relationships among multiple variables, the underlying mechanisms are still unclear. Therefore, it is necessary to develop mechanistically-based eco-environmental models in terms of river algal blooms.

4.3. Ecological dynamics models

An ecological dynamics model couples hydrodynamic processes with ecological processes, and considers the interactions among multiple subsystems. Most early-stage algal ecological models were developed based on the conceptual "box-type" water quality models (Chen, 1970). For instance, Jørgensen et al. (1978) developed the ecological phytoplankton model and simulated the formation process of algal blooms, where the conventional single-pollutant water quality model was extended to account for multiple variables in the water body, such as suspended solids, sediment release, and multiple organic and inorganic nutrients. The Jørgensen's model was further incorporated into a comprehensive water quality model, which represented the generation and disappearance of phytoplankton and zooplankton with light conditions, air temperature, and nutrient availability (Panda et al., 2010). Owing to the advancement of computer performance and Geographic Information System technology, the river eutrophication model has been closely coupled with hydrodynamic and water quality models since 2000. Commercial software for large-scale integrated water quality modelling has been developed, such as MIKE, WASP *(Water Quality Analysis Simulation Program)*, EFDC *(Environmental Fluid Dynamics Computer Code)*, and QUAL2E. For example, Shen et al. (2016) develop a hydrodynamic model for long-term simulation of water quality processes and harmful algal blooms of the Tidal James River of Virginia, results show that freshwater discharge is the most sensitive for an accurate simulation of salinity and transport time. Kim et al. (2017) aimed to improve the prediction accuracy for harmful algal bloom in the lower Han River (Seoul, Korea_, by using the Environmental Fluid Dynamics Code (EFDC) to understand algal dynamics and thus better develop management alternatives for government decision making. O'Hare et al. (2018) develop a conceptual model to describe how aquatic plants respond to river eutrophication, and the application of the model to management, system remediation, target setting, and understanding of multi-stressor systems was discussed. Different from the "Black-Box Models" that systematically represented the relationship between a single output and multiple inputs, the ecological dynamics models mechanistically integrated the physical, chemical, biological, and hydrodynamic processes driven by multi-factors and multi-pollution-source-inputs. Although these process-based models have well described the mechanisms for river algal blooms influenced by multiple factors, they often include a large number of parameters and require huge amounts of data for model calibration and validation (Han et al., 2003; Liang et al., 2006; Elliott et al., 2010; Elliott, 2012a, 2012b) Therefore, the development and application of river algal blooms models remains challenging, such as (i) how to optimize and improve modular structures of the model; (ii) how to effectively determine the parameters in multiple processes (physical, chemical, biological, and hydrodynamic) by the experimental data; and (iii) how to identify the influences of multi-factors on various processes related to algal blooms in the drainage basin.

4.4. Research progress in water system models

Since the outbreak of river algal blooms is a multi-factor influencing process with relatively more complicated changes in hydrodynamic conditions than lakes and reservoirs (Whitehead et al., 2015), researchers have paid attention to the interaction between hydrological and ecosystem processes impacted by human activities and socioeconomic development (Cha et al., 2016; Xia, 2011; Xia et al., 2018). With the rapid advances in computer technologies in recent decades, watershed-scale hydrological and water quality models based on coupled land–atmosphere processes have been developed. These models consider not only the ecological dynamics processes in the watercourse but also the influences of hydrological processes and human activity outside the watercourse. Water system models coupling hydrological, water environmental, and water ecological processes have been developed and improved in past decades. Water system models, based on spatially-distributed hydrological models (DHMs), have been extensively used and further developed. Such DHMs include the Xin'an River Model (Li et al., 2007), the Distributed Time-Variant Gain Model (DTVGM) (Xia, 2011; Xia et al., 2001), the Dualistic Water Cycle Model (DWCM) (Wang and Jia, 2016), and the Hydro-informatic Modelling System (HIMS) (Liu et al., 2007). Pyo et al. (2017) simulated seasonal variability of phytoplankton in stream water using the modified SWAT model, results are useful in predicting the dynamics of the three studied algal groups and evaluating the best management practices for algal blooms in watersheds. Yan et al. (2016) proposed a rough set theory to identify the spatial and temporal relation rule acquisition of eutrophication in Da'ning River in China, result indicated that the temporal and spatial differences between eutrophication phenomena in the long river section of the Da'ning River backwater area were significant. All these hydrological models have been extended to represent multi-factor, multi-process and multi-scale water-ecological-environmental processes. However, the interaction and feedback mechanisms, coupling and decoupling processes, and mismatching in spatial scales of data among multiple subsystems have hindered the application of these models (O'Hare et al., 2018). More information regard to the river algal models show in Table 1.

Table 1
Characteristic of different approaches for river algal blooms.

