Driving Mechanism of Spring-Algal-Bloom in Lakes Freeze-Thaw Processes

Subjects: Geology

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Lakes are important carriers of surface water resources, playing a role in protecting biodiversity, maintaining ecological balance within the watershed, and supplying fresh water. The migration pathways and rates of nitrogen and phosphorus nutrients to lakes have exhibited diversity and variability under the dual pressure of global warming and human activities. The algal blooms in mid- to high-latitude lakes are facing challenges such as earlier outbreak times, longer duration, and increased frequency of occurrence. Previous studies have found that the presence of freeze-thaw processes is the key to promoting the mechanism of algal blooms in mid- to high-latitude lakes, which is different from that in low-latitude lakes. Hence, how to reveal the impact mechanism of freeze-thaw processes on the occurrence and development of spring algal blooms is crucial for water-environment management.

Keywords: freezing and thawing processes ; spring algal bloom ; driving mechanism ; nutrient ; transformation ; transparency ; dissolved oxygen

1. Introduction

Lakes are important carriers of surface water resources, playing a role in protecting biodiversity, maintaining ecological balance within the watershed, and supplying fresh water [1][2][3][4]. The migration pathways and rates of nitrogen and phosphorus nutrients to lakes have exhibited diversity and variability under the dual pressure of global warming and human activities [2][5]. The algal blooms in mid- to high-latitude lakes are facing challenges such as earlier outbreak times, longer duration, and increased frequency of occurrence [3][6]. Previous studies have found that the presence of freeze-thaw processes is the key to promoting the mechanism of algal blooms in mid- to high-latitude lakes, which is different from that in low-latitude lakes [4][5][6]. Hence, how to reveal the impact mechanism of freeze-thaw processes on the occurrence and development of spring algal blooms is crucial for water-environment management.

Compared to low-latitude lakes, the growth and melting of lakes' ice would change the living environment of algae in mid–high-latitude lakes [5][6]. The water temperature structure, hydrodynamic conditions, sunshine conditions, and eutrophication degree will change with the freeze-thaw process. These factors will promote changes in the growth mechanism of the plankton and microbial communities in the lake [6][7]. Among them, the freeze-thaw process affects the migration and transformation of nutrients in the lake, and the competition for algae growth is more complex and variable. Taking Lake Washington in the United States as a typical seasonally covered shallow lake, the concentration of nutrients is actually the highest in winter. This situation encourages algae to receive a lot of light and nutrients after the lake's ice melts in the spring [7][8][9]. Subglacial water not only increases nutrients through concentration, it also increases the conductivity of the water by a factor of 1.7–2.7 compared to summer. This phenomenon increases the risk of spring algal blooms. [10][11]. However, there was insufficient research on the competitive living environment and self characteristics of algae growth during different periods such as freeze-thaw, freeze-up, and thawing [11]. Therefore, it is urgent to propose future mechanisms and prevention and control strategies for spring algal blooms by reviewing existing research on the impact of freeze-thaw processes on spring algal blooms. In the current study, the survival of plankton and nitrogen and phosphorus substances in lakes during the ice-covered period has been richly researched, but the changes in these substances during the whole process from freeze-thaw to thawing of lakes have not been sufficiently researched [5][8][9].

2. Effects of Freeze-Thaw Processes on Nutrient Migration and Transformation

Nitrogen and phosphorus were the major drivers of phytoplankton growth, competition, and succession, and directly affect primary productivity in lakes [12]. Excess nutrients could contribute to lake algal blooms [13]. Lakes' spring algal bloom has been expanding to the middle and high latitudes, and the scale, frequency, and intensity of its occurrence are all increasing under the dual pressures of climate change and human activities [14]. The algal blooms in lakes at mid to high latitudes arounds the world are also showing an increasing trend. Most of the studies focused on the mechanism of algal blooms in low-latitude lakes, with a lack of studies on the driving mechanism of algal blooms in mid–high-latitude lakes, especially those with seasonal ice and freeze-thaw phenomena. Therefore, it was important to analyze the mechanism of nutrient transport and transformation during freeze-thaw processes on spring algal bloom in lakes [15]. The freeze-thaw processes of lakes include freeze-thaw, freeze-up, and thawing [16]. During this period, the physical (water temperature, solar radiation, gas release, etc.), chemical (dissolved oxygen, CO_2 concentration, etc.), and hydrology factors (hydrodynamic conditions, water velocities, water circulation, etc.) of the lakes would change significantly, which will directly or indirectly drive the migration and transformation of nutrients [17]. The freeze-thaw effect on the migration and transformation of nutrients in lakes will affect the stability and development of the entire lake ecosystem [18]. During the freezing period of the Ulansuhai Lake in Inner Mongolia, due to the thickness of the snow cover and the shallow depth of the lake, the organisms at the bottom of the water body are able to carry out photosynthesis to promote the migration and transformation of nutrients; as represented by Woods Lake, the nutrient concentration replaces the temperature of the water body as an important controlling factor affecting the stability of the lake ecosystem (**Table 1**) [19][20]. The growth and melting of ice sheets altered the growth of phytoplankton by affecting physical and biogeochemical processes in the water beneath the ice [21]. The study of Norfolk Lake in the UK and Rappbode Reservoir in Germany found that the increase of nutrient concentration caused by ice sheet freezing led to the decrease of plant abundance and biomass in the water [22][23]. Therefore, the effects of the freeze-thaw processes on the nutrient-transport mechanism, transparency, and dissolved oxygen, and the physiological and ecological characteristics of algae in the water column should be considered [24].

