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Eutrophication of Lake Waters in China: Cost, Causes, and Control

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Abstract Lake water eutrophication has become one of the most important factors impeding sustainable economic development in China. Knowledge of the current status of lake water eutrophicatoin and determination of its mechanism are prerequisites to devising a sound solution to the problem. Based on reviewing the literature, this paper elaborates on the evolutional process and current state of shallow inland lake water eutrophication in China. The mechanism of lake water eutrophication is explored from nutrient sources. In light of the identified mechanism strategies are proposed to control and tackle lake water eutrophication. This review reveals that water eutrophication in most lakes was initiated in the 1980s when the national economy underwent rapid development. At present, the problem of water eutrophication is still serious, with frequent occurrence of damaging algal blooms, which have disrupted the normal supply of drinking water in shore cities. Each destructive bloom caused a direct economic loss valued at billions of yuan. Nonpoint pollution sources, namely, waste discharge from agricultural fields and nutrients released from floor deposits, are identified as the two major sources of nitrogen and phosphorus. Therefore, all control and rehabilitation measures of lake water eutrophication should target these nutrient sources. Biological measures are recommended to rehabilitate eutrophied lake waters and restore the lake ecosystem in order to bring the problem under control.

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China is a country with a large number of lakes in the world. Those having an area over 1 km^2 total 2759 in quantity and 91,019 km^2 in area, or 0.95% of the country's territory. About one-third of these lakes are freshwater ones, mostly distributed along the eastern coast and in the middle and lower reaches of the Yangtze River. They make up 60–70% of all freshwater lakes in China. A large majority of them are rather shallow (Wang and Dou 1998) and have been eutrophied or are being eutrophied as a consequence of rapid economic development coupled with irrational exploitation of water resources over the last two decades (Qin 2002).

Lake water eutrophication refers to the changes in water chemical properties triggered by accumulation of excessive nutrients such as nitrogen and phosphorus. It is a joint by-product of light, heat, and hydrodynamics resulting from a series of biological, chemical, and physical processes. Water eutrophication can lead to rapid production of phytoplankton and other micro-organisms and deterioration of water quality, both of which are detrimental to aquatic ecology and the normal functioning of the water bodies (OECO 1982). Subsequently, the lake ecosystem is destroyed and the functionality of the water weakened. In the worst case, water eutrophication can result in frequent outbreaks of algal blooms and threaten the reliable supply of drinking water.

The purpose of this paper is to elaborate on the status and evolution of water eutrophication in shallow inland lakes of China, to evaluate its economic cost, and to explore its causes from pollution sources. Preventive measures are proposed to control water eutrophication.

These measures should serve as useful guidance in redressing water eutrophication of shallow lakes and restoring their degraded ecosystem.

Evolution, Current Status, and Damage of Water Eutrophication

There are 651 shallow lakes with an area >1 km^2 in the middle and lower reaches of the Yangtze River, for a combined area of 16,558 km^2. They account for 60% surface area of all lakes in China. For most of them the 1980s was a major turning point in the evolution of water quality. Prior to the 1980s they enjoyed a relatively good water quality except for a few lakes adjoining urban centers. Since the late 1980s, however, most of them have become moderately or highly eutrophied (Shu and Huang 1996; Jin 1990). Of these lakes, Lakes Tai and Chao are the worst affected. For instance, Lake Tai had a water quality graded as level I (suitable for drinking) or level II (suitable for fishing and bathing) in the mid-1960s owing to the small amount of pollutants discharged to it. Water eutrophication was nonexistent or took place at only a minor level. However, the rapid economic development in the early and mid-1980s changed the situation. The unbridled development of burgeoning township enterprises was accompanied by a steady increase in pollutant discharge. The huge amount of waste water discharged into the Lake catchment area rose 1.7 times from 1979 to 1989. Consequently, the water quality was lowered to an average grade of level III, or a moderate level of eutrophication. In the 1990s rapid industrialization along its shore witnessed an exponential rise in industrial waste water discharged. Following these changes was a high level of water eutrophication in the lake. On average, 29% of the water area in Lake Tai had a moderate level of eutrophication, while the remaining 71% had a worse level in 2000 (Lin 2002).

