Control and remediation methods for eutrophic lakes in the past 30 years
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ABSTRACT
Accelerated eutrophication, which is harmful and difficult to repair, is one of the most obvious and pervasive water pollution problems in the world. In the past three decades, the management of eutrophication has undergone a transformation from simple directed algal killing, reducing endogenous nutrient concentration to multiple technologies for the restoration of lake ecosystems. This article describes the development and revolution of three remediation methods in application, namely physical, chemical, and biological methods, and it outlines their possible improvements and future directions. Physical and chemical methods have obvious and quick effects to purify water in the short term and are more suitable for small-scale lakes. However, these two methods cannot fundamentally solve the eutrophic water phenomenon due to costly and incomplete removal results. Without a sound treatment system, the chemical method easily produces secondary pollution and residues and is usually used for emergency situations. The biological method is cost-effective and sustainable, but needs a long-term period. A combination of these three management techniques can be used to synthesize short-term and long-term management strategies that control current cyanobacterial blooms and restore the ecosystem. In addition, the development and application of new technologies, such as big data and machine learning, are promising approaches.

Key words | bioremediation, eutrophication, nitrogen and phosphorus, physical and chemical techniques

HIGHLIGHTS
• Three control and remediation techniques were evaluated and summarized.
• Biological method is cost-effective and sustainable.
• A combination of the three techniques can be used for short-term and long-term management strategies.
• Possible improvements and future directions of remediation methods are discussed.
• Innovation, sustainability, and efficiency are breakthroughs in existing technologies.
INTRODUCTION

Water resources are of great significance to human survival and economic development. Over the past few centuries, water resources around the world have experienced varying degrees of deterioration. Eutrophication is one of the most important representations of water pollutions and a process of ecosystem degradation and aging of water bodies (Duan et al. 2009; Yan et al. 2017). Eutrophication may be defined as the excessive growth of phytoplanktons and organisms leading to an imbalanced aquatic system and a faster rate of succession caused by nutrient enrichment through run-offs from agroecosystems and/or discharged human waste from settlements (Khan & Ansari 2005; Schindler 2006). Eutrophication is characterized by the rapid growth of algae and other plankton, the decline of dissolved oxygen, the deterioration of water quality, and the mass death of fish and other organisms. It presents a global challenge in environmental management and has adversely affected utilization of water resources, socioeconomic development, and human living conditions (Wang et al. 2007; Conley et al. 2009). Since the beginning of the 20th century, eutrophication has attracted a lot of scholars’ attention. China is one of the countries facing the most serious threat of eutrophication, like in the lakes Taihu and Dianchi (Ni & Wang 2015). At the end of the 1990s, the proportion of eutrophic lakes nationwide increased to 77%. A water quality survey was conducted on 138 lakes with an area of more than 10 km² in China from 2007 to 2010 and found that 85.4% of the lakes were eutrophic and 40.1% of them experienced heavy eutrophication (Yang et al. 2010).

Generally, with the accumulation of nutrients and the deposition of aquatic debris at the bottom of lake, it may take hundreds or even thousands of years for oligotrophic lakes to become eutrophic after natural succession. Industrial and domestic waste water containing nutrients from anthropogenic discharges can manifest this succession in the short term, along with the intake of other pollutants. Human activities enriched the aquatic ecosystem, increased nutrition input rate, speeding up the water of the natural aging process (Khan & Ansari 2005, Luo et al. 2019). Human settlements around Lake Lugano, between Italy and Switzerland, are reported to be discharging excessive amounts of domestic sewage, leading to an acceleration of eutrophication due to population growth and migration of the local population (Barbieri & Simona 2010). One of the important factors leading to eutrophication is excessive nutrients from point pollution, such as waste water from industry and municipal sewage, and non-point pollution like irrigation water, surface runoff water containing fertilizer from farmland, atmospheric deposit, etc. (Smolders et al. 2010). The emergence of eutrophication depends on the ratio of nitrogen (N) and phosphorus (P) in the ecosystem, rather than simply the nutrient concentration in the water. Under the premise of sufficient N content, P concentrations below the threshold are prone to eutrophicated difficultly in lakes, and P concentrations above the threshold will produce the opposite result, such as the cyanobacteria outbreak in Taihu Lake. Văduaneanu et al. (1992) found that species changes were linked to accelerated eutrophication of the lakes, with increased P loading and a reduction in the N/P ratio in the aquatic ecosystems of the Danube Delta. Water body characteristics and the geological and climatic environment are other key factors (Scheffer et al. 2001, Lyu et al. 2019).
Damage to water quality by eutrophication can lead to a range of problems, including ecological integrity, ecological sustainability and loss of aquatic ecosystem biodiversity (Geurts et al. 2003). For example, eutrophication has probably caused changes in the mollusk community in Lake Dianchi (Du et al. 2011). Anoxia, which is one of the adverse consequences of eutrophication and increased algal growth, can easily lead to the increase in the release of P sediments and the death of aquatic organisms (Conley et al. 2009; Paerl & Huisman 2009). Increased nitrite concentration in the eutrophic water will also be dangerous to livestock and human health because products of nitrite nitrification process is a strong carcinogen (Rabalais et al. 2002). Eutrophication has even affected the aquatic ecosystems of Antarctica and the Arctic (Smith et al. 2006).

