American Journal of Biochemistry and Biotechnology

Original Research Paper

Effects of Hydrodynamic Conditions on Algal Organism Growth

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Article history
Received: 12-04-2024
Revised: 19-06-2024
Accepted: 24-06-2024

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Abstract: The growth of algal organisms is influenced by hydrodynamics, making it a crucial aspect of algal biology. We summarize recent studies on the impact of hydrodynamics on algal growth, with a specific focus on current velocity. In the past, extensive attention has been paid to the direct effects of impact factors on algal blooms and there is still a certain gap in the impact mechanisms at the cellular level. Recent literature is compared to review the effects of current velocity, flow change the water level, and the mechanism of hydrodynamic effects on algal blooms, thereby briefly summarizing the effects of temperature, light, DO, and nutrient concentration on algal blooms. The critical thresholds for temporal flow velocity and temporal wind velocity are also provided for two eutrophication lakes, Taihu Lake and Poyang Lake, aiming to provide a reference for the flow velocity classification criteria of the three major water bodies: Nullahs, rivers, and lakes. The mechanism of hydrodynamic conditions on algal growth is mainly reflected in three aspects: (1) It affects the distribution of nutrient salts and then regulates the growth and enrichment of algae; (2) It alters the transport process of nutrient salts and affects the cell function; (3) It destroys the integrity of the cell structure of algae and inactivates them. The results are significant for understanding the growth mechanism of algal organisms under hydrodynamic conditions and provide guidance for future research.

Keywords: Hydrodynamics, Algae, Algal Blooms, Water, Cellular Level

Introduction

Algae are a group of organisms without true differentiation of rhizomes and leaves. Most of them can photosynthesize and reproduce with unicellular spores and conidia. With the intensification of human activities and the increasing prevalence of eutrophication in water bodies, the uncontrolled growth of algal organisms in water bodies is gradually increasing, leading to more frequent algal blooms. Algal blooms cannot only cause serious pollution to aquatic environments but also pose a threat to the stability of aquatic ecosystems, biodiversity, and human health (Thawabteh *et al*., 2023; Zhang *et al*., 2022; Treuer *et al*., 2021).

Algal blooms are an extreme phenomenon after eutrophication in water bodies because the uncontrolled proliferation of algal organisms would cause a number of ecological problems (Zhang *et al*., 2022). In addition to the effects of temperature, light, DO, TN, and TP, hydrodynamic conditions are also considered to be an essential factor affecting the growth and aggregation of algae in oceans, lakes, and rivers (Chen *et al*., 2015). For example, Yang *et al*. (2022) found that the ratio of mixed water depth to true photosphere depth is significantly negatively correlated with the concentrations and growth of algae in the Three Gorges Reservoir. In recent decades, the mechanisms of algal growth have been increasingly studied and one of the focuses has gradually shifted to the effects of hydrodynamic conditions on algal growth. Hydrodynamic conditions include factors such as water velocity, changes in water flow, and water level. These factors directly affect the survival and growth of algae in the water body, which in turn play a crucial role in the occurrence and development of algal blooms.

Previous researchers have reviewed the effects of the influencing factors such as temperature, light, DO, TN, and TP on algal blooms, but more attention has been paid to the direct effects between the influencing factors and algal blooms. The internal reasons are complex and have not been elaborated at the cellular level. There is still a certain gap in the mechanism of influencing factors on the cellular effects, as well as a lack of uniform criteria for the classification of flow rates in different water bodies. To better understand the growth mechanism of algae and prevent the occurrence of algal blooms, as well as explore the mechanism of hydrodynamic conditions on algae growth, we mainly review the effects of current velocity, flow change, and water level on the growth of algal organisms and the mechanism of hydrodynamic effects on algae, thereby briefly summarizing the effects of temperature, light, DO and nutrient concentration on algae. The critical thresholds of temporal flow velocity and temporal wind velocity are also provided for two eutrophication lakes: Taihu Lake and Poyang Lake, aiming to provide a reference for the flow velocity delineation criteria for the three major water bodies: Nullahs, rivers, and lakes.

The purpose is to provide some references for the study of the growth mechanism and cell-level effects of algal organisms under hydrodynamic action and to provide some guidance for future research of algal growth under hydrodynamic conditions, as well as support for the prevention and control of algal blooms.

Materials and Methods

This study focuses on the effects of hydrodynamic conditions on algal growth in freshwater bodies, which are divided into four categories according to different water body types: Nullahs, rivers, lakes, and reservoirs. The lakes cover two typical eutrophication lakes in China: Taihu Lake and Poyang Lake. In terms of rivers, the main tributaries of the Yangtze River and the Pearl River system in China are selected. The distribution of the specific study areas is shown in Table (1). In the following tools, outdoor experiments refer to the measurements and experiments conducted in the field; model simulation refers to the construction of a mathematical model of hydrodynamics for simulation and in-situ observation refers to field observations in the study area or the acquisition of in-situ data through techniques such as satellite remote sensing.

Research data collection is carried out prior to the preparation of the thesis. The data were collected from two major databases, CNKI and Web of Science. During the data collection process, the literature of the last three years is mainly used as a reference to ensure that the data obtained are highly and timely reliable. When collecting data, terms such as hydrodynamics, current flow rate, change in flow rate, algal organisms, cyanobacteria, algal blooms, flow, water level, change in water level, lakes, rivers, and open channels are all included in the collection criteria. The data collected for the study are organized into four categories: Flow rate, flow, water level, and impact mechanisms. The effects of factors such as flow rate, flow rate, and water level changes on the growth of algal organisms in the relevant water bodies are studied by analyzing the collected data, comparing and analyzing the experiments of different authors on the same type of water body, including research methods, data selection and comparison of experimental results.