At present lake water eutrophication is still very serious. The most recent investigation of 67 main lakes around the country reveals that 80% of them have been polluted to a level of grade IV (unhealthy for human contact) or lower. Only about 20% of them have a relatively good quality, grades II–III (Li 2006). Nitrogen and phosphorus levels in 18 lakes are so high that they have been virtually eutrophied to the moderate level, accounting for 37.6% of the total area of the 67 main lakes. The number of severely eutrophied lakes has reached 49, about 62.4% of the entire water area. Roughly, three-quarters of the lakes have been severely eutrophied. Another survey of 50 lakes in the middle and lower reaches of the Yangtze River reveals that an overwhelming majority of them have been seriously eutrophied (Fig. 1).

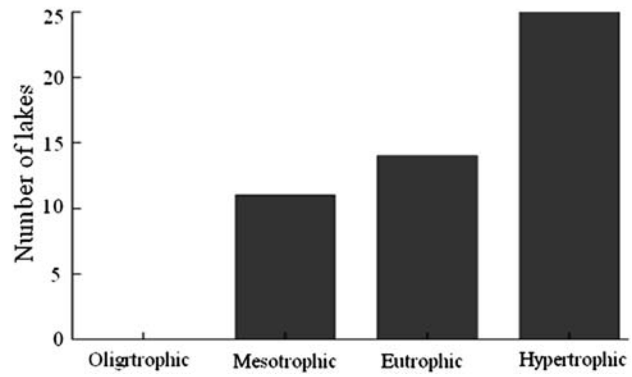

Fig. 1 The current status of lake eutrophication in the middle and lower reaches of the Yangtze River (*Source*: Qin 2007)

Lake water eutrophication has become the most important environmental problem for cities in the catchment area. For example, algal blooms in Lake Tai have adversely affected industrial and agricultural production and the lives of urban dwellers since the 1990s. The 1990 bloom forced the shutdown of the entire water supply system and triggered a crisis in water security for the urban population. The direct economic loss was estimated at 200 million yuan (about U.S.$30 million). The algal bloom in the summer of 1998 once again resulted in an insufficient supply of drinking water for the local residents. The most damaging and extensive outbreak of algal bloom took place on May 25, 2007. It severely affected the supply of drinking water in the shore cities. For instance, the Wuxi municipal government had to shut down its water supply system. Lakes Chao and Dian that had been eutrophied to a serious level also suffered from the attacks by algal blooms (Yu and others 2002).

Associated with the high level of lake eutrophication is the suffocation of the fish population on a massive scale. In 1998 alone there were nine such incidents. Furthermore, algal blooms have degraded the investment environment of the region and damaged tourism and the hospitality industry. The total economic loss incurred from the 1998 algal bloom in the catchment area was estimated at 46.5 billion yuan (about U.S.$6.5 billion) in the Lake Tai catchment area, or 5.9% of the gross domestic product (GDP) of that year in the catchment. Similarly, algal blooms in Lakes Chao and Dian have gravely impeded economic development and affected people living in the catchment area. In sum, lake water eutrophication has led to ecosystem degradation and water quality deterioration and has adversely affected utilization of water resources, socioeconomic development, and human living conditions. It has become one of the paramount problems in achieving sustainable development in the concerned catchment area.

Mechanism of Lake Water Eutrophication

The exact mechanism of water eutrophication in a lake varies with its regional settings, such as the geography, natural environment (e.g., climate), aquatic ecosystem, and characteristics of pollutants. Nutrients such as nitrogen and phosphorus cause algae and other micro-organisms to multiply abnormally, which in turn depletes oxygen in water. The accumulation of nutrients is a process critical to lake water eutrophication. These nutrients originate chiefly from external sources. For shallow inland lakes, the release of nutrients from bottom deposits is also an important source.