A variety of techniques have been employed in eutrophic water bodies, including hydrological management, in-lake reduction or immobilization of P, complementary ecological management, biomanipulation, and top-down control of the food web (Gulati & Donk 2002). Yang et al. (2008) predicted all the urban lakes and most of the medium-sized lakes at the urban–rural fringe areas in China may be eutrophicated or hyper-eutrophicated by 2030. Jin et al. (2005) indicated that both nutrient pollution control and lake ecological restoration should be carried out for the eutrophic control of lakes in China. Hein (2006) used ecological economic models to provide a reference for optimal control measures (related to costs and benefits) in a specific eutrophic lake ecosystem in the Netherlands. In addition, eutrophic lakes can be successfully restored by lanthanum-modified bentonite, but the cost of this may be an indispensable factor (Copetti et al. 2016). Obviously, water eutrophication is imperative to control, and people have been exploring how to control eutrophication more efficiently and quickly.

The main objective of this paper is to discuss and summarize the previous eutrophication control methods from three perspectives in the past 30 years. In addition, we provide discussion and suggestions on improvements and future directions of these methods for governments and researchers, and ultimately provide practicable suggestions for suitable solutions under specific eutrophic conditions.

**CONTROL AND REMEDIATION METHODS IN THREE PERSPECTIVES**

In general, rehabilitation of eutrophic waters encompasses three components: control of pollutant sources, restoration of the damaged ecosystem, and catchment management (Le et al. 2010). The eutrophication process is affected not only by physical and chemical variables, but also by biological variables (Wang et al. 2007). The formation of eutrophication is a continuous process. Although the influence factors have been known for several decades, the control methods have only been slightly successful. Natural factors, including light and temperature, are hard to change and so to improve the nutritional status of lakes it is better to start from controlling human factors.

Over the past three decades, many conventional and novel methods that use physical, chemical, and biological processes have been applied to improve and eliminate contaminants in eutrophic lakes (Deppe et al. 1999; Benndorf 2010; Wang et al. 2012a). The basic measures include endogenous pollution control (fixed nutrient, sediment dredging, isolation), external pollution control (controlling the emission of N, P, and other nutrients), and ecological control (aquatic bioremediation and biomanipulation) (Lau & Lane 2002). In view of the status quo of eutrophication lakes, improving old technology based on discovering new ones is the fastest way to restore lake water quality.

**Chemical methods**

Chemicals could make it work when the stated conventional treatments cannot sufficiently reduce the nutrient concentrations. Usually, chemical methods are more suitable for lakes with a serious nutritional status resulting in blue-green algae outbreaks. Earlier attempts all over the world at chemical eutrophication management mainly involved copper sulfate (CuSO₄), herbicides, and algicde (Schindler 2006). CuSO₄ treatment is widely used as a global and empirical method to remove or control phytoplankton blooms. It was applied to prevent cyanobacteria efflorescence in a small shallow polymeric lake in France; however, it was only effective against Microcystis for two months (Hullebusch et al. 2002). The shallow Fairmont Lakes in Canada have been treated with CuSO₄ for 58 years to reduce excessive algal growth; the conclusion from this study is that although CuSO₄ treatments are popular because of their ability to kill and remove algae almost instantaneously, they cause immediate or cumulative harmful side effects to many aquatic organisms (Hanson & Stefan 2010). The important toxic mechanism of herbicides on algae is the resistance to damaging the oxidative system and inhibiting photosynthesis. The effect of low-toxic herbicides on the growth of algae shows that it has a promoting effect at low concentrations and an inhibitory effect at high concentrations,
while high-toxic herbicides have an inhibitory effect at low concentrations, and herbicides have joint toxicity with other compounds (Ni et al. 2014). A herbicide (fluridone) was used to reduce Hydrilla populations to control the growth of algae in 1988 in the USA, but it caused an increase in nutrient concentrations (O’Dell et al. 1995). Algicides can also inhibit plant growth. There is a new use for algicides involving the oxidation reagent potassium monopersulfate, which prevents cyanobacteria from multiplying (Wu et al. 2014). However, CuSO₄, herbicides, and algicide are usually limited by cost, secondary pollution generation, and risk of toxicity to non-target aquatic organisms, humans, livestock, and wildlife. Fortunately, biodegradable polymer foam can be used as a carrier of the algicide via the salt-leaching method to improve the eco-friendliness and efficiency of the algicide-releasing process (Bae et al. 2015). The salicylic acid algicide carried by cross-linked chitosan allows a long-term inhibition of algae and provides a method for the effective control of eutrophication in water bodies (Guo et al. 2015). These chemical algae removals are all good treatment techniques that can improve water quality effectively, but they may also accelerate the aging of the lake and trigger new long-term ecological problems after the algae are killed. Thus, it seems that we need to continue our efforts to find chemicals with less toxicity and less secondary pollution.