Table 1. Eutrophication in selected high-latitude lakes.

No.	Country	Lake	Algae Bloom State	References
1	**USA**	**Great-salt-sea**	**Escalation**	[25][26]
2	**China**	**Hulun**	**Sharply escalate**	[27][28]
3	**Canada**	**Winnipeg**	**Escalation**	[29][30]
4	**UK**	**Lough Neagh**	**In grave difficulty**	[31][32]

2.1. Effects of Freeze-Thaw Processes on Nutrient Transport in Lakes

Nutrients were mainly distributed on the surface and bottom sediment layers of the water during the non-freezing period of lakes, which was an obvious vertical stratification phenomenon [33]. The dissolved oxygen concentration at the bottom of the water column was relatively low, while the content of organic matter and particulate matter was higher than that at the top of the water column [34]. The formation of ice sheets promoted the transportation of nutrients in ice concentration into the water, resulting in higher nutrient concentrations in the water than during the non-freezing period [35]. Of particular note is the formation of thermocline in deep-water lakes located in cold or temperate regions during freezing and thawing. It is difficult to exchange material between the upper mixed layer (epilimnion) and the lower stagnant layer (hypolimnion) within the lake. Large quantities of particulate organic matter and nutrients are difficult to resuspend into the upper layers of the water column through re-suspension after settling to the bottom of the lake. On the other hand, in shallow lakes, wind, waves, and turbulence can reach the bottom of the lake directly before the ice cap forms. There is an impact on organic matter and nutrients deposited on the lake bottom. These substances can enter the overlying water column through re-suspension, creating a nutrient cycle on the sediment–water inner surface (**Figure 1**) [36].

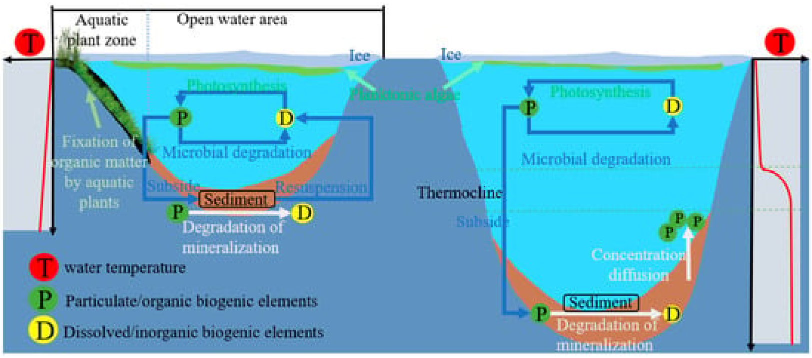

Figure 1. Patterns of nutrient cycling in shallow (left) and deep-water (right) lakes during the freezing period.

When the lake was in the frozen period, the presence of ice sheets and snow promoted significant differences in the physical and chemical environment compared to other periods [37]. The water flow rate was slow, while the nutrient concentration varied greatly in multiple media. Nutrient concentration showed a “C-shaped” distribution in sub glacial water bodies [38]. The concentration of ammonia nitrogen and nitrate nitrogen in water was higher than those in sediment, while the tendency of available phosphorus was opposite [37]. The distribution characteristics of nitrogen and phosphorus at the sediment water interface were relatively different [39]. The concentration of ammonia nitrogen and nitrate nitrogen decreased with the increase of sedimentation depth. However, the concentration of effective phosphorus showed a tendency to increase and then decrease with the increase of sedimentation depth [40]. The presence of lake ice promotes the slowed rheological behavior of ice water, changing disturbance between sediment, and promoting a different distribution of nutrients between ice, water, and sediment compared to other periods [41]. There was a critical value for external factors such as flow velocity and disturbance in water bodies under ice caps, and both above and below this threshold will have different effects on nitrogen and phosphorus releasing [42].