External Injection of Nutrients

Since the economic reform in the late 1970s there have been rapid industrialization and urbanization in the catchment area of lakes. While these industrial activities have brought impressive economic returns, they have also produced a substantial amount of waste water that is disposed without proper treatment. A drastically expanded urban population also produces more domestic waste water than before, owing to the improved lifestyle. Farmers are using ever more fertilizers to boost agricultural yields. The industrial waste water, domestic sewage, and rainwater from agricultural fields eventually end up in lakes. The accumulation of nutrients has lifted the concentration level of such elements as nitrogen and phosphorus in lake waters. In the right environment (i.e., temperature) they worsen the aquatic environment, deteriorate the ecological functionality of lakes, and lead to water eutrophication. The relationship between industrial development and water eutrophication is best appreciated from Fig. 2 (Jin 2006). It shows that nutrient discharge from external sources into a lake (e.g., Lake Tai) coincides closely with the level of economic development in its shore. With the rise in GDP of the catchment area, all indicators of water quality in Lake Tai experienced a general trend of worsening during 1980–2000.

There are two manners of nutrient discharge into lakes from the external sources: point discharge and nonpoint discharge. Point discharge refers to the injection of industrial waste water and domestic sewage into lakes at fixed locations. Nonpoint discharge includes waste water from agriculture, aquaculture, rural dwellers, and soil erosion. Lakes Tai, Chao, and Dian, the three most eutrophied lakes in China, are all subject to both means of discharge to a varying degree (Gao and Yan 2002). Point-source pollutants are relatively easy to handle owing to the controlled way of disposing industrial waste water and domestic sewage. By comparison, waste water discharged from nonpoint sources is much more difficult to handle. It becomes increasingly urgent to tackle nonpoint pollution,

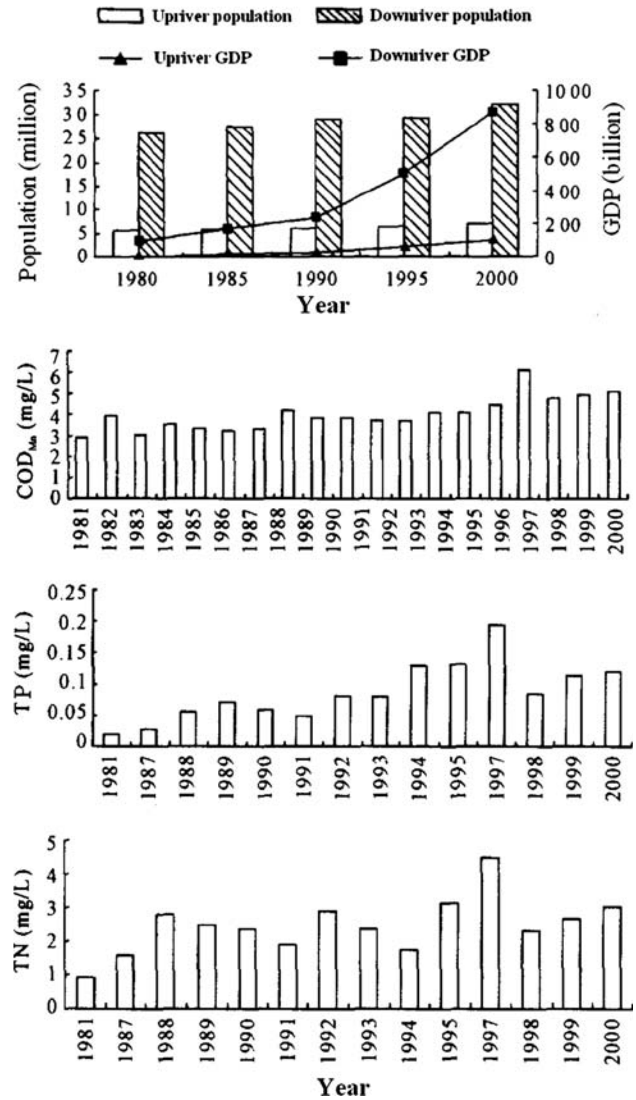

Fig. 2 The rise of the GDP in the Lake Tai catchment area and the variation of major water quality indicators between 1980 and 2000