In recent years, with more in-depth research on nutrient elements and algae growth mechanisms, there are more and more new ideas for improving water quality through chemical methods. Growth patterns and bloom formation of the green seaweed were analyzed in the eutrophic Sacca di Goro lagoon in Italy, indicating an influence of iron (Fe) limitation on N acquisition (Viaroli et al. 2005). Rydin (2014) found that injecting dissolved aluminum (Al) into the anoxic sediments of a eutrophic semi-closed bay in the Baltic Sea inhibited P recovery and further eutrophication. A technique of internally dosing iron compounds in combination with a local water column destratification was developed in order to control Microcystis blooms at a reservoir in Germany, and they concluded that in-lake dosage of Fe²⁺ is an appropriate method of reducing the P loading of hypereutrophic systems (Deppe & Benndorf 2002). Therefore, the water quality can be improved by adding iron or aluminum salt, to inhibit the release of nutrients. Furthermore, removing the killed algae in time or adding chemical reagents to the algae after P release can help achieve more effective effects during the process of aquatic eutrophication control.

Physical methods

Physical methods are also called engineering measures. The most important corrective action for eutrophication in lakes is the reduction of endogenous nutrient loading (bottom-up control) (Estrada et al. 2011).

Dilution and flushing

Flushing and dilution as a potential management technique, which replenishes the lake with water from an extraneous source or another lake that is lower in nutrient levels and preferably higher in Ca²⁺ and HCO₃⁻, directly reduces the concentration of nutrients (Cao et al. 2007; Foster 2010). In low nutrient content lakes, algal growth is limited due to low nutrient supply, which can control blooms and slightly improve water transparency. Hosper (1998) suggested that winter is a good period for preferential flushing due to slow algal growth and easier access to high quality water. In addition, the engineering feasibility of removing sediments deposited in the lake should be examined before implementing drawdown flushing (Ahn et al. 2013).

Flushing and dilution is a simple and rapid technique that is more effective for the treatment of small-scale water bodies. However, its success depends greatly on the sustained availability of good-quality water. With the overall natural water pollution getting worse and the logistics of transporting good-quality water to polluted lakes being neither easy nor cheap, this technique is difficult to achieve. Furthermore, for medium and large-scale water bodies, it is hard to apply because of the large investment, long flushing-time, and unobvious effect. Only a few cases have successfully improved water quality by flushing and dilution. To facilitate dilution of eutrophic water, it is recommended to introduce river circulating water, artificially blended low-nutrient water, low-nutrient reclaimed water below the reuse standards, or even rainwater from urban areas that experience heavy rainfall. The high nutrient concentrations in water bodies, particularly artificial lakes, can be reduced by these measures.

Deep aeration

The nutrient concentration of the lake bottom is higher than that of the surface. The release of P from the sediment can be efficiently prevented through the use of mechanical stirring, air injection, oxygen injection, or other measures. These measures can also reduce phytoplankton photosynthesis by improving the oxygen concentration (Kuha et al. 2014).
Deep aeration mainly has two purposes: (1) to improve the concentration of dissolved oxygen (DO) without changing the water layer, thereby stimulating transformation of the anaerobic environment into an aerobic environment; and (2) to enhance the growth environment of benthonic organisms and increase the food supply. This technique also reduces the concentration of ammonia (NH₃), Fe, manganese (Mn), and other ionic substances (Beutel & Horne 1999; Singleton & Little 2006). Several countries, including the Netherlands and the United Kingdom, have applied deep aeration to small lakes and reservoirs and received good feedback (Chong et al. 2003). The economic and technological restrictions of large lakes make it hard to alleviate eutrophication using deep aeration; therefore, this approach is often applied to small-scale water bodies. As far as current deep aeration technologies are concerned, it is necessary to improve the efficiency of the aeration devices and reduce the cost of the technology.