Table 1: Research area distribution and research factors

Research area	Type of water body	Research tools	Research factors	References
Wuhan university proving ground	Nullah	Outdoor tests	Flow velocity	Shaoyi *et al*. (2024)
Waquoit bay	Stream	Indoor tests	Flow velocity	Escartín and Aubrey (1995)
Middle and lower reaches of the Han river	Stream	Model simulation	Flow velocity	Jian *et al*. (2022); He *et al*. (2024)
Huizhou section of the Dongjiang river basin	Stream	Indoor tests	Flow velocity	Zhou *et al*. (2018)
Taihu Lake	Lake	In situ observations and tests	Flow velocity	Li *et al*. (2023); Wu *et al*. (2013)
Poyang Lake	Lake	In situ test	flow velocity	Ping *et al*. (2024)
Pampean	Stream	In situ test	flow rate	Acuña *et al*. (2011)
Middle and lower reaches of the Han river	Stream	Model simulation	Flow rate	He *et al*. (2024)
Zipingpu	Reservoir	In situ test	Water level fluctuation	Liao *et al*. (2024)
The three gorges	Reservoir	In situ test	Water level fluctuation	Cui (2018)
Shiyan	Reservoir	In situ test	Water level fluctuation	Ke *et al*. (2019)
Jialing	Stream	Indoor tests	Water level fluctuation	Wang *et al*. (2021a)

Results

Effects of Water Velocity on Algae

Water currents are the main driver of underwater algal transport and current speed and direction play an important role in the distribution and aggregation of algae in the water column (Cui *et al*., 2023; Wu *et al*., 2023). If the propulsive force is insufficient, too many algae can accumulate in the water, leading to algal blooms in the lower reaches of rivers and in the center of lakes, with serious consequences for aquatic ecosystems (Wu *et al*., 2023).

Numerous studies (Pan *et al*., 2023; Sun *et al*., 2023; Mondal and Banerjee, 2023; Cao *et al*., 2022) have shown that the response of algal blooms caused by different algal species to flow velocity varies significantly in different water bodies (nullahs, rivers, lakes, etc.). The changes in flow velocity have a great effect on algal biomass and physiological and biochemical characteristics. For example, there is a gap in the response of cyanobacteria, methanogens, and diatoms to changes in flow velocity. When the flow velocity was lower than 0.05 m/s, the proportion of cyanobacteria and diatoms was the largest; when the flow velocity was between 0.05 and 0.10 m/s, the proportion of cyanobacteria decreased and the proportion of methanobacteria and diatoms increased; when the flow velocity was greater than 0.10 m/s, the proportion of methanobacteria decreases and the proportion of diatoms increased continuously (Li *et al*., 2019). The sensitivity of different algal cells to changes in flow velocity is different and there is a single-peak curve relationship between algae and flow velocity. The internal reasons for the sensitivity differences in the response of different algae to flow velocity changes need to be further investigated, such as changes in flow velocity caused by changes in the activities of various enzymes in the algal cells. The mechanism of flow velocity on the growth of live algae has been studied (Calvo *et al*., 2022; Shaoyi *et al*., 2024). It was found that increasing the flow velocity can accelerate the transport of nutrients and promote the cellular metabolism of algae as well as the uptake of nutrients, thereby promoting the growth of live algae. However, if the flow velocity is too high, the living algae will be abraded and stripped under the action of shear force and scouring of suspended particles, or the attached sediment substrate will be eroded by the water flow and directly shed. This will reduce the biomass of living algae and change the composition of the community.

Nullah

Open nullahs do not contribute to eutrophication or algal blooms. Eutrophication is caused by the introduction of excess nutrients (e.g., nitrogen, phosphorus, etc.,) into the water column and nullahs can promote or exacerbate eutrophication under certain circumstances (Xia *et al*., 2020). For example, when there is agricultural land or agricultural activity around the nullahs, fertilizers, and pesticides discharged from agriculture can enter the nullahs through drainage from the agricultural land, resulting in an increase of nutrients in the nullah water bodies and triggering eutrophication. Similarly, wastewater discharged into nullahs from municipal sewers can cause eutrophication of nullahs if the wastewater is not adequately treated with nutrients rich in N, P, and organic matter.

Therefore, open nullahs do not cause eutrophication per se, but under certain conditions, they can be one of the transmission pathways of eutrophication. Algal growth in open nullahs is also an important area.

Shaoyi *et al.* (2024) found that the biomass of epiphytic algae increased and then decreased with the increase of flow velocity in the nullah. The highest biomass was found at a flow rate of 0.6 m/s, while the lowest biomass was found at a flow rate of 0.8 m/s. The results showed that the maximum algal biomass was at low flow velocities (0.8 m/s) and the lowest biomass was the lowest. The results showed that low (0.2 m/s) to moderate (0.6 m/s) flow rates promoted the growth and reproduction of live algae, while high (0.8 m/s) flow rates inhibited the growth of living algae. There is a critical threshold of about 0.6 m/s for the influence of flow velocity on algal growth in open channels. The water flow rate in the nullah can be controlled to a range of more than 0.8 m/s, effectively scouring the sediment substrate, stripping off the growth of algae, and improving the aquatic environment of the nullah.

An in-depth study of the growth mechanisms of algae in open channels is of great importance for the prevention and management of eutrophication in water bodies and also provides a scientific basis for the sustainable use of water resources. Further studies on the adaptation mechanism of algae in open channels and the threshold range of flow velocity in open channels are needed to better assess and control the impact of open channels on eutrophication and algal bloom occurrence.

