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Discussions

An optimisation approach for shallow lake restoration through macrophyte management

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Abstract

Lake eutrophication is a serious global environmental issue. Phytoremediation is a promising, cost-effective, and environmentally friendly technology for water quality restoration. However, besides nutrient removal, macrophytes also deeply affect the hydrologic cycle of lake system through evapotranspiration. Changes in hydrologic cycle caused by macrophytes have a great influence on lake water quality restoration. As a result of the two opposite effects of macrophytes on water quality restoration (i.e. an increase in macrophytes can increase nutrient removal and improve water quality while also increasing evapotranspiration, reducing water volume and consequently decreasing water quality), rational macrophyte control through planting and harvest is very important. In this study, a new approach is proposed to optimise the initial planting area and monthly harvest scheme of macrophytes for water quality restoration. The month-by-month effects of macrophyte management on lake water quality are considered. Baiyangdian Lake serves as a case study, using the common reed. It was found that water quality was closest to Grade III on the Chinese water quality scale when the reed planting area was 123 km^2 (40 % of the lake surface area) and most reeds would be harvested at the end of June. The optimisation approach proposed in this study will be a useful reference for lake restoration.

1 Introduction

As a global environmental issue, lake eutrophication has become an enormous challenge in the water resources protection and water safety management field (Anderson and Garrison, 1997; Smith, 2003). As a result of over discharge of nutrients from agricultural runoff and untreated industrial and urban sewage, many lakes are experiencing eutrophication (Smith et al., 1999; Jin, 2003). Degradation of water quality can lead to a series of side effects and result in loss of ecological functions and degradation of aquatic ecosystems (National Research Council, 2000). Eutrophication has a severe effect on many sectors of the economy, with high social, ecological, and policy response costs (Pretty et al., 2003). Frequent algal blooms caused by eutrophication are inedible or even toxic to consumer species, resulting in foodweb alterations and potentially detrimental effects on biodiversity and fisheries (Paerl et al., 2001; Qin, 2009). An eco-friendly and effective measure for water quality restoration is needed urgently in eutrophic shallow lakes.

Reducing the discharge of nutrients from point and non-point sources is the primary measure to control eutrophication. Measures to remove nutrients from lakes are also necessary for severely eutrophic lakes (Klapper, 1991; Wade et al., 2007; Hamilton and Landman, 2011). Phytoremediation is a promising, cost-effective, and environmentally friendly technology for water quality restoration (Salt et al., 1995). Phytoremediation is defined as the use of green plants to remove pollutants from the environment or to render them harmless (Salt et al., 1998). Nutrient pollutants are one of the major targets of phytoremediation, and can be removed from lakes through plant uptake and rhizosphere denitrification. Plant uptake happens when macrophytes convert nutrients into organic compounds, as building blocks for cells and tissues (Vymazal, 1995). Denitrification is the biological mechanism through which bacteria break down inorganic nitrogen such as nitrate and nitrite into innocuous fundamental nitrogen gas in low-oxygen environments (Lee et al., 2009). Various kinds of macrophytes have been successfully used for lake water quality control, such as the common reed (*Phragmites australis*), cattail (*Typha* spp.), and bulrush (*Scirpus* spp.). Research into nutrient removal by these macrophytes has been carried out in recent years and has proven that they are effective for water quality restoration (Wu et al., 2011; Borin and Salvato, 2012).

Phytoremediation can remove nutrients although the macrophyte community also leads to high evapotranspiration, which results in significant loss of water in lakes (Sun and Song, 2008; Borin et al., 2011). It was reported that the evapotranspiration of reed-dominated shallow lakes was one to seven times as high as the evaporation of those without vegetation cover (Baird and Wilby, 1999; Zhou and Zhou, 2009). Shallow lakes are very sensitive to evapotranspiration due to their large area and low water depth. The loss of water leads to higher nutrient concentrations, which will aggravate the deterioration of water quality. As a result of the two opposite effects of macrophytes on water quality restoration – i.e. increased macrophytes can increase nutrient removal and improve water quality while also increasing evapotranspiration, reducing water volume in a lake and consequently decreasing water quality – the management of macrophyte populations is very significant for shallow lakes.

