Phytoplankton dynamics at a reservoir in northeast China

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Abstract. This study assessed the impact of water quality parameters on phytoplankton in the various spatial and seasonal scales of the Nierji reservoir. The research data covered three sites along the mainstream of the Nierji reservoir which is located in the northeast China. The seasonal and spatial variations were the essential factors regulating phytoplankton dynamics. Dominant influencing factors of the chlorophyll-a (Chl-a) content of phytoplankton were different according to the spatial and seasonal scales. Although total phosphorus was the limiting factor influencing the phytoplankton in the various spatial and seasonal scales, Chl-a was weakly correlated to total phosphorus in the upstream, midstream, and downstream during the flood season. A weak correlation between Chl-a and total nitrogen was found when ammonia nitrogen or nitrate displayed a stronger correlation with Chl-a. Ammonia nitrogen or nitrate was significantly correlated to total nitrogen when the correlation between Chl-a and total nitrogen was not significant. The Chl-a increased with decreasing the Secchi depth in the reservoir.

1. Introduction

In recent years, wastewater discharge from agriculture and industry has led to the phytoplankton blooms and eutrophication in reservoirs[1]. Meanwhile, surface runoff's contribution to phytoplankton's growth has reached a very great degree by transporting nonpoint source pollutants to reservoirs[2]. This water quality deterioration is a critical threat to aquatic ecosystems and human health. The seasonal climatic and hydrological fluctuation also affects the phytoplankton biomass and the composing of species, which is increased by excessive growth in nutrients and higher temperatures[3]. Moreover, humans' activities and behaviors around reservoirs can produce new relationships between phytoplankton biomass and nutrient by enriching the nutrients[4]. The Nierji reservoir, located in northeast China, is characterized by obvious seasonal variations in meteorological factors. In the flood season with heavy rainfall, there is warmer air temperature and longer sunshine duration, in where there is windy and cold in the non-flood season. Furthermore, this reservoir exposed to a point source of wastewater discharge, which caused its water quality fluctuation in spatial scales. This paper assessed the phytoplankton response to water quality parameters spatially and seasonally of the Nierji reservoir during 2011-2015.
2. Material and method

Monthly samples were collected over five consecutive years (2011–2015) in three sites located in the mainstream of the Nierji reservoir. The site1 is situated in the upstream with a higher depth. The site2 is situated in the middle. The lower depth is in the site3 at the downstream. The environmental indicators used in the analysis mainly include Chl-a, TN, TP, Secchi depth (SD), permanganate index (PMI), dissolved oxygen (DO), chemical oxygen demand (COD), ammonia nitrogen (NH\textsubscript{3}N), and nitrate (NO\textsubscript{3}N). Monthly sampling was performed at a depth of half a meter below the surface of the water. When the snow cover's thickness was more than half a meter, samples were collected at a depth of more than half a meter below the water surface after chiseling. To determine spatial and seasonal patterns of phytoplankton response to water quality parameters, we established the ordinary least square equations (OLS) between Chl-a and water quality indicators. The manual variable excluding-selecting method was adopted to avoid multi-collinearity between environmental factors [5]. The Pearson correlation was measured to determine the relationship between TN, NH\textsubscript{3}N, and NO\textsubscript{3}N.

3. Results and Discussion

3.1 Spatial-seasonal patterns of Chl-a

The movement of Chl-a concentrations during 2011-2015 is illustrated in Fig.1. According to the same water environmental background along the stream gradient, the Chl-a concentrations and its occurrence time recorded in different monitoring sites were the same patterns. Nevertheless, the peak value of the Chl-a concentrations in the upstream in 2014 was higher than the midstream and downstream. This significant spatial variation might be caused by restoring the wastewater treatment plant near the upstream in that year. The Chl-a concentration increased steadily year by year until the peak value was reached in 2014 during the flood season. The average annual peak values of 9.675 ug/l, 15.55 ug/l, and 22.175 ug/l were in the downstream, midstream, and upstream sites, respectively. This peak period coincides with the peak period of TN and TP, indicating that the enormous growth of phytoplankton caused by nutrients. Moreover, the peak value of DO coincides with the peak value of Chl-a, where the highest DO concentration of 12.65 mg/l was in 2011 for downstream during the non-flood season. The highest DO concentrations for upstream and midstream were 11.24 mg/l and 11.48mg/l respectively in 2014 during the non-flood season. The rising Chl-a concentrations and phytoplankton absorption processes might increase DO levels due to photosynthetic effectiveness cycling. The Chl-a concentrations showed a significant downward trend after reaching the peak value in the 2015 year.