Stream

Eutrophication in rivers is one of the reasons for the destruction of river ecosystems in recent years and the abnormal proliferation of algae in river ecosystems has become the most important point of concern in the study of eutrophication in water bodies. The flow rate is one of the key environmental factors in river water ecosystems, which is of great importance in the study of the abnormal proliferation of algae and understanding the formation mechanism of eutrophication in water bodies.

Through his research, Escartin was the first to propose a minimum flow velocity for the destruction of algal structures of rivers. Based on the results of the flume study, he pointed out that in order to destroy the algal community structure, the flow velocity must reach 0.10 m/s, i.e., 10 cm/s, and that the heterogeneity of the algal structure plays an important diffusion role in the dispersal of algae (Escartín and Aubrey, 1995). This indicates that the algal community structure is relatively stable at a velocity of less than 0.10 m/s.

Jian *et al*. (2022) proposed that the threshold flow rate for water bloom control in the middle and lower reaches of the Han River was between 0.20 and 0.67 m/s. He *et al*. (2024) further found that when the flow rate reaches 0.462 m/s, the flow rate will continue to increase and inhibit the growth of algae. The former used the Mike 21 model to simulate and invert the flow velocity during the bloom occurrence, which was longer than the latter and the data selection was more targeted. However, it is insufficient because it only focuses on the initial period of blooms and the beginning of bloom recession. The latter selected the point data from 2015-2019 to study the relationship between flow velocity and algal density in different months, as shown in Fig. (2). The flow rate reaches its maximum in summer, and algae are transported through hydrodynamics, making it difficult for algae to aggregate and eutrophication to occur in the water. The negative correlation between algal density and flow velocity is more intuitive. Considering the effect of water temperature on algal density, the algal data affected by water temperature was excluded in Fig. (3). The suitability curves for flow rate and algal density were obtained by fitting polynomial curves. The fit $R^2$is 0.954, with a p-value less than 0.05, which is better than that in Fig. (1). The fitting was 0.79 in the Sha yang area and 0.69 in the Xian Tao area, with a smaller error and strong correlation between the two.

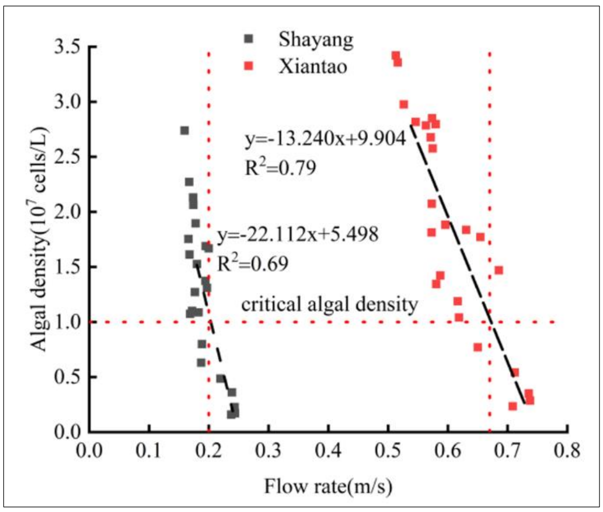

Fig. 1: Critical algal densities and critical flow velocities at Shayang and Xiantao sections (thin dashed lines are critical values) (Jian *et al*., 2022)

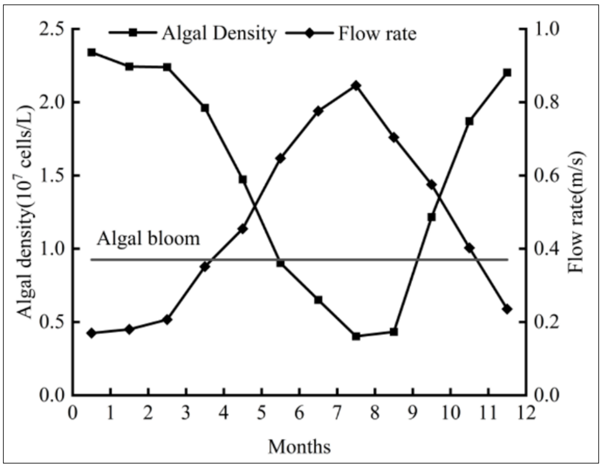

Fig. 2: Characteristics of algal densities and flow rates over time at different time periods (He *et al*., 2024)

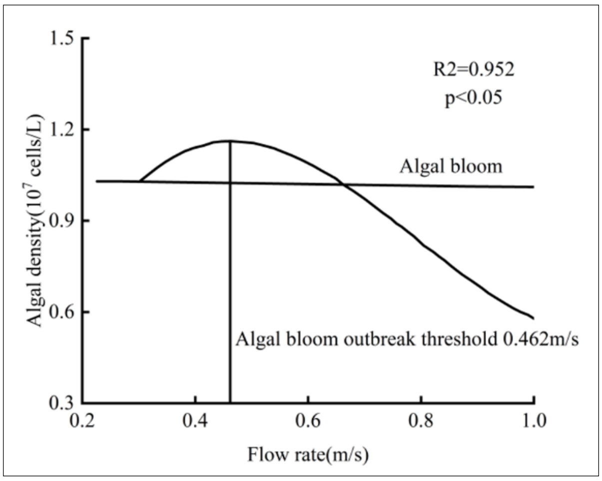

Fig. 3: Algae density versus flow suitability curve (He *et al*., 2024)

Zhou *et al*. (2018) used an annular Plexiglas flume to cultivate algae in the raw water of Huizhou River, Guangdong Province, Dongjiang River Basin. It was found that: Microcystis aeruginosa had weak growth under different flow rates and the reproduction rate of Microcystis aeruginosa and Microcystis aeruginosa was faster under low flow rate (<0.075 m/s). This had a promoting effect on algal growth with an increasing flow rate of the water body. The growth of algae was inhibited with increasing flow rate under a high flow rate (>0.075 m/s). Different continuous flow conditions are important factors influencing the changes in plank tonic algal abundance and physiological indices.