Zhao et al. (2012) determined optimal reed density through a field simulation experiment considering the two effects of macrophytes on water quality. The average reed density in the current reed growth zone of Baiyangdian Lake is 120 plants m^{-2}. Their results indicated that water quality was the best when reed density was reduced to 72 plants m^{-2}. Thus they proposed that the reed density should be adjusted to 72 plants m^{-2} in the reed growth zone of Baiyangdian Lake. However, optimising plant density is not enough for lake restoration. Plant area also affects the total amount of macrophytes, and thus water quality restoration. Both planting density and area are key parameters for managing macrophytes in a lake although no research has proposed an optimisation approach for macrophyte planting area.

Zhao et al. (2012) suggested that the aboveground biomass of reeds should be harvested in September because the highest aboveground nutrient storage occurred in this month. The underlying rationale for this suggestion is that this harvest scheme could remove most of the nutrients from the lake and consequently make the water quality better in the following months. However, this harvest scheme may not be best for water quality in the following months, because in addition to nutrient removal reeds also undergo evapotranspiration. If reeds are harvested earlier than September, fewer nutrients would be removed, although the evapotranspiration also would be less. Both nutrient removal and evapotranspiration would decrease, which may lead to better water quality in the following months. Thus harvest in September may be not the best harvest scheme for water quality in the following months. For the months before September, harvest in September may also be not the best scheme for the water quality. For example, if the evapotranspiration of reeds in August and September was significant, while the amount of nutrients absorbed by reeds in these two months was small, harvesting reeds at the end of July may be better for water quality in August and September than harvesting at the end of September. We do not know in which months reed growth is advantageous for water quality given the two opposite effects of reeds. Thus all the months of the growing season are potentially the best time to harvest reeds.

In this study, a method will be proposed to optimise macrophyte management for water quality restoration, including the initial planting area and monthly harvest scheme. The month-by-month effects of macrophyte management on lake water quality are considered. The goal of the optimisation method is to meet the water quality demand according to the national water quality standards. If the demand cannot be achieved through macrophyte management, the water quality is optimised to approach the demand as close as possible. Adaptive Genetic Algorithm (AGA) will be applied to solve the optimisation model. Monthly nutrient balance and water quantity balance will be investigated in this study. Baiyangdian Lake, the largest shallow lake in North China, is chosen as a case study using the common reed.

2 Materials and methods

2.1 Description of the study site

Baiyangdian Lake ($38^\circ 43'$ N to $39^\circ 02'$ N, $115^\circ 45'$ E to $116^\circ 07'$ E), the largest shallow freshwater lake in northern China, is a famous natural wetland due to its significant ecological functions and high tourist value. It is very important for controlling floods, regulating regional climate, and providing habitat for various animals and plants. Its largest water surface area is 308 km^2 when the water level reaches 8.8 m. The drought level is 6 m, which occurs when the lake's surface area decreases below 50 km^2. Its climatic and geographical conditions provide a favourable growing environment for macrophytes. The common reed is the dominant wetland species in the region, covering an area of about 80 km^2. Because of its vitality, high biomass production, and capacity for nutrient accumulation, the common reed has been widely planted as a potential remediation macrophyte in lake ecosystems (García et al., 2004; Huett et al., 2005). The reed yield of Baiyangdian Lake removes significant amounts of nutrients from the lake and produces economic benefits. In recent years, Baiyangdian Lake has suffered serious eutrophication because of increasing nutrient inputs from sewage discharge, aquaculture, and industrial waste. The monthly average nutrient inputs for total nitrogen (TN) and total phosphorus (TP) are 21.83 and 0.56 t, respectively (Zhao et al., 2010). The monthly average TN and TP concentrations in the lake were respectively 5.15 and 0.54 $\text{mg}\,\text{L}^{-1}$ from 2000 to 2009, which are much worse than the desired level for Grade III on the Chinese water quality scale (State Environmental Protection Administration of China, 2002).