During the thawing period, nutrients in snow quickly entered the water body, which resulted in a sudden increasing of nutrient concentration in the water body [12]. The increasing of water temperature accelerated the metabolism of algae [16]. During the thawing period, the water flow rate increased, and the nutrient cycling rate and biogeochemical reaction rate both accelerated [43]. In addition, studies had shown that the comprehensive eutrophication index of water during the freezing and thawing periods was higher than that during non-freezing period [35]. These variations will lead to the spring algal blooms [44].

2.2. Effects of Freeze-Thaw Processes on Nutrient Transformation

Nitrogen and phosphorus, as important components of biogeochemical cycles in lakes, are the material basis for the growth and reproduction of phytoplankton and microorganisms [45]. At present, studies showed that a variety of factors such as temperature, dissolved oxygen content, acidity, alkalinity, and solar radiation were subject to change. Regrettably, there were fewer studies on the polymorphic transformation of nitrogen and phosphorus in lakes with the freezing and thawing process. The response of each substance was difficult to quantify, which greatly restricted an in-depth understanding of the mechanism of spring algal bloom in mid–high latitude lakes [46].

The main chemical reaction mechanisms of nitrogenous nutrients in lakes included anaerobic denitrification, anaerobic ammonium oxidation, aerobic denitrification, and anaerobic methane oxidation [47]. The transformation of nitrogen forms in water mainly includes processes of ammonification, nitrification, and denitrification [48]. The existence of freeze-thaw processes in lakes led to lower water temperature and dissolved oxygen concentration in the lake [5]. Anaerobic and low-temperature environments led to a decrease in microbial activity, promoting a decrease in the rates of nitrification, denitrification, and ammonification reactions [49]. Anaerobic environment also promoted further reduction of nitrate into nitrogen and nitrous oxide [50]. However, the contribution of freezing and thawing processes to ammonification and nitrification can not be specifically quantified.

Phosphorus is an essential macronutrient for phytoplankton growth, which plays a more important role in phytoplankton succession than nitrogen in lakes. The occurrence forms of phosphorus included orthophosphates ($H_2PO_4^{-}$, HPO_4^{2-}, PO_4^{+}), polymerized phosphates ($P_2O_7^{4-}$, $P_3O_{10}^{5-}$), and organophosphates (phosphatidylinositol) [51][52]. The rate phosphorus migration and its transformation in lakes was higher than that of nitrogen and silicon [53]. The phosphorus content decreased below the critical value required for algae growth (2 μg/L) due to the long-term low-temperature and hypoxic environment during the frozen period [52]. The process of converting organic phosphorus into inorganic phosphorus and orthophosphate into adenosine triphosphate (ATP) was greatly inhibited due to the decrease in microbial activity during the frozen period [53]. Phosphate can form insoluble precipitates with metal cations $Fe^{+}{}_3$, $Al^{+}{}_3$, $Ca^{+}{}_2$, $Mg^{+}{}_2$, and the reaction speed was also affected by the temperature and oxygen content (**Figure 2**). Phosphate exhibited vertical stratification due to the decomposition of dead vegetation residues by microorganisms during the frozen period [54]. The anaerobic environment promoted the transformation of insoluble $Fe(ON)_3$ into soluble $Fe(ON)_2$, providing a material-source basis for the improvement of primary productivity in spring [55]. Some anaerobic microorganisms in the frozen sediments accelerated the conversion of organic to inorganic phosphorus in the sediments. This phenomenon also increases phosphorus levels in the overlying water column [56]. Hence, the complex phosphorus transformation process during the frozen period can better explain the spring-algal-bloom phenomenon compared to nitrogen.

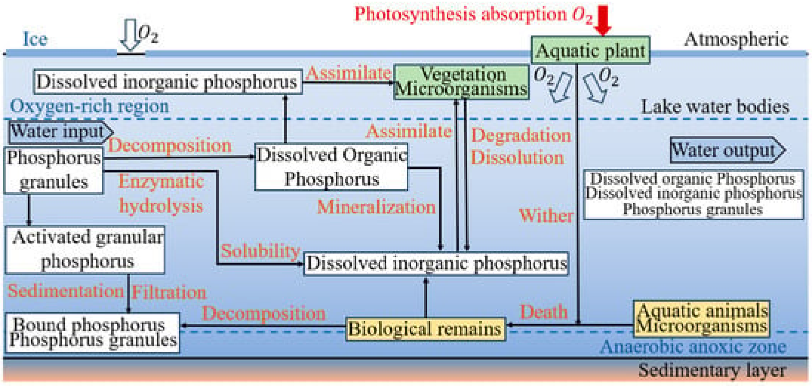

Figure 2. Mechanisms of phosphorus-containing nutrient transformation in lakes during freezing and thawing processes.