Song (2023) proposed that direct hydrodynamic effects could inhibit algal growth, while indirect hydrodynamic effects could promote algal blooms. This viewpoint is consistent with the conclusions obtained from previous studies. The riverine water environment is more complex than other water environments and the

DOI: 10.3844/ajbbsp.2024.292.301

influencing factors are more diversified. There are interactions between the influencing factors to regulate each other (Wang *et al*., 2021b). The influence and mechanism of the coupling effect of flow velocity and other environmental factors on algal organisms remain unclear and its coupling effect and mechanism of action need to be studied in depth.

Lake

Large lakes have been prone to serious eutrophication, resulting in cyanobacterial blooms. This is caused by the abnormal proliferation of algae that gradually forms over time. Therefore, the growth process, mechanism, physiological characteristics, and factors affecting algae growth are still hot topics. The water flow rate and water body disturbance in lakes are important factors that influence the hydrodynamic conditions of lakes.

In eutrophic lakes, the hydrodynamic process has a significant impact on the vertical movement and horizontal migration of algae (Ranjbar *et al*., 2022), e.g., flow velocity can have an impact on algal community structure and colony migration. Wu *et al*. (2013) demonstrated that when the average flow velocity of the water body exceeded 5.7 cm/s, the cyanobacterial community was entrained by wind-induced hydrodynamics. The vertical migration of algal biomes was controlled by hydrodynamics, mixing with algal organisms at different depths throughout the water body, ultimately leading to the disappearance of the surface bloom of Taihu Lake. Water flow velocity affects the nutrient transport process in lakes. Wan *et al*. (2013) found that the critical velocity of the Phosphorus (P) exchange process at the sediment-water interface of Taihu Lake ranged from 7-15 cm/s. Below the critical flow velocity, Particulate Phosphorus (PP) migrates to the Suspended Particulate Matter (SPM), whereas above the critical flow velocity, PP is released in the water. The changes in Total Phosphorus (TP) in the water column have a direct effect on algal growth and nutrient transport under flow conditions. Knowing the critical flow rate and wind speed is crucial for dealing with algal bloom in water bodies. For instance, in Poyang Lake, the critical flow rate and wind speed for algal bloom are 5 and 3-4 m/s, respectively (Ping *et al*., 2024). The critical thresholds for the occurrence of algal blooms in different lakes are shown in Table 2, while Table 3 presents the division of flow velocity and critical thresholds for different water bodies. In Table 2, the time span of the references is large and the statistical samples are numerous. The statistical results show Gaussian distribution and the critical thresholds obtained are basically consistent with the predicted values of the model. Table 3 shows the critical thresholds of the flow rate referring to the occurrence of algal bloom in the water body and the division of the flow rate is only for the purpose of investigating the effect of the flow rate on the growth of algae, providing an optional interval for the study.

Table 2: Critical thresholds for flow/wind speeds triggering algal blooms in lakes

Lakes	Flow rate	Wind velocity	References
Taihu lake	5.7cm/s	3.4 m/s, 6 m/s	Li *et al*. (2023); Wu *et al*. (2013)
Poyang lake	5 cm/s	3~4 m/s	Ping *et al*. (2024)

Table 3: Classification of flow velocities and critical thresholds for various water bodies

Water bodies	Low flow rate	Critical thresholds	High flow rates	References
Nullah	0.2 m/s	0.6 m/s	0.8 m/s	Shaoyi *et al*. (2024)
Stream	0.075 m/s	0.462 m/s	/	He *et al*. (2024); Zhou *et al*. (2018)
Lake	5 cm/s	5.7cm/s	/	Wu *et al*. (2013); Ping *et al*. (2024)

Flow velocities can provide information about the speed and stability of water flow, helping to understand the dynamic behavior of water bodies. However, flow velocity alone cannot provide insight into the internal flow characteristics around algal cells, nor can it accurately describe flow phenomena at the microscopic scale. The microscopic flow characteristics are the critical factors in the growth of algal cells. These characteristics involve intracellular biological processes, such as the transport of materials, nutrient supply, and waste excretion. Therefore, to obtain a more comprehensive understanding of the growth mechanism of algal cells, future research should focus on exploring the complex flow behavior of algal cells using sophisticated technological tools and analytical methods, such as microscopic flow simulation and intracellular hydrodynamics.

Effects of Flow Changes on Algae

Human activities, such as constructing reservoirs and dams to hold floodwaters, can significantly impact the flow of water in rivers. This, in turn, affects the physiological activity of algae in the water column.

Studies have shown that alterations in water flow can impact the environment of algal growth, ultimately affecting algal blooms. For instance, during high-flow conditions, the concentration of dissolved oxygen in the water column increases, providing oxygen for algal growth. On the contrary, under low or no flow, the concentration of dissolved oxygen decreases and limits algal growth (Yang *et al*., 2015). In addition, alterations in flow rate can impact the aggregation and dispersion of algae. Typically, under a high flow rate, the forced exclusion of water heightens the degree of algae dispersion, thereby decreasing the likelihood of algae aggregation. Under low or no flow rate, algae are more prone to aggregating and forming blooms (Xu *et al*., 2024; Acuña *et al*., 2011).

Changes in flow rate can impact the nutrient content of the water body and cause the occurrence or disappearance of eutrophication. The increase in flow rate will promote the dilution of organic matter and nutrients (such as nitrogen and phosphorus) in the water body. This will change the nitrogen-phosphorus ratio and other limiting factors on algae growth, so as to control eutrophication and prevent algal blooms. Acuña *et al.* (2011) demonstrated that the primary productivity of algae increased under low flow (13.8 L/s) and decreased by an order of magnitude under high flow (1300 L/s). This is because the dilution of nitrogen and phosphorus concentrations in the water column affects the survival of algae. Controlling flow conditions can provide new indicator parameters and treatments for managing algae in streams to prevent algal blooms.