as it has become the leading factor in degrading the aquatic environment and lowering water quality. Of these nonpoint sources, agricultural waste water has an overwhelming effect (Gao and others 2002). Study of many lakes in China reveals that approximately half of the pollutants discharged into lakes originate from nonpoint sources (Jin 2001). Take Lake Chao, for example. Of all the nutrients entering it, those from nonpoint sources make up about 68% of the total discharged phosphorus, or 74% of the total nitrogen within the lake (Zhang and others 1999), far exceeding the quantity from point sources. As for Lake Tai, the amount of nitrogen from nonpoint sources makes up 57% of the total nitrogen entering it, while the nitrogen from domestic sewage makes up another 40%. Agriculture-produced phosphorus accounts for 39% of the total phosphorus entering the lake (Hu 2003). The nonpoint sources of

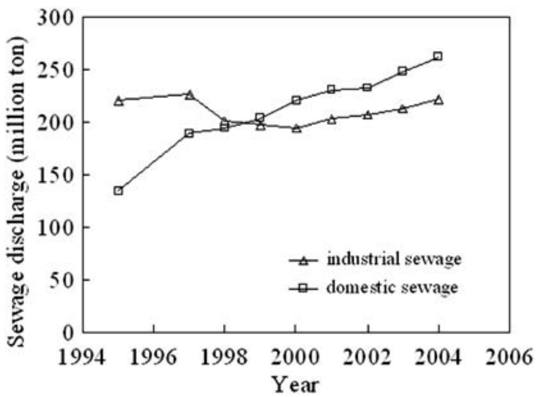

Fig. 3 The total amount of waste water discharge by sector

pollutants in the Lake Dian catchment area are restricted chiefly to soil erosion, surface runoff from agricultural fields, and the atmosphere. Of these sources, surface runoff and agricultural production contribute over 70% of the nitrogen and phosphorus entering the lake (Guo and Sun 2002). Of all the nitrogen sources, industrial waste contributed only 2% in 2002. Domestic sewage made up 53%, a figure slightly outnumbering 45% for agricultural fields. Of all the phosphorus, only 4% originated from industrial waste, in sharp contrast to the 69% from domestic sewage and 27% from agricultural fields (Wan and others 2007). Therefore, nonpoint discharge of nutrients has become the main means for external pollutants to enter lakes in China. How to control such nutrient discharge is the key to bring lake water entrophication under control.

Internal Loading of Nutrients

Internal loading of nutrients refers to the process in which organic particulates within lacustrine deposits are decomposed into dissolvable nutrients via hydropower, oxidation, and deoxidation (Qin and Fan 2002). All the substances displaced over the catchment area are eventually deposited on the lake floor where all nutrients, heavy metals, and organic particulates accumulate. Together with the remains of plants, they serve as a large reservoir of lacustrine pollutants (Qin and Zhu 2005). Of the phosphorus in the domestic sewage discharged into the East Lake in Wuhan, approximately 60% are retained within the lake, resulting in a marked rise in the phosphorus content of the lake deposit (Xie and Xie 2002). The release of such retained nutrients from the deposit is directly responsible for raising the nutrient load in the lake water.

The concentration level of nitrogen and phosphorus in the floor deposits is not vertically uniform. The mixing between lake water and nutrients within the deposits takes place most frequently within the top 0–25 cm (Wang and others 2002), but less so deeper down (Gao and others 2004). This mixing is occasionally interrupted by waves and current-induced turbulences. The resuspension of lacustrine deposits accelerates the diffusion of nutrients within the voids of deposits and their release from these internal sources. The net effect is accelerated water eutrophication. This release becomes the major source of in-water nutrients within certain periods (Gao and others 2004; Hu and others 2005).

Nutrients may be released internally in two modes, statically and dynamically. The static mode of release refers to the upward diffusion of nutrients under calm conditions as a result of the nutrient gradient at different water depths. This kind of release is accomplished via the dispersion at the molecular level. By comparison, the dynamic mode of release requires waves and currents that resuspend deposits at the lake floor. Both modes of internal release apply to large shallow lakes. Under static conditions, the quantity of released NH_4^+–N totals about 10,000 tons per annum for Lake Tai (Qin and others 2005). The figure is lower, at 900 tons, for PO_4^{3-}–P. The total quantity of nitrogen and phosphorus released annually under the action of waves is, respectively, 81,000 and 21,000 tons. Both are about two to six times the externally replenished nutrients.