**Sediment dredging**

Eutrophic lakes are seriously affected by internal P loading from the sediments. When the external load reduced, the presence of an internal load causes continued eutrophication and the re-release of contaminants from sediments (such as P) is a major factor in endogenous contamination. Sediment dredging, a tool for rapidly improving water quality, is one of the most direct and effective lake remediation techniques. It can be used to remove the contaminant-rich sediment surface layers and control contaminant release, as well as reduce the impact of internal loading in the lake (Demelo 1992). The location and depth of the excavation are important for applying sediment dredging (Martinez & Hornbuckle 2011). Chinese scholars analyzed the effects of dredging on the release of 30 cm sediment deposits at the top of Lake Taihu. The conclusion is that dredging can be a useful measure for restoring the aquatic ecosystem when the internal load is the main source of nutrient loading and the nutrient settling rate is low (Zhong et al. 2008). A typical example of successful cyanobacteria control by sediment dredging occurred at Lake Trummen (Vaxjo, Sweden) (Bormans et al. 2016). This method is not particularly sophisticated and is more suitable for small and shallow lake systems, but it is a short-term, extremely costly method of recovery. Recent studies investigated the long-term effects of sediment dredging on the release of pollutants after dredging. Based on the changes of P content after sediment dredging, a small percentage of aquatic areas were monitored to assess the success of the remediation work. It is not always successful at controlling the release of contaminants (Hélène et al. 1999). Resuspension of contaminated sediment and destruction of the surface sediment structure of the water body follows sediment dredging, leaving the lake with secondary pollution. The results show that dredging without the reduction of external loading may only provide temporary improvement followed by a slow return to the pre-treatment conditions (Weston et al. 2010). With respect to dredging as a remediation technique for large-scale contaminated deposition sites, there is still uncertainty in the ability of this method to reduce environmental pollution and human health risks in the long term (Martinez & Hornbuckle 2011).

**Other physical approaches**

For many years, artificial mixing has been used to prevent lake eutrophication and cyanobacterial growth. Visser et al. (2016) argued that for deeper lakes, mixing is more effective than reducing external nutrient loading because it results in an increased oxygen content and effective transformation from cyanobacteria to green algae and diatoms. Some experts consider oxygenation to be a valid short-term lake remediation method (Nygrén et al. 2017). Aquatic plants and algae can absorb a large amount of nutrients. They can be directly harvested by machines to improve the ecological environment of the lake surface. This is a simple and safe method that has been used in different lakes in various areas; however, it consumes much energy and increases the cost of algal disposal (Sim et al. 1988). Sediment capping can be achieved by several methods to decrease sediment P-release (e.g. gravel, plastic films, pulverized fly ash, calcareous mud), but these measures probably have negative effects on the development of submerged macrophytes. Improving the operation and maintenance costs of existing technologies is therefore key to the normal development of physical methods.

Figure 1 lists a kind of treatment technology for cyanobacterial outbreaks for lakes in China. The high-concentration algal liquid can be absorbed and reclaimed by integrated cyanobacteria dehydration equipment. Solid dehydrated algae are formed by gravity separation, high-efficiency air flotation, floculation treatment, and filtration dehydration. The efficient collection and transfer of cyanobacteria are carried out to conduct emergency treatment of cyanobacterial outbreaks.
The applicability, investment, and ecological response of widely used physical methods are listed in Table 1.

### Biological methods

Lake ecological remediation is the key measure for ecosystem re-establishment of natural cycles, which is considered the ultimate target of eutrophication control. Ecological remediation is used to adjust the stability of lake and buffer the speed of nutrient circulation by restoring and rebuilding the relatively complex ecosystem, ultimately re-establishing a healthy ecosystem. Biological methods could reinforce the interaction between microorganisms and aquatic organisms and the self-purification ability of waters when treating aquatic pollution. Bioremediation uses specific microorganisms, aquatic plants, and aquatic animals to degrade, absorb, and transform lake nutrients. The factors affecting bioremediation include energy sources (electron donors), electron acceptors, nutrients, pH, temperature, and inhibitory substrates or metabolites. Treatment of the Alaskan shoreline of Prince William Sound after the Exxon Valdez oil spill in 1989 is a famous example in which bioremediation methods received public attention (Boopathy 2000).