To prevent and control algal blooms, it is important to determine the flow threshold of key sections. According to He *et al.* (2024), the optimal flow rate threshold for preventing and controlling algal blooms in the middle and lower reaches of the Han Jiang River was 0.462 m/s, and the ecological flow rate of it was determined using the section flux method, and the flow inhibition method. When the flow rate was 890, 918, 953, and 1075 m^3/s in the Sha Yang, Qian Jiang, Xian Tao, and Han Chuan sections respectively, Han Chuan can meet the ecological flow demand of the river without causing algal bloom. Among them, the section flux method uses Eq. (1). The ecological flows at key sections of the Han River for algal bloom prevention and control are shown in Table (4):

$$Q_c \geq \frac{C_0(\mathrm{PM_d}-\mathrm{WS_d})}{\mathrm{K}(\mathrm{C_2}-\mathrm{C_1})} \quad (1)$$

where, C_0 is the initial density of algae (g/m^3); C_2 is the density of algae inflow (g/m^3); C_1 is the density of algae outflow (g/m^3); PM_d is the net growth rate of algae (d^{-1}); WS_d is the mortality rate (d^{-1}); K is the period conversion factor and Q_c is the cross-sectional flow (m^3/s).

The changes in river runoff will directly affect the habitat of aquatic organisms in the water body, the primary productivity of aquatic algae, and the transport and cycling of nutrients, thereby affecting the structure and function of the ecosystem of the entire watershed from the bottom up. In flow management, the responses at the water column replacement and cellular levels should be considered separately to effectively regulate algal growth in rivers. An in-depth understanding of flow changes on algal growth and nutrient transport is of great significance to ecology.

Effect of Water Level on Algae

Several studies have demonstrated a negative correlation between the water level and the amount and growth of algae in lakes and rivers. Fluctuations in water level have an indirect effect on the growth of algae and changes in nutrient salts and water retention time due to fluctuations in water level are among the main factors affecting the growth of algae (Liao *et al*., 2024; Ye *et al*., 2022; Ferencz *et al*., 2023).

In natural water bodies along shorelines, rising water levels increase erosion of the shoreline and flash a large amount of sediment into the water from rivers. This sediment contains a high concentration of nutrient salts, which increases the nutrient content of the water. In artificial shoreline waters, the growth of algae is affected by water levels. The high water level dilutes the nutrient salt content and reduces the concentration of nitrogen and phosphorus, as well as the concentration of algae, which helps alleviate the high density of algae aggregation. The study of the three gorges reservoir, (Cui, 2018) found that the impoundment process can promote the deepening of the mixed layer in different sections of the reservoir bay, increase the vertical movement of algae, reduce the time of algae to receive light, thus reducing the rate of algal proliferation. The impact of mixing during the discharge process is relatively small and the stratification of the water body is strong. Algae explode and proliferate on the surface of the reservoir, forming water blooms.

The growth of algae is not only affected by the water level but also by the water level fluctuation in the reservoir. For instance, (Ke *et al*., 2019) investigated the impact of water level fluctuations on the concentration of algal chlorophyll a. Through experiments, it is found that alternately raising and lowering the water levels can destroy water stratification caused by the stratified heterogeneous flow, increase water exchange and effectively prevent the stratification of water temperature. In addition, this method can shorten the time of water stagnation and disrupt the reproduction and survival of algae, thereby slowing down the frequency of eutrophication and blooms. The daily amplitude of change in the water level of the reservoir also increases with this method. At the same time, the daily variation of the reservoir water level increased, shortening the water retention time and disrupting the conditions necessary for algal reproduction and survival. As a result, the frequency of eutrophication and algal bloom slows down. Wang *et al.* (2021a) concluded that algal blooms do not occur when the water level fluctuates by more than2 m/d. Moreover, as the water level fluctuations increase, the intensity and frequency of algal blooms decrease.

Liao *et al*. (2024) studied the impact of water level operation on algal blooms in Zipingpu Reservoir. They found that a decrease in water level leads to a slower water flow rate and an increase in the retention time of the water body. They also observed that the temperature tends to rise fast when the water body becomes shallow, which promotes the growth of algal blooms that thrive in low flow rates and high temperatures.

Table 4: Ecological flow at key sections of Han River for algae bloom prevention and control

Sha Yang	Qian Jiang	Xian Tao	Han Chuan
890 m^3/s	918 m^3/s	953 m^3/s	1075 m^3/s

Understanding the effect of water level on algal growth can provide a theoretical basis for the prevention and control of algal bloom in reservoirs. In the dry season, maintaining a high water level and controlling the bottom flow rate can control the density of algal growth and avoid the release of nutrient salts in bottom sediments. During the flood season, maintaining the water level in a fluctuating state through hydraulic mobilization can effectively regulate the structure of algal groups and the environment in which the algae grow in the reservoir for algal bloom prevention and control.

Effects of Other Environmental Factors on Algae

In addition to hydrodynamic conditions, other environmental factors can also have an impact on algal growth. Moresco *et al.* (2024) found that elevated temperatures can promote algal primary production and that there was a potential positive feedback relationship between cyanobacteria and elevated temperatures. Chunzhuk *et al.* (2023) demonstrated that it was possible to increase algal biomass productivity through light by culturing microalgae under five different light intensities. Dissolved Oxygen (DO) is essential for aerobic respiration of algae in the water column. Low DO levels can lead to slow growth or even death of algae, while high DO levels can inhibit photosynthesis and be harmful to algal growth. In addition, an increase in atmospheric CO_2 concentration may increase the concentration of dissolved CO_2 in the water column through atmosphere-water exchange. The increase in CO_2 concentration in the water column may increase the efficiency of phosphorus utilization by cyanobacteria and a high CO_2 concentration may affect the activity of enzymes related to phosphorus assimilation (Ma and Wang, 2021). A change in one environmental factor may cause a chain reaction of other environmental factors. Wang *et al.* (2021b) analyzed that phosphorus concentration has a negative effect on water transparency and a positive effect on dissolved oxygen content. The study of algal growth should take into account the mutual influence and interaction between environmental factors.