Models	Process	Model Factors	Study Area	References
Logistic regression	water quality	Chl-a, COD, TP	Jialing River, China	Wang (2006)
Neural network	hydrodynamic and water quality	Flow, Chl-a	Darling River, Australia	Hou et al. (2006)
BP network	meteorological,hydrodynamic, water quality, water ecology	temperature, water flow, TP, TN, algal density	Hanjiang River, China	Xia et al., 2012a, 2012b
Fuzzy-based model	meteorological, water quality	water and air temperature, Wind speed, BOD, DO	Ganges river basin, India	Srinivas and Singh, 2018
Ensemble Kalman filter (EnKF)	hydrodynamic and water quality	DO, TP, TN, COD, Chl-a, Flow	Han River, South Korea	Kim et al. (2014)
The rough set theory (RST)	water quality	Chl-a, TP, TN, COD_{Mn}, SD	Da'ning River, China	Yan et al. (2016)
Bayesian hierarchical approach	hydrodynamic and water quality	Chl-a, TP, Flow	Nakdong River South Korea	Cha et al. (2016)
Hydrodynamic Model	hydrodynamic and water quality	Chl-a, Salinity, temperature, flow, wind	Tidal James River, Virginia	Shen et al. (2016)
SWAT	Hydrologic, water quality, water ecology	Flow rate, TN, TP, Cyanobacteria, green algae, and diatoms	Sangju Reservoir basin, South Korea	Pyo et al. (2017)
EFDC	hydrodynamic and water quality	TP, TOC, TN, Chl-a	Han River, South Korea	Kim et al. (2017)
Conceptual Model	water ecology	Light, nutrients, biomass	–	O'Hare et al. (2018)
Support vector machine (LS-SVM)	hydrodynamic and water quality	Flow, TSS, TN, TP, light,	James River estuary, USA	Shen et al. (2019)

5. Future research

In the next 10 years, we expect that cross-disciplinary integrated study will become the trend of hydrological-ecological-environmental science (FE, 2014; Baattrup-Pedersen et al., 2016a, 2016b; Zhang et al., 2017). Future research regarding large-scale river algal blooms should focus on the following aspects. First of all, the interaction mechanism between the influence factors of river algal blooms is complicated under actual conditions. Such conditions include the direct and indirect influences of rainfall and temperature on the river hydrological regime during the algal growth process, the influences of the downstream hydrological regime change caused by sluice-dam operations, as well as the increase of multiple nutritive salts in the water body due to industrial and domestic pollution discharges. It is important to scientifically separate and identify key factors causing the outbreak of river algal blooms and their respective contributions. AI algorithms and machine learning based on big data could be one of the advanced methods that help to solve the problems. Future studies should focus on the “detection”, “effect” and “attribution” analyses of the three interrelated key scientific issues, namely, hydrological change under changing environment, nutrient load changes caused by human activities and bloom problems caused by river runoff changes that result from engineering water diversion.

Second, the relationship between complicated river hydrological conditions and the outbreak of algal blooms should be identified. Relative to lakes and reservoirs, the hydrological conditions of river are more complicated. For instance, the river algal blooms occurred in the downstream of Hanjiang River in China was located near an estuary, where Hanjiang and Yangtze Rivers intersect. The downstream hydrological processes were not only impacted by water discharge from the Danjiangkou Reservoir on the upper Hanjiang River, but also closely related to the inflow from the main stream of the Yangtze River. Therefore, how to comprehensively consider and identify the influence of river hydrological regimes, as well as the effect of upstream water diversion project on the occurrence of river blooms, are important in providing scientific and technical support for revealing the mechanisms of algal blooms under complex river hydrological conditions.

Third, scientific research regarding water system modelling need to be further conducted. These studies should combine the water system theory to identify the key factors and driving mechanism of river bloom formation under the background of water conservancy project, in order to establish a multi-process and multi-factor coupled algal bloom model that is applicable to simulate complicated hydrological conditions in large rivers. Some key technologies should be further investigated, for example the distributed hydrologic modelling technologies for large-scale watershed, coupling of physically-based model and conceptual model, as well as the modelling of water quality and ecological processes under complex hydrological conditions. Moreover, the effects of human activities, such as reservoir operation, land use change, water usage, industrialization, and urbanization on watershed hydro-environmental and ecological processes should be also considered. Most phytoplankton ecological models are built based on lake environment without specific consideration of the influences of hydrological and hydrodynamic processes in the drainage basin on algal growth process. With the hydrological cycle as the core medium, a “water cycle–water quality–water ecology” system model should be developed, which can reflect the changes of hydrological conditions, the transport of pollutant sources in river channels, and the algae growth and death. Only in this way can the contribution of each factor to the occurrence of river algal blooms be quantitatively analyzed.

Last but not least, a regulation scheme to inhibit the outbreak of river algal blooms under limited runoff should be developed. Flow regulation is being used in China as a preventive measure to control river and lake algal blooms. For instance, increasing reservoir water release to dilute the concentration of downstream pollutants during river blooms could inhibit algal growth. However, an outbreak of river algal blooms is commonly closely related to the construction of large-scale water conservancy projects. For instance, the Danjiangkou Reservoir is located on the lower reaches of Han River and plays a strategic role in the middle route of the SNWDP. However, the algal blooms usually outbreak during the dry season in spring. Although increasing water release rate might dilute algal accumulation within a short time, it would waste a considerable amount of water, further increasing the water supply pressure in North China. Therefore, exploring the influence of the water diversion project on river algal blooms is important to prevent the outbreak of river algal blooms by changing hydrodynamic conditions under limited water resources.

This paper reviewed existing literature and modelling studies on river algal blooms in recent decades to explore the nature of the cause of large river blooms. We concluded that: (i) river algal blooms are a comprehensive water ecosystem issue impacted by multi-factors, including climate change and human activities; (ii) the interactive mechanism between the influence factors of river algal blooms is complicated under natural conditions, and the understanding the causes of river algal blooms depends on how to scientifically separate the multiple impact factors and quantify their respective contributions; (iii) regarding the complex interactions between hydrological processes and river algal blooms, it is essential to develop an integrated water system model of algal blooms under complicated hydrological conditions; and (iv) future studies should focus on the multi-scenario simulation and prediction of the outbreak of river algal blooms and the identification of multi-factor effects. The model-data integration accounting for multi-factor effects was expected to provide scientific guidance for the prevent and control of algal blooms in large river systems.

Conflicts of interest

No conflict of interest exits in the submission of this manuscript.

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Appendix A. Supplementary data

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