2.2 Nutrient balance calculation

Large amounts of nutrients put pressure on lake ecosystems, although natural lakes have strong decontamination functions to remove a considerable part of them. The removal of phosphorus from a water body is mostly due to plant uptake and exchange with sediments, while the removal of nitrogen is more complex (García-Linares et al., 2003). Generally, nitrogen can be removed from a water body mainly through ammonia volatilisation, chemo-denitrification, and the contribution of plants and sediments. The plant contribution includes uptake and rhizosphere denitrification. Nutrient release due to rhizome decay also needs to be considered. The sediment contribution includes biological denitrification at the sediments of plant non-growing zone and exchange between water and sediments. Ammonia volatilisation describes the escape of nitrogen from the lake as ammonia gas, which is not significant when pH ranges between 7.5 and 9.3 (Reddy et al., 1984). Chemodenitrification is a chemical process of nitrite decomposition to gaseous N compounds (Chalk and Smith, 1983), that usually takes place at low pH values (Van Cleemput and Baert, 1984). The pH value in Baiyangdian

Lake is about 8.0, with small yearly fluctuation (Zhao et al., 2010), so the ammonia volatilisation and chemodenitrification processes are not significant and N removal by these methods can be neglected. To sum up, the removal of nitrogen from this water body is mostly due to the contributions of plants and sediments.

The mass balance equations in the water body can be shown as follows.

$$\mathbf{TN}_i = \mathbf{TN}_{i-1} + \mathbf{TN}_{\text{input},i} - \mathbf{TN}_{\text{plant},i} - \mathbf{TN}_{\text{sediment},i} \tag{1}$$

$$\mathbf{TP}_i = \mathbf{TP}_{i-1} + \mathbf{TP}_{\text{input},i} - \mathbf{TP}_{\text{plant},i} - \mathbf{TP}_{\text{exchange},i} \tag{2}$$

$$\mathbf{TN}_{\text{plant},i} = \mathbf{TN}_{\text{uptake},i} + \mathbf{TN}_{\text{rhiz, deni},i} - \mathbf{TN}_{\text{release},i} \tag{3}$$

$$\mathbf{TP}_{\text{plant},i} = \mathbf{TP}_{\text{uptake},i} - \mathbf{TP}_{\text{release},i} \tag{4}$$

$$\mathbf{TN}_{\text{sediment},i} = \mathbf{TN}_{\text{sedi, deni},i} + \mathbf{TN}_{\text{exchange},i} \tag{5}$$

where $\mathbf{TN}_i$ and $\mathbf{TP}_i$ are total amounts of nutrients in month i (10^2 t); $\mathbf{TN}_{\text{input},i}$ and $\mathbf{TP}_{\text{input},i}$ are the amounts of nutrients input in month i; $\mathbf{TN}_{\text{plant},i}$ and $\mathbf{TP}_{\text{plant},i}$ are the amounts of nutrients removed by the contribution of plants; $\mathbf{TN}_{\text{sediment},i}$ is the amount of nitrogen removed by the contribution of sediment; $\mathbf{TN}_{\text{uptake},i}$ and $\mathbf{TP}_{\text{uptake},i}$ are the amounts of nutrients absorbed by plants; $\mathbf{TN}_{\text{release},i}$ and $\mathbf{TP}_{\text{release},i}$ are the amounts of nutrients released due to rhizome decay; $\mathbf{TN}_{\text{exchange},i}$ and $\mathbf{TP}_{\text{exchange},i}$ are the amounts of nutrients removed through the exchange with sediments; and $\mathbf{TN}_{\text{rhiz, deni},i}$ and $\mathbf{TN}_{\text{sedi, deni},i}$ are the amounts of nitrogen removed by biological denitrification at plant rhizosphere and sediment, respectively.

In Baiyangdian Lake, the majority of plant uptake of nutrients occurs by the common reed, the dominant species in the region. Reeds grow in the submerged and terrace zones. Only those in the submerged zone are available to absorb nutrients from the lake through their rhizome system (Haslam, 1972; Ailstock et al., 2001). Only a small amount of nutrients is absorbed from the atmosphere by their leaves and can be ignored. Most total nitrogen in the sediment is unavailable for biotic use; available nitrogen mainly occurs in soluble form in the lake water and interstitial sediment water (Wetzel, 2001). Therefore, the nutrients assimilated by reeds in the submerged zone essentially come from the lake water. Reeds absorb nutrients for developing their aboveground and belowground tissues. The latter mainly refers to their perennial rhizome system. During the growing season, belowground tissues absorb nutrients for growth. When reeds senesce, the aboveground part dies and translocates some nutrients to the belowground part, if they are not harvested (Juneau and Tarasoff, 2013), and the belowground part enters dormancy and stores nutrients for new tissues in the next year (Granéli et al., 1992; Juneau and Tarasoff, 2013).