### Microbial remediation

Eutrophication can enhance the biogeochemical cycling of both organic and inorganic contaminants (Smith & Schindler 2009). The microbial bioremediation method is accomplished by adding appropriate amounts of microorganisms (various strains) to accelerate the decomposition of pollutants. During the process of microorganism reproduction at a geometric growth rate, a large amount of the decomposed organic matter serves as nutrients to be absorbed. The higher the microbial biomass and productivity are, the faster the nutrient cycles (Qin et al. 2016). Contaminants that have accumulated in the water body, such as organic matter, N, and P, can be eliminated through nutrient cycling in the ecosystem. Thus, microbial remediation could gradually promote the balance of the aquatic ecosystem, including the plants, animals, and microorganisms, and finally achieving ecosystem remediation.

### Table 1 | Comparison of widely used physical methods

<table>
<thead>
<tr>
<th>Methods</th>
<th>Applicability</th>
<th>Cost</th>
<th>Advantages</th>
<th>Ecological impact</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Flushing and dilution</td>
<td>Small-scale lakes</td>
<td>High</td>
<td>Simple; quickly</td>
<td>Inconspicuous</td>
<td>Foster (2010)</td>
</tr>
<tr>
<td>Deep aeration</td>
<td>Small-scale lakes; large hypolimnion with depth &gt;15 m</td>
<td>High</td>
<td>Direct</td>
<td>Little impact on overall water quality; increasing the density of fish and zooplankton</td>
<td>Kuha et al. (2016); Nygrén et al. (2017)</td>
</tr>
<tr>
<td>Sediment dredging</td>
<td>Internal load is the source of nutrients; low settling rate</td>
<td>Extremely high</td>
<td>Direct</td>
<td>Exposition of unwanted toxic substances; destroying the sediment environment; nutrient source cannot be completely removed</td>
<td>Wang et al. (2004); Martinez &amp; Hornbuckle (2011)</td>
</tr>
<tr>
<td>Mechanical algae removal</td>
<td>Various lakes</td>
<td>High</td>
<td>Simple; safe</td>
<td>Not removing dead algae in time is harmful to environment</td>
<td>Sim et al. (1988)</td>
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</table>
Microbial activity is affected by many physicochemical environmental parameters. Bioactivity has long been recognized to have an influence on the rate of bioremediation. Enhancing bioactivity implies optimization of biodegradation (Blackburn & Hafker 1995). For the purpose of ensuring that the selected microorganisms can maintain good activity, they must be screened regularly to minimize the microbial effects. Successful microbial remediation requires several conditions. First, the target compound must be usable to microorganisms and not contain substances that inhibit bacterial degradation. Second, the microorganisms must be highly metabolically active. Third, the technical costs must be as low as possible (Yang et al. 2016). Microbial remediation offers several advantages over conventional techniques such as land filling or incineration. These benefits include a small environmental impact, broad application prospects, and the ability to minimize pollutant concentrations. It can be done on-site and coupled with other physical or chemical treatment methods. The disadvantages are the long-term remediation time, the difficulty in establishing microbial growth under harsh conditions, and the need for contaminant-specific microbial populations. Furthermore, in some cases, microbial metabolism of contaminants may produce toxic metabolites (Boopathy 2000).

Biofilm technologies. Biofilms can be defined as communities of microorganisms attached to a surface (Davey & O’Toole 2000; O’Toole & Kolter 2000; Gün & Eki’nci 2009). They can exist on all types of surfaces, including plastics, metals, glass, soil particles, wood, medical implant materials, and food products (Kokare et al. 2009). Biofilm technologies use filters with a large specific surface area and a polymer material as a carrier for biofilm-forming microorganisms to purify water (Beklioglu et al. 2005). Pollutants can be effectively intercepted, adsorbed, and degraded by a large number of microorganisms on the carrier. The diversification of microorganisms is beneficial for improving the degradation efficiency and removal rate of pollutants, and it is easy to maintain and manage. Wu et al. (2005) improved the quality of eutrophic water with algal–bacterial biofilms that covered an artificial aquatic mat made from a type of mend macromolecular material, thereby markedly inhibiting algal blooms. Huang et al. (2011) used three active barrier materials (zeolite, ceramic, and a lightweight porous media) to support biofilms that prevent N release from eutrophic lake sediments, with bio-zeolite capping being the most effective. Yuan et al. (2014) used filamentous bamboo and plastic filling as biofilm carriers for bioremediation of nitrogenous compounds from eutrophic water. The exploration of suitable carrier materials has become a hot issue in current research.

Biomanipulation technologies. Biomanipulation, also known as food-web manipulation, manages biomes by altering their structure. This technology is supported by the trophic chain theory and has become a widely applied technique. Shapiro et al. (1975) first proposed the concept of biomanipulation, defined as promoting some beneficial relationships and outcomes for lake users through a series of manipulations of organisms and their environment in the lake. Biomanipulation received much attention in North America and Western Europe (particularly in the Netherlands, Germany, and the Nordic countries) during the 1990s (Van Liere 1992). In 1989, the first international conference on lake biomanipulation, entitled ‘Biomanipulation: A tool for lake management’, was held in Amsterdam (Gulati 1990). This technology can improve nutrient-rich water quality and change food webs to restore the health of the ecosystem. The overall result is decreased phytoplankton species and number.