Cytological-Level Response of Algae to Hydrodynamic Perturbations

Two possible mechanisms have been proposed for the influence of hydrodynamics on algal growth: First, hydrodynamics will indirectly affect algal growth by influencing the distribution of nutrient salts required for algal growth; second, at the cytological level, hydrodynamic perturbations will directly affect the structure and system function of algal cells, change the efficiency of nutrient salt transport or directly destroy the structure of the algal cell, inactivating them (Chen *et al*., 2015).

Chen *et al.* (2015) proposed three conceptual mechanisms for hydrodynamic effects on algal growth from a cytological perspective: (1) Low-intensity hydrodynamic perturbation causes the outer diffusion layer of the algal cells to become thinner, facilitating nutrient delivery from surrounding water to algal cells and promoting algal growth; (2) Moderate intensity hydrodynamic disturbances can damage the nutrient absorption and photosynthetic capacity of algal cells, inhibiting their growth; (3) High-intensity water shear leads to the breakage of algal cell walls. Therefore, scientists believe that effective control of algal growth and prevention of algal blooms in flow management requires consideration of the critical flow rates of water replacement and cytology. The results can provide important theoretical support for the strategy of maintaining water quality levels and controlling algal blooms.

Discussion

The next step in hydrodynamic research should construct a targeted dynamic model covering different water bodies and different algae. Future research can be carried out in the following directions:

(1) Explore the hydrodynamic flow characteristics of algal cells at the microscopic scale, the response mechanism of their physiological characteristics and nutrient transport, and comprehensively understand the growth mechanism of algal cells
(2) Refine the differences in the responses of different types of algal cells to hydrodynamic conditions, analyze the reasons for the differences, and obtain a deeper understanding of the influence of hydrodynamics on different algal species, especially on the organisms that cause blooms
(3) Study the influence of hydrodynamic conditions on the function of algal ecosystems: Explore the mechanism of hydrodynamic conditions on algal ecosystems, including nutrient cycling and carbon sink effects, and reveal the relationship between hydrodynamics and the health of algal ecosystems

Conclusion

The influence of hydrodynamic conditions on algal growth is mainly reflected in three aspects: (1) It affects the distribution of nutrient salts, which in turn regulates algal growth and enrichment; (2) It alters the nutrient transport process and affects the cellular function; (3) It destroys the integrity of the cellular structure of the alga and inactivates it.

There is a critical threshold for hydrodynamic effects on algal growth, where critical flow rates vary in different water bodies and their surroundings, (e.g., different sections of the same river) vary depending on the algal characteristics. Therefore, it is necessary to refine differences from the surrounding environment. Due to the influence of nutrient salts, water disturbance, algal cell growth, enrichment, and extinction, critical flow rates in natural environments have multiple thresholds. Specific research should be carried out for each water body and algal species. We only provide a reference for critical thresholds. Specific studies should be conducted for each water body and algae species. This topic only provides a reference for critical thresholds.

Acknowledgment

Thank you very much to Mr. Wang Zhifu, Mr. Feng Weihua, and Mr. Huang Baoxing for their suggestions and support in writing this article.

Funding Information

The study was funded by the National Key R and D Program of China (No. 2022YFF0802203; 2019YFD0901101) and supported by "Pioneer" and "leading Goose" R&D program of Zhejiang Province (2023C03130).

Author's Contributions

Bingxin Zhong: Conducted the data analysis and authored the manuscript.

Zhifu Wang and Baoxing Huang: Critically reviewed the manuscript.

Weihua Feng: Conceived the study design and supervised the project.

Ethics

The authors accept full responsibility for any ethical issues that may arise following the publication of this manuscript.

Conflict of Interest

The authors declare that they have no competing interests. The corresponding author affirms that all of the authors have read and approved the manuscript.

References

Acuña, V., Vilches, C., & Giorgi, A. (2011). As Productive and Slow as a Stream can be—the Metabolism of a Pampean Stream. *Journal of the North American Benthological Society*, *30*(1), 71–83. https://doi.org/10.1899/09-082.1

Calvo, C., Pacheco, J. P., Aznarez, C., Jeppesen, E., Baattrup-Pedersen, A., & Meerhoff, M. (2022). Flow Pulses Shape Periphyton Differently According to Local Light and Nutrient Conditions in Experimental Lowland Streams. *Freshwater Biology*, *67*(7), 1272–1286. https://doi.org/10.1111/fwb.13916

Cao, P., Xu, F., Gao, S., Baoligao, B., Li, X., Mu, X., Mendes, A., & Shang, X. (2022). Experimental Study on the Impact of Pulsed Flow Velocity on the Scouring of Benthic Algae from a Mountainous River. *Water*, *14*(19), 3150. https://doi.org/10.3390/w14193150

Chen, R. H., Li, F. P., Zhang, H. P., Chen, L., Zhao, J. F., & Huang, Z. H. (2015). Conceptual Mechanism of Hydrodynamic Impacts on Freshwater Algae for Flow Management. *Journal of Lake Sciences*, *27*(01), 24–30. https://doi.org/10.18307/2015.0103