The amounts of nutrients absorbed by the aboveground part annually can be calculated by multiplying TN or TP concentrations in reed tissues and their aboveground biomass. The nutrient concentrations and aboveground biomass can be measured by experiment. However, for the perennial, belowground part, it is much more complicated to calculate the annual amounts of nutrients absorbed because it is difficult to distinguish which tissues developed in the current growing season, and the annual biomass increment of old tissues is also hard to measure (Karunaratne et al., 2004). To better calculate the annual increment of belowground biomass, some research has built a relation between annual net production of belowground tissues and maximum aboveground biomass (Valk and Bliss, 1971; Fiala, 1976). Based on Fiala's (1976) research, the average annual value of net production of belowground reed tissues would be 45 % of the maximum aboveground biomass. This value is cited in this study, although the accuracy is suspect because this value differs for different sites. The concentrations of TN and TP in the belowground tissues are relatively constant during the growing season (Quan et al., 2007). These two concentrations can be measured by experiment. On the basis of the increment of belowground biomass, the nutrients absorbed by belowground tissues can be obtained.

Besides absorbing nutrients, reeds also release nutrients to the lake when they senesce. In this study, the aboveground part will be harvested after the growing season, while the belowground part will be retained in the lake. Some tissues of the belowground part will die and release nutrients, and others will be dormant until the next growing season (Chapin et al., 1990; Granéli et al., 1992). According to research by

Granéli et al. (1992), the rhizome mortality of reeds is about 30 %, and the release of their nutrients should be considered in this study.

The field simulation experiment was conducted in Baiyangdian Lake during the growing season from April to November 2010. The rhizome breeding method was used for reed cultivation and the experiment was exposed to full sun and ambient temperatures (Huett et al., 2005). The reed rhizomes, water, and sediment for the simulation experiment were all sampled from the lake at the beginning of April. According to the control group without reeds, an average of 57.6 mg m^{-2} TN and 6.5 mg m^{-2} TP could be removed from the water body by the contribution of sediments. The efficiency of rhizosphere denitrification is approximately twice that of sediments because the plant rhizosphere environment supports a higher potential for the exchange of aerobic and anaerobic processes that facilitate denitrification (Højberg et al., 1996). From the experiment group with growing reeds, the amounts of nutrients absorbed by different parts throughout the growing season can be obtained as shown in Table 1.

During the growing season, the lake area was divided into two zones: a zone without reeds and with reeds. The area of the zone with reeds varies with harvesting activity and water level fluctuation. Plant uptake and denitrification in reed rhizospheres occur in the zone with reeds, while denitrification in the sediment occurs in the whole lake area.

2.3 Water quantity balance calculation

Besides the amounts of nutrient, water quantity is another crucial factor that affects water quality. Water sources include inflows from upstream and rainfall supplement. Consumption of water occurs through outflows, permeation, and evapotranspiration, which includes water surface evaporation and plant transpiration. Baiyangdian Lake is a semi-closed water system with no natural outflows (Yang, 2011), so water consumption by outflows can be ignored. On this basis, the water balance equation to research monthly water quantity variations can be built as shown below.

$$\mathbf{W}_i = \mathbf{W}_{i-1} + \mathbf{W}_{\text{inflow},i} + \mathbf{W}_{\text{rainfall},i} - \mathbf{W}_{\text{eva},i} - \mathbf{W}_{\text{per},i} \quad (6)$$

where $\mathbf{W}_i$ is the lake water volume in month i ($10^8\,\text{m}^3$); $\mathbf{W}_{\text{inflow},i}$ is water inflows in month i ($10^8\,\text{m}^3$); $\mathbf{W}_{\text{rainfall},i}$ is supplementary water from rainfall in month i ($10^8\,\text{m}^3$); $\mathbf{W}_{\text{eva},i}$ is total evapotranspiration volume in month i ($10^8\,\text{m}^3$); and $\mathbf{W}_{\text{per},i}$ is the volume of water consumed by permeation in month i ($10^8\,\text{m}^3$).