As presented in Fig.1, the lowest Chl-a of phytoplankton was in the non-flood season in the different spatial scales. The low air temperature and high wind speed in this season can inhibit the growth of species and phytoplankton biomass. The annual average wind speed is 2.8 m/s, and the largest wind speed is in the spring, which can reach more than 5 m/s. The previous studies showed that low wind speed could promote cyanobacterial blooms in the water surface. Meanwhile, the cyanobacterial cell concentrations can be distributed quickly in the water column by gas vesicles that are negatively correlated with high wind speed [6]. At the end of spring and the beginning of summer, the water temperature increases. The wind and waves frequently disturb the nutrient salt in the sediment. The algae's dormant body on the surface of the sediment begins to float into the water[7]. Moreover, phytoplankton growth might be promoted in the surface water by increasing stratified temperatures and reducing mixing depth during this period more than other periods. The anaerobic in the bottom of the reservoir can release the nutrient to the surface water and promote the phytoplankton biomass[8].

Due to the appropriate hydrodynamic and environmental conditions characterized by heavy rainfall in the summer, many nutrients can be recharged to the reservoir[5]. The biomass of the reservoir water would increase and constitute a very thick cyanobacteria bloom layer. The dense cyanobacteria are easy to trigger spring bloom in sufficient light, sunshine, and high humidity. And the light intensity could increase the photosynthesis of phytoplankton and produce oxygen that promotes the breathing of algae. Moreover, there is high transparency detected during the flood season. Thus, the likelihood of
photosynthesis of algae would be high under the high intensity of light in summer, resulting in increased phytoplankton.

Figure 1. Spatial and seasonal patterns of Chl-a during 2011-2015 in the Nierji reservoir.

Moreover, the consumption of DO and the release of CO$_2$ in the reservoir water would provide more nutrients and appropriate carbon sources for phytoplankton growth. Furthermore, the rise of water temperature promotes algae's growth[9]. In the autumn, the surface water temperature decreases; thus, the thermal stratification would be decreased, and mixed water column increases and then nutrients settle in the bottom of the reservoir, which leads to inhibit the growth of phytoplankton[10]. The spatial variations are ranked as upstream > midstream > downstream. The upstream of the reservoir is the direct recipient of wastewater discharging to the river that increases nutrients and promotes the phytoplankton biomass. As organisms, algae breathe by using oxygen and releases carbon dioxide, lowering the water's pH, the opposite of photosynthesis. Thus, the phytoplankton would be increased in the upstream. In contrast, the downstream showed significant downward compared with the upstream and midstream during the flood season. While heavy rainfall and runoff in this season would easily decrease the downstream's thermal stratification because of its small depth, then reduce the releasing of nutrient and algal blooms[8].

3.2. Impact analysis of water quality parameters on phytoplankton

The ordinary least square equations between water quality indicators and Chl-a are presented in Table 1. Indicating that the dominant influencing factors of phytoplankton growth are varied in the different spatial and seasonal scales. The SD was included as a significant factor in all spatial and seasonal scales except the downstream site during the non-flood season and the upstream site during the flood season. Indicating that the decline of the water clarity is caused by the excessive growth of phytoplankton more than external suspended particles in these scales. Therefore, the phytoplankton biomass reflects the change in the reservoir's light climate[11]. The decline of water transparency could prevent the growth of submerged macrophytes, and hence the phytoplankton growth and reproduction of Chl-a levels would be increased[12]. However, the SD was not included in all OLS equations of the various spatial and seasonal scales. It suggests that the light intensity was not the dominant factor modifying the algal growth in the sites and seasons in which SD was excluded. If the light is significantly strong or significantly weak, it will be unfavorable for phytoplankton's growth [12].