Chunzhuk, E. A., Grigorenko, A. V., Kiseleva, S. V., Chernova, N. I., Vlaskin, M. S., Ryndin, K. G., Butyrin, A. V., Ambaryan, G. N., & Dudoladov, A. O. (2023). Effects of Light Intensity on the Growth and Biochemical Composition in Various Microalgae Grown at High CO_2 Concentrations. *Plants*, *12*(22), 3876. https://doi.org/10.3390/plants12223876

Cui, J., Xu, H., Cui, Y., Song, C., Qu, Y., Zhang, S., & Zhang, H. (2023). Improved Eutrophication Model with Flow Velocity-Influence Function and Application for Algal Bloom Control in a Reservoir in East China. *Journal of Environmental Management*, *348*, 119209. https://doi.org/10.1016/j.jenvman.2023.119209

Cui, Y. J. (2018). *The Sensitive Ecological Dynamic Processes and their Simulations of Algal Growth of Xiangxi Bay in the Three Gorges Reservoir [D*. Wuhan University.

Escartín, J., & Aubrey, D. G. (1995). Flow Structure and Dispersion within Algal Mats. *Estuarine, Coastal and Shelf Science*, *40*(4), 451–472. https://doi.org/10.1006/ecss.1995.0031

Ferencz, B., Toporowska, M., & Dawidek, J. (2023). Role of Hydrology in Cyanobacterial Blooms in the Floodplain Lakes. *Water*, *15*(8), 1547. https://doi.org/10.3390/w15081547

He, S. F., Hu, W., Yang, Z. L., Feng, T., Yan, H. L., Lin, Y. Q., & Chen, Q. W. (2024). Characteristics of Algal Bloom and its Threshold of Ecological Flow in the Middle and Lower Hanjiang River. *China Environmental Science*, *44*(1), 363–370.

Jian, L., Wei, Y., Haiyan, J., Xiaokang, X., & Chao, W. (2022). Study on the Ecological Regulation of Algal Bloom Control in the Middle and Lower Reaches of the Hanjiang River. *Journal of Lake Sciences*, *34*(3), 740–751. https://doi.org/10.18307/2022.0304

Ke, S. Z., Zhang, L. W., Gao, J. S., Fei, S. D., Zhu, J., & Liang, D. (2019). Effect of Water Level Fluctuation on Algae Chl-a Concentration in Source Water Reservoir. *China Water and Wastewate*, *35*(13), 78–83.

Li, Y., Zhang, H., Xiao, J., Qiu, X., & Wang, B. (2019). Effects of River Hydrology on Phytoplankton Dynamics in Dammed Rivers. *Earth Environ*, *47*(6), 857–863.

Li, Y., Zhu, S., Hang, X., Sun, L., Li, X., Luo, X., & Han, X. (2023). Variation of Local Wind Fields under the Background of Climate Change and Its Impact on Algal Blooms in Lake Taihu, China. *Water*, *15*(24), 4258. https://doi.org/10.3390/w15244258

Liao, N., Zhang, L., Chen, M., Li, J., & Wang, H. (2024). The Influence Mechanism of Water Level Operation on Algal Blooms in Canyon Reservoirs and Bloom Prevention. *Science of the Total Environment*, *912*, 169377. https://doi.org/10.1016/j.scitotenv.2023.169377

Ma, J., & Wang, P. (2021). Effects of Rising Atmospheric CO_2 Levels on Physiological Response of Cyanobacteria and Cyanobacterial Bloom Development: A Review. *Science of the Total Environment*, *754*, 141889. https://doi.org/10.1016/j.scitotenv.2020.141889

Mondal, A., & Banerjee, S. (2023). Impact of Critical Eddy Dffusivity on Seasonal Bloom Dynamics of Phytoplankton in a Global Set of Aquatic Environments. *Scientific Reports*, *13*(1), 17141. https://doi.org/10.1038/s41598-023-43745-z

Moresco, G. A., Dias, J. D., Cabrera-Lamanna, L., Baladán, C., Bizic, M., Rodrigues, L. C., &Meerhoff, M. (2024). Experimental Warming Promotes Phytoplankton Species Sorting Towards Cyanobacterial Blooms and Leads to Potential Changes in Ecosystem Functioning. *Science of the Total Environment*, *924*, 171621. https://doi.org/10.1016/j.scitotenv.2024.171621

Pan, L., Zhao, L., Zhang, M., & Lai, Z. (2023). Experimental Study of the Hydrodynamics of an Open Channel with Algae Attached to the Side Wall. *Water*, *15*(16), 2921. https://doi.org/10.3390/w15162921

Ping, Y., Jutao, L., Fang, H., Chunyun, W., Hui, W., Jiang, W., Shasha, F., & Guofei, D. (2024). Influence of Wind Field on Surface Cyanobacteria Density of Lake Poyang in Wet Season, China. *Journal of Lake Sciences*, *36*(2), 377–388. https://doi.org/10.18307/2024.0213

Ranjbar, M. H., Hamilton, D. P., Etemad-Shahidi, A., & Helfer, F. (2022). Impacts of Atmospheric Stilling and Climate Warming on Cyanobacterial Blooms: An Individual-Based Modelling Approach. *Water Research*, *221*, 118814. https://doi.org/10.1016/j.watres.2022.118814

Shaoyi, D., Mengwei, Y., Guanghua, G., Yuxuan, Z., & Yonghong, B. (2024). Response of Periphytic Algae Community Structure Characteristics to Hydrodynamic Conditions in an Open Channel. *Journal of Lake Sciences*, *36*(2), 364–376. https://doi.org/10.18307/2024.0212

Song, Y. (2023). Hydrodynamic Impacts on Algal Blooms in Reservoirs and Bloom Mitigation Using Reservoir Operation Strategies: A Review. *Journal of Hydrology*, *620*, 129375. https://doi.org/10.1016/j.jhydrol.2023.129375