In Baiyangdian Lake, the inflows are mainly controlled by upstream reservoirs. The monthly average water released for Baiyangdian Lake is $0.05 \times 10^8\,\text{m}^3$ (Yang, 2011). This region's annual average precipitation is 461.9 mm, with most of this precipitation falling between June and September. The permeability coefficient in Baiyangdian Lake is 3 mm every day (Beijing Normal University, 2011).

Evapotranspiration in lakes is a complex process. Outside the growing season, water surface evaporation decides the total evapotranspiration volume. During the growing season the lake has to be divided into two zones to calculate total evapotranspiration volume. In the zone without plants, only water surface evaporation needs to be considered. In the zone with plants, both water surface evaporation and plant community transpiration need to be considered. Surface evaporation in the zone without reeds and the total evapotranspiration in the plant growing zone during the growing season for Baiyangdian Lake are shown in Table 2. From December to February, the lake is frozen and water surface evaporation can be ignored.

2.4 Development of an optimisation model

In Baiyangdian Lake, reeds begin to germinate at the end of March or the beginning of April every year. People usually plant reeds at this time. In this study the initial planting area is optimised for this time. Nutrient removal and evapotranspiration of reeds in March and April are negligible and can be ignored. After April, reeds will grow quickly from May to September. Both the amounts of nutrients absorbed and water evapotranspiration are large during this time. In October, reeds will stop growing and release nutrients to the lake, so the harvest of aboveground reed tissues should be finished before this time. All months from May to September are the potential optimal time to harvest reeds. In this study, a certain proportion of reeds would be harvested at the end of each month from May to September. The harvest ratios of these months should be optimised. In summary, the reed planting area in March or April and harvest ratios from May to September are variables that need to be optimised in the model.

In actual conditions, plant density is very difficult to quantify and control, because the reed rhizome system has high reproductive capacity (Lavergne and Molofsky, 2004). Thus, the reed density in this study is set as the current density in the reed growing zone of Baiyangdian Lake. It is assumed that nutrients distribute uniformly in the lake, so nutrient concentrations can be calculated based on the amounts of nutrients and lake water volume. After nutrient balance and water quantity balance analysis of Baiyangdian Lake, the relations between nutrient concentrations and reed management can be built.

Baiyangdian Lake is expected to satisfy the standard for Grade III of the Chinese water quality scale according to the requirement of local government, i.e. the concentrations of TN and TP are required to be no higher than 1.0 and 0.05 mg L^{-1}, respectively. These two values are defined as the target values (C_{target}). In this study, we attempt to make water quality meet the target by reed growth management. If water quality could not meet the requirement in some periods, it was expected to be as close to the target concentrations as possible. To better show the gap between actual water quality and the target, a new gap index, δ, will be defined. When the actual concentration of nutrients is not higher than the target value, the gap index is zero. Otherwise, the index has to be calculated as the relative error. The equations are shown as follows.

$$\delta = \begin{cases} 0 & (C_{\text{actual}} \le C_{\text{target}}) \\ (C_{\text{actual}} - C_{\text{target}})/C_{\text{target}} & (C_{\text{actual}} > C_{\text{target}}) \end{cases} \quad (7)$$

where δ is the gap index for some nutrient; C_{actual} is the actual nutrient concentration in the lake (mg L^{-1}); C_{target} is the target concentration (mg L^{-1}). It is obvious that water quality is better when the gap index is smaller.

An optimisation model for macrophyte management of water quality restoration will be developed in this study. For TN and TP, a monthly gap index can be obtained. The average value of the index over a year for each nutrient indicates the water quality for that year. The objective of the model is to make water quality meet the target and make the gap index as small as possible. The best result for the lake would be if the index remained zero throughout the year.

The objective of the model is as follows:

$$\min \overline{\delta} = \min(\overline{\delta}_{\text{TN}} + \overline{\delta}_{\text{TP}}) \tag{8}$$

where $\overline{\delta}$ is the total gap index used to show the water quality for a year, and $\overline{\delta}_{\text{TN}}$ and $\overline{\delta}_{\text{TP}}$ are the monthly average gap indexes for TN and TP, respectively.

2.5 Scenario creation and model solution

Reeds grow well at elevations between 0.64 m above the water level and 1.01 m below the water level in north China (Pagter et al., 2005; Cui et al., 2006). Beyond this range, the growth of reeds is significantly suppressed. Reed area control normally occurs at the end of March or beginning of April, when reeds are seedlings. The average water level at this time is 7.8 m. Considering the suitable water depth for reeds (−0.64 to 1.01 m), the possible surface area for reed growth is 197 km^2, which accounts for about 60 % of the greatest surface area (308 km^2) of Baiyangdian Lake.