There are classic and non-classic biomanipulation techniques. The former is applied to control lower nutrient levels, while the latter is suitable for controlling large-scale cyanobacterial populations with high nutrient levels. Biomanipulation has been shown to remove most carnivorous fish in the ecosystem and transform the water turbidity to clear (Klinge et al. 1995; Müller 2004). Due to food-chain characteristics, artificially increasing or decreasing organisms could control the number of target organisms and avoid the emergence of algal reproduction (top-down growth control of algae) (Søndergaard et al. 2010; Tang et al. 2015). It can be used to foster microorganisms that are harmless to humans but compete with phytoplankton for nutrients, which then degrade dead algae to improve eutrophication. The Netherlands successfully restored the small eutrophic Lake Zwemlust through biomanipulation techniques (Van Donk et al. 1990). However, some failures have shown that nutrient loading in some lakes minimally decreased after biomanipulation and planktonic fish increased rapidly a few years after treatment (Gulati & Donk 2002). Fishery manipulation a technique that focuses on achieving water quality protection from the perspective of material flow and maximizes the use of aquatic organisms, such as fish. Fish can be carriers to extract plant nutrients, such as P, thereby reducing the nutrient load in the water and sediment layers to purify lakes (Wang et al. 2017).
Constructed wetlands. Wetland systems are important places to improve water quality and protect biodiversity (Fisher et al. 2009). Constructed wetlands (CWs) were initially developed approximately 40 years ago in Europe and North America for the purpose of exploiting and improving the biodegradation abilities of plants. China had its first CWs application system in 2004 (Shutes 2001). Total phosphorus (TP) of 30–67% and total nitrogen (TN) of 30–52% in a hypereutrophic lake can be reduced by wetland filtration systems (Coveney et al. 2003). The eutrophic Lake Taihu in China has been successfully treated by three parallel units of pilot-scale CWs (Li et al. 2008). There are three main types of CWs, namely vertical CWs, subsurface flow CWs, and surface flow CWs. The best removal effect on ammonia nitrogen (NH$_3$N), TN, and TP is attained by vertical CWs. Better removal effects based on the Permanganate Index (COD$_{Mn}$) and chlorophyll-a (Chl-a) content can be obtained by subsurface flow CWs, a kind of wetland that has good thermal insulation and sanitary conditions and is the most widely studied wetland in research and application (Nie et al. 2007). During the flow process of surface flow CWs, the water stream contacts the biofilm of the soil, plants, and plant roots, thus purifying the water through physical, chemical, and biological reactions while simultaneously contributing to the natural reoxygenation of sewage. However, it needs a low hydraulic load and large footprint. The surface flow CWs also affects the aesthetics of landscape because it is prone to odors.

Compared with conventional treatment systems, CWs are low cost, effective, easily operated and maintained, and environmentally friendly. They have been frequently used for nutrient removal from polluted lakes in developing countries and to solve non-point source nutrient introduction into water bodies (Mitsch 1995; Li et al. 2010). The disadvantage of this system is its relatively slow operational rate (Shutes 2001). Due to space and waterline limitations in urban rivers and lakes, the application of wetland technologies has been greatly affected. In addition, precipitates formed by chemical reactions are released when environmental conditions, such as temperature and pH, are changed. With the contaminated area increasing, the processing cost will become higher (Mackay et al. 2014). Once the nutrient input is too large, the ecosystem will quickly collapse.

Aquatic phytoremediation

Aquatic bioremediation method includes aquatic phytoremediation and aquatic animal remediation. For example, a field survey in a temperate lake in France indicated that facultatively anaerobic ciliates, such as nitrate-utilizing Loxodes, may be significant contributors to denitrification in eutrophic planktonic ecosystems (Aleya et al. 1992). Some lake environments, and their symbiotic microenvironments, can also enable degradation of toxic chemicals. However, most remediation accomplishments in recent years have been attributed to the success of aquatic plants.

In lakes with high nutrient concentrations and low flow, phytoplankton proliferation is often considered to be the main cause of eutrophication (Schinder 2012). Aquatic phytoremediation is an effective way to control, regulate, and inhibit eutrophic environments. Aquatic plants can effectively absorb nutrients during their growth and can remove, destroy, or isolate harmful substances from the environment (Glick 2005).