Control of Water Eutrophication

In general, rehabilitation of eutrophied lake waters should encompass three components: control of pollutant sources, restoration of the damaged ecosystem, and catchment management. They all aim at reducing nutrient loads and restoring the lake ecosystem (Qin and others 2006; Jobgen and others 2004). To control lake water eutrophication, efforts should be directed at harnessing the external point discharge and the nutrients released from floor deposits. Restoration of the damaged ecosystem should center around the regeneration of vegetation along lakeshores and aquatic plants in lakes. The restored ecosystem along the lakeshore can effectively intercept pollutants originating from the catchment area before they enter the lake. Aquatic lake plants can help to reduce the amount of suspended matter and internally released nutrients.

Control of Nutrient Loads

Nutrient loads in a lake may be controlled through restructuring industrial layout, catchment management, and human intervention.

Restructuring of industrial layout

Point-source pollutants originating from mines, factories, and residence form one of the most important sources of nutrients in lake water (Fig. 3). Take Lake Tai, for example. Its catchment area used to be full of heavy industrial polluters, such as chemical and dye factories, and ferrous metallurgic refineries. These township enterprises did not have adequate facilities for treating their waste water before disposal. In fact, only about 40–70% of industrial waste water in the cities surrounding the lake is treated (Liu and others 2001). The sewage-like waste water from these plants has severely polluted the lake water and turned its color to red and black (Wang 1997). Thus, it is imperative to shut down heavily polluting industries, such as chemical and dye factories, paper mills, and electroplating workshops. This closure makes economic sense, as the environmental destruction caused by all the township enterprises in China during the 1980s and 1990s is as high as about 79.79% of the entire profits they produced during the same period (Wang 1997). The less polluting plants should be relocated to a designated industrial park so that the treatment of their waste water can be centralized and effectively handled. Their replacement should be high-tech enterprises and the service industry, which cause little or no pollution.

Catchment Management

Owing to the relative ease of controlling point-source pollutants, nutrients discharged from agricultural fields into shallow lakes has risen to become the chief external source of pollution, which is best addressed with catchment management or rationalization of land use. Land use significantly affects hydrology and the hydroenvironment. Land use changes alter the characteristics of the underlying soil and exert a profound influence on water circulation and substance transfer (Budherdra and others 2003). In the Lake Tai catchment area, urbanization resulted in an annual rise of 4.11% in surface runoff during 1980–2000 (Li and others 2006). The yield of total nitrogen increased, on average, by 5.35% (maximum = 21.62%). However, in rapidly urbanizing cities, such as Suzhou, Wuxi, and Changzhou in Jiangsu Province, land use change has caused a much higher yield of total nitrogen, at 17.11%. The figure is lower, at 10.72%, in Pudong and Puxi in Shanghai. Surface runoff and sediments are correlated with rainfall at the 95% significance level. To reduce the yield of nonpoint pollution from agricultural fields, land use should be rationalized with the proper layout of cultivated fields. In this way most of the nutrients are absorbed by crops instead of entering waterways. One way of achieving this goal is to reshape and reuse farmland in mountainous areas because the annual yield of nutrients follows the regularity of sloping farmland > terraced farmland > terraced orchards > sloping orchards. Another strategy is to spatially juxtapose different land uses, rotate crops, and simultaneously cultivate multiple crops (Yan and Bao 2001). In addition, it is also necessary to construct a wetland protection zone and restore riparian vegetation along the lakeshore to absorb any residual nitrogen and phosphorus (He 2002).