The planting area can be optimised as a discretionary value below 197 km^2, and then managers can define the boundaries of the planting area according to the optimal results. However, defining boundaries in the actual lake environment is a complex process, which includes two main tasks. First, we need to define the boundaries on a topographic map. Then measurements need to be made to determine the actual boundaries in the lake. If the optimal area varies randomly below 197 km^2, managers need to define the boundaries accordingly every year. This work is time consuming. In this study, several scenarios for different planting areas are created. Managers can define the boundaries for each of these scenarios at once. In the following years, managers only need to choose the best scenario and do not need to redefine the boundaries. This method may reduce the accuracy of the optimal result, but it is much easier to implement in practice. Six scenarios will be created, for reed areas of 60 % (185 km^2), 50 % (154 km^2), 40 % (123 km^2), 30 % (92 km^2), 20 % (62 km^2), and 10 % (31 km^2) of the lake surface. The harvest ratios under each scenario will be optimised in the model. The gap index will also be obtained from the model under the optimal harvest scheme for each scenario.

We apply an Adaptive Genetic Algorithm to solve the optimisation model. AGA is one kind of global optimisation algorithm, which is widely used in various scientific computing fields. In recent years, AGA has been used in the field of environmental science and water resources management (Kaini et al., 2012). In this study, the fitness of AGA is to make the total gap index of one year as small as possible. There are five optimization variables, which are the reed harvest ratios from May to September. After modelling all scenarios, we can determine the best reed planting area and harvest scheme, under which the most satisfactory water quality will be attained in Baiyangdian Lake.

3 Results

Pollution in the lake deeply affects the optimal results of the model. The reed management scheme may vary yearly because the pollution level will change. The model in this study covers one year, considering the water quality both in the reed growing season and the rest of the year. The year runs from May in one year to April of the following year. Although reeds begin to grow at the end of March, nutrient removal and evapotranspiration in March and April are negligible. Reeds begin to affect water quality in May every year. The water quality from January to April is affected by the reed management scheme of the previous year. Thus, setting May as the beginning month for the model is more rational.

This study used the average level of pollution in Baiyangdian Lake for recent years. Six scenarios were created for the model. The initial reed area was set as 185 km^2 (scenario 1), 154 km^2 (scenario 2), 123 km^2 (scenario 3), 92 km^2 (scenario 4), 62 km^2 (scenario 5), and 31 km^2 (scenario 6). For each scenario, optimised harvest ratios from May to September and the total gap index of the year will be obtained through AGA. Total gap index shows the water quality level in the model year. After modelling, the harvest ratios for each scenario are optimised, as shown below (Table 3).

From Table 3, we find that almost all reeds are expected to be harvested at the end of June for each scenario. Under these harvest schemes, water quality is the most satisfactory. This phenomenon can be explained by the two opposite effects of reeds on water quality. Compared with other months, the most nutrients are absorbed by reeds in June and evapotranspiration is not very high. After June, evapotranspiration of reed community greatly increases. Water consumed by evapotranspiration in July is about two times more than that in June, and severely damages water quality. Although reeds absorb some nutrients in July, the amount absorbed is less than half of that in June. Therefore, reed growth after June has more negative effects on water quality, making the end of June the best time to harvest them.

The total gap index of water quality is also obtained for each scenario after modelling (Table 4). All the gap indexes are calculated under the optimal harvest scheme. From Table 4, the obvious difference between the maximum and the minimum gap index under different scenarios shows that planting area has a profound effect on water quality. Scenario 3 has the lowest total gap index, indicating that the water quality in this scenario is closest to the target and that a planting area of 40 % of the lake surface (123 km^2) and harvest of 99 % at the end of June is best for the water quality of Baiyangdian Lake.