It has been established that different plant species have different effects on the removal of pollutants in floating islands. Aquatic plants can be categorized as wet plants, emergent plants, floating leaf plants, floating plants, and submerged plants. Among them, the ability of the former four plant types to remove nutrients can exceed terrestrial plants under eutrophication conditions. Plants are usually chosen based on their effectiveness and cost, with some of the most commonly selected being canna, cattail, Scutellaria, water hyacinth, duckweed, Vettiveria zizanioides, calamus and Cyperus alternifolius. Reports indicate that compared with other plants, canna exhibits better effects on DO levels, hydraulic efficiency, and percentage of nutrient removal attributable to plant uptake (Bu & Xu 2013). Furthermore, the removal rates of TP, TN, and COD$_{Mn}$ are improved in canna, calamus and mixed canna–calamus systems (Wang et al. 2011). Table 2 shows several plant species and their comprehensive phytoremediation effects in eutrophic waters. In practical application, it is necessary to select the best plant combination type in combination with pollution characteristics and plant absorption characteristics.

A technique called artificial floating islands/floating beds could repair eutrophic lakes utilizing ecological engineering principles to degrade the COD$_{Mn}$, N, and P contents (Zhu et al. 2016). This technology uses floating beds as carriers of aquatic or wetland plants. Ecological remediation of eutrophication waters in Hongfeng Lake shows that floating island carriers can make land plants grow well on the water’s surface and can be applied to ecological remediation of polluted waters in deep water lakes (Wang et al. 2012b). Due to the wide adaptability and flexibility of the plant species, more attention has been paid to planted flotation bed systems. Floating beds have been used in Europe, the United States (Stewart et al. 2008), China (Zhang et al.
and limited biomass of the chosen plants (Li et al. 2010) and many other places. The purification mechanism of the artificial floating bed is shown in Figure 2. A combination of aquatic ecological floating islands/beds and other water treatment technologies not only broadens the application range of the floating islands, but also notably improves water purification. This technology has the advantages of being low-cost, eco-friendly, and is easy and effective to use (Chen 2013). It also broad application prospects due to its water scopes.

However, there are some disadvantages of using planted floating beds for lake remediation. These systems are particularly vulnerable to natural disasters, such as hurricanes or typhoons, which often occur in tropical and subtropical areas. Plants are unavoidably restricted by the growth rate and limited biomass of the chosen plants (Li et al. 2010). Therefore, this technology can be improved to make it more suitable for current eutrophic work. There are several improved floating island technologies. Remediation-promoting integrated floating beds (RPIFBs) were designed to combine water purification and large plant remediation processes that promote institutional transition from phytoplankton dominance to large plant dominance to resist some natural disasters. This is a promising eutrophication and remediation technology for submerged plant remediation (Guo et al. 2014). Green-energy artificial floating islands (GAFIs) are designed to increase the efficiency of ordinary floating islands while decreasing repairing time. The synergetic effects of water spinach, Asiatic clams, and biofilms could enhance the eutrophication treatment performance of floating beds compared to conventional treatment with vegetation as the single biological component (Song et al. 2014). The main advantages of this system are reduction in NH₃-N, nitrate nitrogen (NO₃-N), and nitrite nitrogen (NO₂-N) contents, together with increased DO and redox potential. Canna floating beds combined with immobilized denitrifying bacteria and aeration can enhance N removal efficiency (Sun et al. 2009), but there are many limitations exist for the large-scale application of this improved technology.

In order to enhance phytoremediation effects, further research and application of the following aspects should be pursued: (1) the cultivation and screening of plants with a higher nutrient accumulation capacity should be improved by identifying more plants with strong enrichment abilities; (2) more research should be conducted on the combined application of various remediation techniques; and (3) strengthening the ability to recycle plants after remediation can maintain a relatively stable ecological environment, while simultaneously achieving environmental and economic benefits.

Table 3 lists the primary advantages and disadvantages of the three technologies presented in this article.

![Figure 2](http://iwaponline.com/wst/article-pdf/81/6/1099/768737/wst081061099.pdf)
Remarkable advances have been made in eutrophication treatment in the past 30 years. This paper provides a comprehensive and systematic description of the sources, hazards, and three control technologies for eutrophic lakes. Physical and chemical methods are limited in that they can provide temporary solutions but fail to address the root of the problem due to high cost and technology limit. Once human intervention stops, nutrients will bounce back to the former level. Physical methods are more dependent on manpower and machinery. Chemical methods easily produce secondary pollution and residues and are usually used for emergency situations lacking a sound treatment system. Biological methods are economical, sustainable, and can achieve complete remediation, but requires a long time. Although the physical, chemical, and biological treatments have been proven effective, there are still limitations for application in eutrophic lake remediation. It is difficult to effectively control eutrophication through any single measure, especially for large-scale and complex ecosystems. Furthermore, comprehensive prevention and management of pollutants must be achieved by taking watershed integrated management into account in controlling eutrophic lakes, and drawing up a long-term working plan and periodic goals. The use of ecological remediation is also significant when conserving biodiversity.