The COD was included as a negative factor in the downstream site during the non-flood season and the upstream site during the flood season. The strong oxidization of the excessive amount of organic would inhibit the proliferation of algae. Mostly that COD concentrations were relatively high in the reservoir. According to the Chinese Environmental Quality Standards for reservoirs (GB3838-2002), the average COD concentrations for the period of (2011-2015) are exceeded the limit value of class III. Therefore, The excessive consumption of oxygen by a large amount of organic substance would create an anoxic environment at the bottom of the reservoir and destroy algae biomass[13].
As shown in Table 1, the impact of nutrients on phytoplankton's growth could be inferred by shifting nutrient deficiency by measuring TN/TP ratios in the various spatial and seasonal scales. The average values of TN/TP demonstrated that the TN/TP was optimal for algal growth in the midstream site during the non-flood season, and TP was limiting the algae’s growth in the other spatial and seasonal scales [3]. TN has included in OLS equations in all spatial and seasonal scales except the downstream site during both seasons and the upstream site during the non-flood season. The TN in the water body was sufficient or even excessive for the algal growth and thus was not a limiting factor affecting the Chl-a concentrations. Meanwhile, it is evident that when dissolved inorganic nitrogen (DIN) compounds strongly affect the phytoplankton, TN will not be a significant factor influencing phytoplankton growth. The NH$_3$-N that composed a large portion of TN in the downstream site during the flood season was considered a dominant factor. Where NH$_3$-N was strongly correlated to TN with Pearson correlation coefficient of (r = 0.58; p < 0.050), while NO$_3$- was weakly correlated to TN(r = 0.16; p < 0.050). Indicating that nitrogen compounds were influencing Chl-a in downstream during the flood season, but the rate of TN production was faster than the growth of phytoplankton, so TN was excessive for the phytoplankton growth. Therefore, it suggests that the other components that form TN may be responded to other meteorological factors during the flood season in which these factors could accelerate nitrogen's total production. Thus, the TN pulsation timing from the streams in the flood season, such as storm runoff, could yield high TN before fulfilling the phytoplankton biomass's growth conditions. Hence, the phytoplankton species was saturated by nitrogen through its fast absorption, so the cellular Chl-a content unaffected by TN[2].

Moreover, the increase of TN may have coincided with the rising of crustacean zooplankton biomass that may have affected Chl-a; thus, the relationship between nitrogen and phytoplankton was weakened. Whereas Havens et al. reported that phytoplankton was decreased after extreme weather events in Lake Okeechobee in the southeast United States, while the crustacean zooplankton was increased[14]. The same pattern was shown in the downstream and upstream during the non-flood season, in where NO$_3$- has been included in OLS equations. The NO$_3$- was playing a prominent role in the relationship mechanism between nitrogen compound and Chl-a, where the stronger Pearson correlation of (r = 0.48; p < 0.050) and (r = 0.35; p < 0.050) between TN and NO$_3$ were in the downstream and upstream sites, respectively, during the non-flood season. Therefore, most of the fertilizer is generally applied during this season, which accelerates and encourages the growth of TN by irrigation and low rainfall before the phytoplankton biomass had time to grow under the lower temperature during the non-flood season[2;5].

It was noted that the Pearson correlation between TN and DIN compounds (NO$_3$- and NH$_3$-N) was insignificant (p>0.05) in the spatial and seasonal scales that displayed a stronger correlation between TN and Chl-a. Indicating that NO$_3$- and NH$_3$-N were not prominent factors that compose TN in these spatial and seasonal scales. Thus, NO$_3$- and NH$_3$-N don't affect Chl-a. The Microbial community in the reservoir water can play important roles in the autotrophic and heterotrophic denitrification process. Autotrophic and heterotrophic bacteria (such as Thiobacillus, Thauera,.. etc.) would result in a high denitrification rate and reduce nitrate to nitrogen gas. Therefore, as other nitrogen compounds were composing TN rather than NO$_3$ and NH$_3$-N, more nitrate will be denitrified by these bacteria. The bacteria would speed up the denitrification process before the phytoplankton had time to fertilize NO$_3$[15]. As well as ammonia nitrogen will be nitrified by organic carbon in the reservoir rapidly before the phytoplankton had time to fertilize it.