The differences among the gap indexes for scenarios 4, 5, 6 are large, while the differences among the first three scenarios are small. This indicates that reed area has a significant effect on water quality when the planting area is less than 40 % of the lake surface. When the area is larger than 40 %, most incremental reeds will be planted at the lakeshore, and the effect of incremental reeds on water quality restoration will be inapparent. Thus the effect of reed area variation on water quality is not obvious when the area is larger than 40 %. Although scenario 3 is the optimal scheme, the gap index is not zero. This indicates that the water quality of the best scenario cannot completely meet the target of Grade III on the Chinese water quality grade scale. Macrophyte management alone is unable to maintain satisfactory water quality throughout the year for the current conditions of Baiyangdian Lake.

4 Discussion

4.1 Effect of initial reed area on water quality

The current reed area in Baiyangdian Lake is 80 km^2. According to the results of this study, the optimal reed area is 123 km^2. Lake water quality throughout the year for these two planting areas is compared (Fig. 1). The result of the figure is extrapolated based on the nutrient balance and water quantity balance investigated in this study. In both these situations reeds are harvested at the end of September, according to prior research (Zhao et al., 2012). The time period in the figure runs from the beginning of May in one year to the same time in the following year. It is clear that water quality under the optimal reed area is better than that of the current situation. The water quality improves in May and especially in June. This is due to the increased amount of nutrients absorbed by reeds in June and the low evapotranspiration. With the exception of these two months, water quality steadily deteriorates. Although reeds still remove nutrients from July to September, water quality does not improve because of the high evapotranspiration. Water quality under the current reed area is unable to meet the target all year. In the optimal situation, water quality can meet the target from July to December.

4.2 Effect of harvest scheme on water quality

A new harvest scheme, indicating that reeds should be harvested at the end of June, is also proposed in this study. The effects of two different harvest schemes (at the end of June or end of September) on water quality are compared under the same initial reed area (123 km^2) (Fig. 2). The water qualities are the same in May and June, after which the variation trends for TN and TP are different for the two harvest schemes. If reeds are harvested at the end of June, the TN concentration is lower than under the other scheme, while the TP concentration is higher. The difference in TN is greater than that of TP, so June is chosen as the optimal harvest time based on the objective of the optimisation model in this study. This result gives us guidance in choosing a harvest scheme. If the main nutrient of a lake is TN, harvesting reeds in June will be better. If the main nutrient is TP, harvesting reeds in September will be more rational. Choosing a harvest scheme should be based on the actual conditions or the management target of the lake.

In the optimal situation meaning that the reed area is 123 km^2 and harvest occurs in June, water quality can meet the target from July to December. In other months, the water quality is much closer to the target than it is under the current reed area. If lake water quality is expected to meet the target all year, the period from January to June needs more attention.

5 Conclusions

This study proposed an optimisation model for macrophyte management of water quality restoration in a shallow lake. Using the optimisation approach, an optimal planting area and monthly harvest scheme can be obtained. Baiyangdian Lake was used as a case study, with common reed as the dominant plant. After modelling, it was found that water quality was closest to the standard for Grade III of the Chinese water quality scale when the initial reed area was controlled as 40 % of the lake surface (123 km^2) and 99 % were harvested at the end of June.

Although the optimal reed management scheme has been determined, the water quality of Baiyangdian Lake could not meet the target. The period from January to June is the main challenge to satisfactory water quality. If water quality is expected to meet requirements throughout the year, some other restoration measures are needed besides macrophyte management. Water release from upstream reservoirs also has a significant influence on water quality, and the operation schedule of reservoirs has not yet considered this influence. Future research on water quality restoration should consider the effects of water release from upstream reservoirs and try to propose a management scheme to ensure lake water quality meets the target all year.

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Table 1. Amounts of nutrients absorbed by aboveground and belowground parts of reeds per unit area each month during the growing season in Baiyangdian Lake (g m^{-2}).

Month		May	Jun	Jul	Aug	Sep
Aboveground part	TN	4	23	12	19	7
	TP	0.5	2.4	1.1	1.9	0.9
belowground part	TN	0.9	5.3	3.6	5.8	2.7
	TP	0.1	0.8	0.6	0.9	0.4

Table 2. The total evapotranspiration capacity of the two lake zones in each month (mm).

Month	1	2	3	4	5	6	7	8	9	10	11	12
Zone 1	0	0	52	62	85	113	119	124	95	71	32	0
Zone 2	–	–	–	–	213	696	1200	615	162	–	–	–

Zone 1 is the lake zone without reeds; zone 2 is the lake zone with reeds, which only occurs in the growing season (May–September).