Sun, L., Wu, L., Liu, X., Huang, W., Zhu, D., Wang, Z., Guan, R., & Liu, X. (2023). Reducing the Risk of Benthic Algae Outbreaks by Regulating the Flow Velocity in a Simulated South–North Water Diversion Open Channel. *International Journal of Environmental Research and Public Health*, *20*(4), 3564. https://doi.org/10.3390/ijerph20043564

Thawabteh, A. M., Naseef, H. A., Karaman, D., Bufo, S. A., Scrano, L., & Karaman, R. (2023). Understanding the Risks of Diffusion of Cyanobacteria Toxins in Rivers, Lakes, and Potable Water. *Toxins*, *15*(9), 582. https://doi.org/10.3390/toxins15090582

Treuer, G., Kirchhoff, C., Lemos, M. C., & McGrath, F. (2021). Challenges of Managing Harmful Algal Blooms in US Drinking Water Systems. *Nature Sustainability*, *4*(11), 958–964. https://doi.org/10.1038/s41893-021-00770-y

Wan, J., Wang, Z., Li, Z., Duan, H., & Yuan, H. (2013). Critical Velocity in Phosphorus Exchange Processes across the Sediment-Water Interface. *Journal of Environmental Sciences*, *25*(10), 1966–1971. https://doi.org/10.1016/s1001-0742(12)60254-x

Wang, H. Y., Yang, X., Ma, J., Yang, Z. J., & Liu, D. F. (2021a). Influence of Regulating Small and Medium Floods on Algal Blooms in Tributaries of Three Gorges Reservoir in Flood Season. *Journal of Hydroelectric Engineering*, *40*(07), 61–72. https://doi.org/10.11660/slfdxb.20210706

Wang, J. H., Li, J. L., Jiang, D. S., Wu, H. H., Wang, S. G., & Lin, A. J. (2021b). The Potential Impact of Phosphorus Concentration in Typical Lakes in China on Water Bodyindicators and Cyanobacteria Bloom Trends Based on Meta-Analysis. *Journal of Beijing University of Chemical Technology (Natural Science Edition*, *48*(02), 59–67. https://doi.org/10.13543/j.bhxbzr.2021.02.008

Wu, L. F., Zhu, Y., & Zhu, X. (2023). Analysis on Influencing Factors of Continuous Cyanobacteria Outbreak in Taihu Lake from 2007 to 2020. *Water Resources Development and Management*, *9*(2), 43-49. https://doi.org/10.16616/j.cnki.10-1326/TV.2023.02.11

Wu, T., Qin, B., Zhu, G., Luo, L., Ding, Y., & Bian, G. (2013). Dynamics of Cyanobacterial Bloom Formation during Short-Term Hydrodynamic Fluctuation in a Large Shallow, Eutrophic, and Wind-Exposed Lake Taihu, China. *Environmental Science and Pollution Research*, *20*(12), 8546–8556. https://doi.org/10.1007/s11356-013-1812-9

Xia, Y., Zhang, M., Tsang, D. C. W., Geng, N., Lu, D., Zhu, L., Igalavithana, A. D., Dissanayake, P. D., Rinklebe, J., Yang, X., & Ok, Y. S. (2020). Recent Advances in Control Technologies for Non-Point Source Pollution with Nitrogen and Phosphorous from Agricultural Runoff: Current Practices and Future Prospects. *Applied Biological Chemistry*, *63*(1), 1–13. https://doi.org/10.1186/s13765-020-0493-6

Xu, Y., Zhang, D., Lin, J., Peng, Q., Lei, X., Jin, T., Wang, J., & Yuan, R. (2024). Prediction of Phytoplankton Biomass and Identification of Key Influencing Factors using Interpretable Machine Learning Models. *Ecological Indicators*, *158*, 111320. https://doi.org/10.1016/j.ecolind.2023.111320

Yang, Q. Q., Wu, S. Q., Wu, X. F., Zhou, J., Dai, J. Y., & Lv, X. Y. (2015). Effects of Simulated Water Diversion on Water Quality and Phytoplankton Community in Meiliang Bay. *Journal of Hydroecology*, *36*(4), 42–49. https://doi.org/10.15928/j.1674-3075.2015.04.006

Yang, Z., Wei, C., Liu, D., Lin, Q., Huang, Y., Wang, C., Ji, D., Ma, J., & Yang, H. (2022). The Influence of Hydraulic Characteristics on Algal Bloom in Three Gorges Reservoir, China: A Combination of Cultural Experiments and Field Monitoring. *Water Research*, *211*, 118030. https://doi.org/10.1016/j.watres.2021.118030

Ye, L., Tan, L., Wu, X., Cai, Q., & Li, B. L. (2022). Nonlinear Causal Analysis Reveals an Effective Water Level Regulation Approach for Phytoplankton Blooms Controlling in Reservoirs. *Science of the Total Environment*, *806*, 150948. https://doi.org/10.1016/j.scitotenv.2021.150948

Zhang, W., Liu, J., Xiao, Y., Zhang, Y., Yu, Y., Zheng, Z., Liu, Y., & Li, Q. (2022). The Impact of Cyanobacteria Blooms on the Aquatic Environment and Human Health. *Toxins*, *14*(10), 658. https://doi.org/10.3390/toxins14100658

Zhou, J., Gou, T., Zhang, L. H., Lan, Y., Ma, Q. L., Liang, R. C., & Zhao, X. (2018). The Effect of Flow Velocity on the Growth of Different Phytoplankton. *Ecological Science*, *37*(06), 75–82. https://doi.org/10.14108/j.cnki.1008-8873.2018.06.01