Human Intervention

The key to restore the degraded ecosystem of shallow eutrophied lakes lies in controlling the amount of internally released nutrients. Past practice demonstrates that the nutrient load and algal blooms of shallow lakes respond sluggishly to the control of external nutrient sources, or minimally because of the nutrients replenished from lacustrine deposits (Padisak and Reynolds 1998). Such nutrients can be reduced via physiochemical and physiomechanic methods. Both measures aim at trapping the nutrients and removing bottom deposits. Physiochemical methods include oxidation of deposits, chemical sedimentation, and enclosure of floor deposits. Physiomechanic methods include flushing and dredging of floor deposits (Qin and others 2006). These methods are limited in that they can provide temporary solutions but fail to address the root of the problem. Once human intervention stops, nutrients will bounce back to the former level.

Ecosystem Restoration

Ecological restoration aims at rehabilitating the functionality of the damaged ecosystem and its relevant physical, chemical, and biological properties. The essence of ecological restoration lies in the establishment of a natural, self-regulating ecosystem that forms an integral part of the entire ecological landscape (Li and others 2007). Ecological restoration may be accomplished through reduction of algae via aquatic plants. As primary producers, advanced aquatic plants and micro-organisms compete with each other for ecological resources, such as nutrients, light, and living space. During their growth, advanced aquatic plants release chemical substances that are conducive to inhibiting algal production, in addition to directly absorbing nitrogen and phosphorus in water. Storage of these elements in the plants means that they can be effectively extracted from the water via physical removal of these plants from the lake, thus reducing the nutrient level in lake waters (Yang and others 2007). An added advantage of submerged aquatic plants is the suppression of resuspension of floor deposits and hence considerable improvement in water quality (Drenner and others 1997). Ecological restoration takes advantage of this competitive relationship between aquatic plants and micro-organisms. Propagation of aquatic plants in lakes helps to transform the former algae dominated ecosystem into a sound grass-dominated ecosystem.

The success of ecological restoration lies in selecting the right kind of plant species that are most suitable for growth, taking into account the uniqueness of the lake water. Because of their biological propensity, different aquatic plants require different growing environments. They differ in their ability to adsorb, eliminate, and condense nutrients in water and to decompose algae. Once an aquatic plant ecosystem becomes established, it will have the ability to self-cleanse water and rehabilitate lake water eutrophication. However, caution must be exercised in selecting the right aquatic plants. Otherwise, the introduction of inappropriate exotic plants could mean another environmental disaster if their growth cannot be controlled effectively.

Summary

Lake water eutrophication results from the high concentration of nutrients that cannot be adequately absorbed by water. Water eutrophication in most shallow lakes of China was initiated in the 1980s but is still serious at present, with frequent algal blooms, which have disrupted the normal water supply in the shore cities and caused a direct economic loss valued at billions of yuan. Over recent years increasing attention has been directed at treating point-based industrial waste water. By comparison, untreated domestic sewage in urban areas and nutrients from agricultural fields have become the lead contributors of shallow lake eutrophication, together with nutrients released from floor deposits. These nonpoint sources of pollutants have a gradual, delayed impact on water quality that is spatially varying. They have not been properly addressed because the sources of discharge are usually located away from the polluted area. To effectively control water eutrophication, more efforts are required to control such nonpoint sources of pollution.

The most fundamental step in tackling shallow lake water eutrophication is to control the amount of waste water discharged to lakes through restructuring the industrial layout in the catchment area, catchment management, and human intervention. Heavy pollution industries should be shutdown while moderate pollution industries should be relocated away from the catchment area. Catchment management includes rationalization of land use. In controlling internally released nutrients, the emphasis should be placed on studying the characteristics of nutrients in lacustrine deposits and nutrient diffusion at the water-deposit interface. More research is needed to study and control pollution from agricultural fields, such as the regularity and quantity of nutrient transfer within different types of land use. Ecological measures are recommended to rehabilitate eutrophied lake waters and to restore the lake ecosystem. Such ecological means as establishment of a wetland buffer zone and riparian vegetation around lakes and propagation of aquatic plants within water are preferred to physiomechanical and physiochemical means, as they are not sustainable. With the combined use of diverse means, it is hoped that the problem of shallow lake water eutrophication in China can be brought under control in the near-future.

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