The use of waste water treatment plants to reduce P content in domestic sewage is also a source control method for the rapid recovery of urban lakes. Biological dephosphorization and denitrification are commonly used in waste water treatment plants to control eutrophication. Sewage treatment plants rely on biological P removal, and only a small part of P can be removed by chemical precipitation (Jonsson et al. 1996; Maurer et al. 1999). For example, reductions in P loadings by improved waste water treatment and banning the use of P detergents succeeded in stopping algal blooms in freshwater portions of the Neuse River estuary, North Carolina, USA (Paerl et al. 2004). In many countries, the use of nitrilotriacetate (NTA) in place of sodium tripolyphosphate (STPP), which contributes to lake eutrophication, has been quite successful for a while (Lo & Huang 1995).

Eutrophication control is a long-term systematic project. It is a complex issue of controlling and managing the regulations, which requires the collective efforts of scientists, policy makers, and citizens. Although many cities have passed legislation to regulate point source nutrient loading, eutrophication and cyanobacterial blooms are still prevalent in surface water around the world. The information in this review can provide a scientific reference for policy makers to create suitable solutions for eutrophic lakes and support researchers to further develop eutrophication treatment technologies. Large-scale policy development to alleviate eutrophication is a challenge that is significant and costly. The pressure to develop an algal bloom control strategy will continue to exist (Heisler et al. 2009). The shortcoming of this article is that some of the latest technologies and measures have not been systematically included and that new technologies combining multiple methods have not been elaborately explained. Subsequent research can target the combination of multiple technologies.

**CONCLUSION**

**FUTURE DIRECTIONS FOR EUTROPHIC LAKES**

A combination of physical, chemical, and biological management techniques can be used to synthesize short and long-term management strategies that effectively control...
current cyanobacterial blooms and ultimately restore the ecosystem. It is therefore important to better understand the importance of the interactions between nutrient abundance and key physical, chemical, and biological characteristics in the water. First, the enrichment of nutrients can be reduced by prevention strategies; then, some physical methods can be used to prevent the regeneration of nutrients themselves; and finally, specific treatment measures combining physical–biological methods or chemical–biological methods can be carried out to restore the aquatic system. Urban lake management measures often need to consider both ecological and human influences. Thus, it may be beneficial to combine aeration or chemical precipitation with any one of the biological methods to create hydrological landscapes, especially in heavily polluted lakes. Lakes with lower nutrients can directly grow some aquatic organisms to maintain stable surroundings. Lakes located in the suburbs can be repaired with a combination of sediment dredging and ecological methods. It is clear that recovery of eutrophic water might require years or even decades.

In addition, with economic and technical support and the development and application of new technologies, such as big data and machine learning, accurate and targeted control measures could be implemented based on the actual conditions of the lake. Numerical modeling is a low-cost and reliable tool for forecasting. Understanding and modeling are key to any successful treatment strategy. The basis for simulating the growth of algae is the change of organic carbon, N, P contents in lakes, P contents in sediments, and temperature over time. In most cases, both P and N control measures must be taken to control eutrophication. Single nutrient management strategies, such as reducing NO3 inputs to lakes by reducing the amount of N applied by farmers in the basin can trigger the remobilization of P in lake sediments. Three types of eutrophication models are commonly used today, namely the single nutrient load model, the phytoplankton-nutrient-related model, and the ecological kinetic model. Not only do these models organically combine theoretical analysis with experimental research, effectively simulating flow conditions and water quality evolution, but they can also provide a theoretical reference and support decision making for eutrophication planning and management. Therefore, future technologies and measures for handling eutrophic water bodies will become more advanced and effective.

In the future, we can begin with the following steps to facilitate eutrophication management:

- Assess the effects of seasonal changes on phytoplankton growth and community composition so as to conduct targeted conservation work.
- Identify repair and treatment technologies for large-scale water bodies.
- Determine priority management targets and implement control measures based on lake nutrient composition.
- Develop optimal control policies for specific lakes or areas.
- Recycle nutrients from eutrophic water by adsorption, desorption, and other technologies to increase the source of fertilizer (Oliveira & Machado 2013).

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REFERENCES


Bay, California, USA. *Environmental Toxicology & Chemistry* **21** (10), 2216–2224.


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