Table 3. The optimal harvest ratios from May to September for each scenario.

month	May	Jun	Jul	Aug	Sep
Scenario 1	0	98 %	1 %	0	1 %
Scenario 2	0	97 %	0	1 %	2 %
Scenario 3	0	99 %	0	0	1 %
Scenario 4	0	99 %	0	0	1 %
Scenario 5	0	100 %	0	0	0
Scenario 6	0	100 %	0	0	0

Table 4. The total gap index under optimized reed harvest scheme for each scenario.

Scenario	1	2	3	4	5	6
Gap index ($\overline{\delta}$)	1.78	1.71	1.41	4.85	21.83	28.98

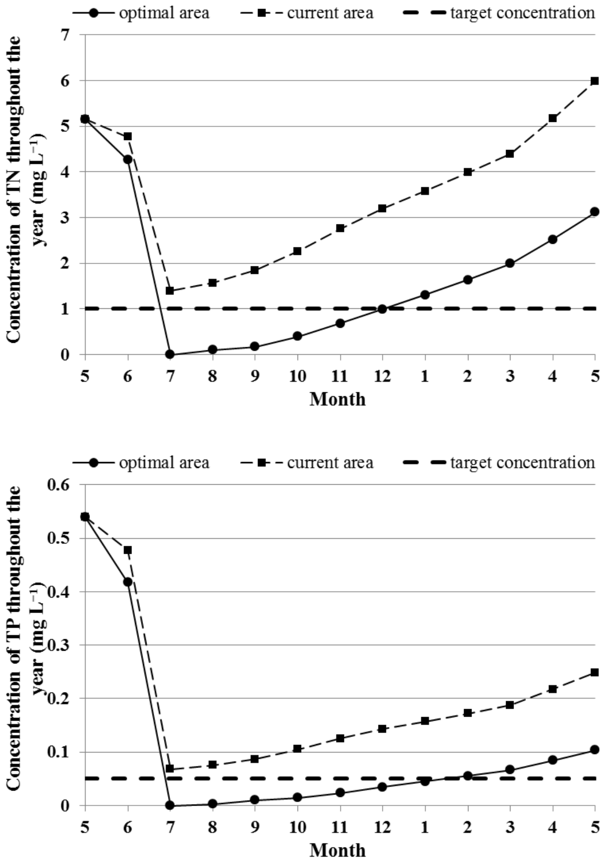

Fig. 1. Lake water quality throughout the year under the optimal and current reed areas.

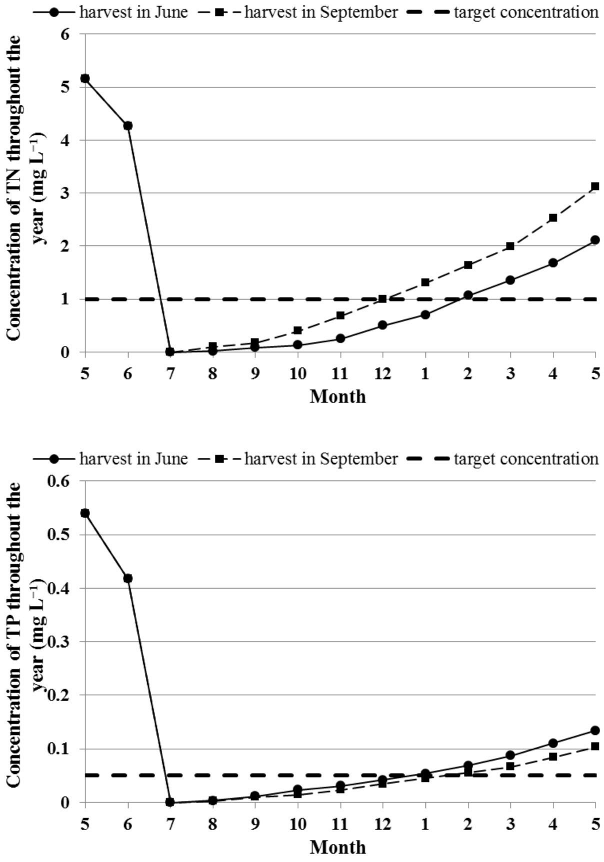

Fig. 2. Lake water quality throughout the year under different harvest schemes.