3. Effect of Freeze-Thaw Processes on Transparency and Dissolved Oxygen

The presence of snow and ice layers weakened the intensity of solar radiation entering sub-glacial water bodies, promoting a decrease in sub-glacial light intensity to inhibit algal photosynthesis [57][58]. The lake ice also temporarily buffered atmospheric sedimentation and reduced wind disturbance, suppressing the resuspension of sediment [59].

Ice caps are influenced by a number of factors during their formation. The freezing temperature of the ice, the rate of ice growth, and the salinity of the water together determine the density, crystal structure, and internal microstructure of the ice. They lead to a decrease in the transparency of the ice, making less light receivable under the ice [60]. The weakening of photosynthesis led to a further decrease in dissolved-oxygen content [61]. In addition, the nutrient concentration in the ice and the freezing separation coefficient also increased with the decreasing of freezing temperature, promoting the release of nutrients from the ice into the water body [62]. Ice caps redistributed nutrients between water bodies and ice layers through freezing, salt discharge, and melting dilution [63]. The research found that the formation of ice sheets redistributed nutrients among ice, water, and sediment [64]. The ice sheet weakened the disturbance of wind, blocks the exchange of substances between the atmosphere and water, and reduced the re-suspension of particles caused by wind [63][64]. The pollutants in the overlying water became more uniform during the frozen period, which promoted the increasing of transparency [64][65][66]. Hence, transparency of different lakes reacts differently during freeze-thaw processes, while it all led to a decreasing of dissolved oxygen due to the ice sheets.

4. Effect of Freeze-Thaw Processes on Algae Physiology

Phytoplankton, as the basis of material circulation and energy flow in lake ecosystems, plays an important role in maintaining the balance of the entire ecosystem [67]. Freezing and thawing had direct or indirect effects on the physiological and ecological characteristics of planktonic algae from physical (temperature, light intensity, dissolved sample content), chemical (nutrient salt concentration, metabolic rate) and hydrological (hydrodynamic conditions, water circulation) [66].

According to the previous research, the freeze-thaw process greatly limited the activity of underwater organisms [68]. However, scholars found that the diversity of benthic phytoplankton species during the frozen period was still relatively high in recent years [69][70][71]. Currently, the research has found that the freezing period promoted a decreasing of phytoplankton diversity over time [72]. However, the driving mechanism of phytoplankton population succession during the freezing period was not clear (**Figure 3**). Cyanobacteria had the greatest dominance during the freeze-up period; with the further reduction in temperature and the extension of the freeze-up time, the cyanobacteria entered into a dormant period [73]. Diatoms had a clear dominance during the freeze-up period, which had a direct relationship to their physiological characteristics of regulating the water, sugar, and fat in the cells to increase the ability of drought resistance [74]. During the thawing period, cyanobacteria and green algae dominate, due to maximal photosynthesis [75].

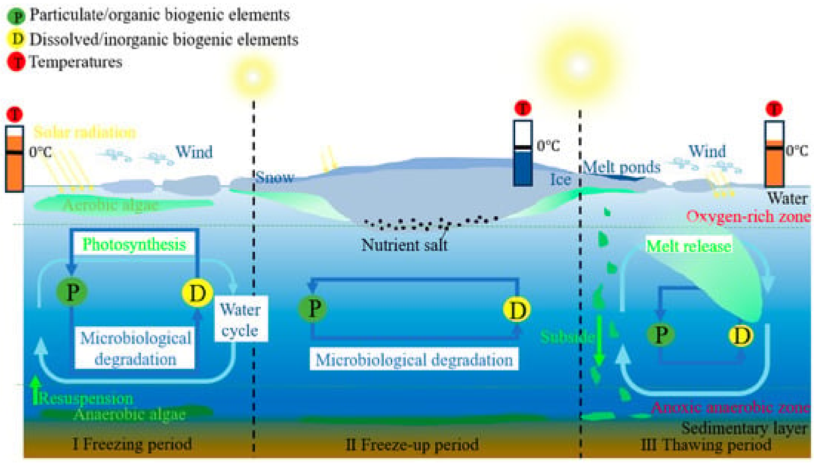

Figure 3. Mechanisms of lake-algal-bloom occurrence during freezing and thawing processes.

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