Although TP was exceeded the limit of class III of Chinese environmental quality standards (GB3838-2002) in all spatial and seasonal scales, TP was not considered a significant factor in the different sites' flood season. Statically, the Pearson correlation between the Chl-a and TP was negative with a coefficient of (r = -0.48; p < 0.050) in the midstream site during the flood season. Indicating that algae were absorbing and limiting TP by photosynthesis under the light intensity during the flood season, so TP was not included as a dominant influencing factor of the phytoplankton growth midstream site.

Despite the Pearson correlation between TP and Chl-a in the downstream and upstream sites during the flood season were significant with the coefficients of (r = 0.35; p < 0.050) and (r = 0.56; p < 0.050), respectively. TP was not included in OLS equations as a significant factor affecting the Chl-a
concentrations. It suggests that other factors (such as crustacean zooplankton biomass, macrophytes, etc.) influence the relationships between the Chl-a content of phytoplankton biomass and TP under a storm runoff, high temperature, and light intensity during the flood season. Moreover, storm runoff could dilute TP. And the submerged macrophytes biomass tends to be increasing under high temperature and light intensity. Macrophytes could assimilate a high amount of TP. Hu et al. showed that the Chl-a contents of phytoplankton were significantly negatively correlated to macrophytes' dry weight [16]. Moreover, it is possible that suspended solids were adsorbing the highest amount of TP during the flood season. It was demonstrated by Drewry et al. that TP, TN, suspended solids, and flow have a positive correlation with each other [17]. DO and PMI were not included in OLS equations in the various spatial and seasonal scales. While the phytoplankton absorption process, aerobic organisms, and aquatic plants might produce and consume DO in the light and dark of the day. Moreover, the depth of water, flow, and water temperature could control DO concentrations. The rising temperatures promote the expansion and reproduction of aquatic organisms in the water body, which results in decreased DO concentrations [18].

**Table 1.** The ordinary least square equations between the Chl-a and water quality indicators

| Location          | Season       | OLS equations                                                                 | Adjusted $R^2$ | $R$  | Sig    |
|-------------------|--------------|-------------------------------------------------------------------------------|----------------|------|--------|
| Downstream        | Flood season | Chl-a = 19.156+2.164NH$_3$N-15.045SD                                            | 0.648          | 0.829| 0.001  |
| of reservoir      | Non-flood season | Chl-a=5.212+18.822TP-0.08COD+3.987NO$_3$$^-$                                    | 0.593          | 0.805| 0.0001 |
| Midstream         | Flood season | Chl-a=-2.612+13.69TN                                                            | 0.412          | 0.644| 0.001  |
| of reservoir      | Non-flood season | Chl-a= 2.024 +7.936TN+19.918 TP-4.097 SD                                      | 0.732          | 0.877| 0.0001 |
| Upstream of       | Flood season | Chl-a= 13.957+15.571TN-8.002SD-0.403COD                                          | 0.761          | 0.872| 0.0001 |
| reservoir         | Non-flood season | Chl-a =7.468-5.435SD+30.584TP+7.699NO$_3$$^-$                                  | 0.356          | 0.666| 0.001  |

4. Conclusion
The phytoplankton dynamics were examined in two degrees of seasonal variations (Flood season and Non-flood season) and three spatial scales (upstream, midstream, and downstream) and showed various relationships with the phytoplankton. The COD, TN, NH$_3$N, NO$_3$$^-$$^-$ and TP were significantly affecting phytoplankton biomass besides water transparency, while their effects' level varied with spatial and seasonal scales. TP was limiting the growth of phytoplankton in the different spatial and seasonal scales. However, it did not affect the phytoplankton in the downstream, midstream, and upstream sites during the flood season. TN was not affecting the phytoplankton in the downstream area during both seasons and upstream during the non-flood season. It was apparent that when NH$_3$N and NO$_3$$^-$$^-$ strongly influence the phytoplankton, TN is not a dominant influencing factor of phytoplankton. The COD was negatively related to Chl-a in the downstream during the non-flood season and the upstream during the flood season. This study showed the importance of meteorological and anthropogenic factors in promoting the phytoplankton, which can produce new relationships between nutrients and phytoplankton by fluctuating the nutrients.

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