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Water quality problems in Japanese lakes: a brief overview

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Abstract Japan experienced serious environmental pollution during the period of high economic growth. As a result of targeted management and remediation strategies, the pollution problems have generally declined. However, eutrophication, invasive alien species and lake warming all continue to represent major issues for Japanese lakes. These pressures are disturbing indigenous lake ecosystems and affecting the physico-chemical condition of the waterbodies. To help prevent eutrophication and its ecological impact, there is a need to reinforce control measures for diffuse pollution and small-scale wastewater treatment, and a concomitant need to develop an economical nitrogen-removal technology. Lake warming is projected to be more serious in the future, and this will alter vertical mass transport patterns, the redox state of sediments and ultimately lake ecosystems. However, we have little knowledge of the potential influence of lake warming at present. Therefore, further detailed limnological studies on lake warming and monitoring of lake environments should be encouraged.

Key words lake pollution; environmental administration; eutrophication; invasive alien species; lake warming; Japanese lakes; Lake Biwa

INTRODUCTION

The Earth is sometimes referred to as the "water planet". About 70% of the global surface is covered by water and about 1.386 billion m^3 of water is stored on the Earth. However, freshwater represents only 2.53% of the total volume (Shiklomanov & Rodda, 2003). Moreover, most of the freshwater exists as glaciers and ice on the continent of Antarctica. The world's freshwater resources are threatened by various pressures including, amongst others, population growth, increased economic activity and lack of pollution control measures. As a result, one third of the world's population currently live in countries that experience medium to high water stress and the ratio is expected to grow to two thirds by 2025 (Agarwal *et al.*, 2000). Given this global context for freshwater resources, lakes and reservoirs can be identified as extremely valuable freshwater sources.

Japan is located in a temperate and rainy region. Accordingly, Japan may seem to be free from water stress. However, Japanese rivers are very steep and most rainwater reaches the sea within a day of falling to the land surface. Therefore, Japan is subject to some water stress, especially during the dry season. Figure 1 shows the mass balance water budget for an average year in Japan (Ministry of Land, Infrastructure, Transport and Tourism, 2012). Surface water supplies about 88% of water demand, whereas about 89% of rainwater is discharged or evaporated. As a result, the preservation and careful use of surface water is very important in Japan. Against this context, this paper summarizes Japanese experience of water pollution control and the current key water quality problems facing Japanese lakes, whilst also providing a perspective for the future.

JAPANESE EXPERIENCE OF WATER POLLUTION CONTROL

The history of water pollution control policy and management

World War II had catastrophic impacts on the Japanese economy. But, in contrast, the outbreak of the Korean War in 1950 triggered high-rate growth of the Japanese economy due to war-related procurement. As a result of the high economic growth, heavy water pollution became a significant problem. For example, in 1955 fish disappeared from the Sumida River in Tokyo, which was previously a healthy fishery, because of problems associated with wastewater discharges. Heavy metal pollution by organic mercury compounds and cadmium caused serious diseases: Minamata mercury poisoning and itai-itai disease.

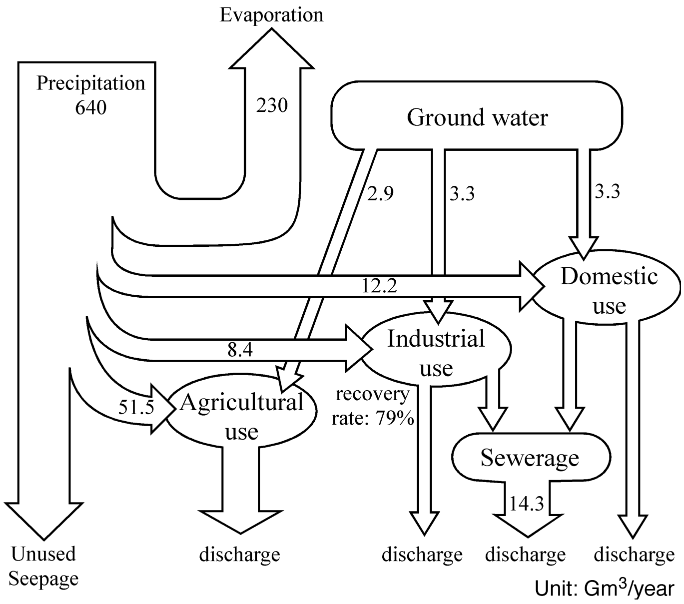

Fig. 1 Water budget for a typical year in Japan (Ministry of Land, Infrastructure, Transport and Tourism, 2012).

The heavy water pollution pressured the Japanese government into establishing a comprehensive management strategy for the water environment, and subsequently, the Basic Law on Pollution Control was enacted in 1967. This Law described the concept and the policy of pollution control, and was a key milestone in environmental administration in Japan. After the enactment of this Law, the Water Pollution Preservation Law was subsequently enacted in 1970 to regulate wastewater discharge into public waters. Furthermore, the Environmental Agency was founded in 1971 to centralize environmental administration. Environmental administration based on the Water Pollution Preservation Law successfully improved river water quality (Fig. 2), but water pollution in lakes remained serious because such systems are closed water bodies, where pollutants can be easily retained and stored. Therefore, the Law Concerning Special Measures for the Preservation of Lake Water Quality was enacted in 1984, which promoted the control of pollutant loadings from domestic and non-point sources for the designated lakes. In 1993, the Basic Law on Pollution Control was updated into the Basic Environment Law, which aimed at global environmental conservation and the establishment of a low-emission society in addition to pollution control. The Environmental Agency was also upgraded to the Ministry of the Environment in 2001.

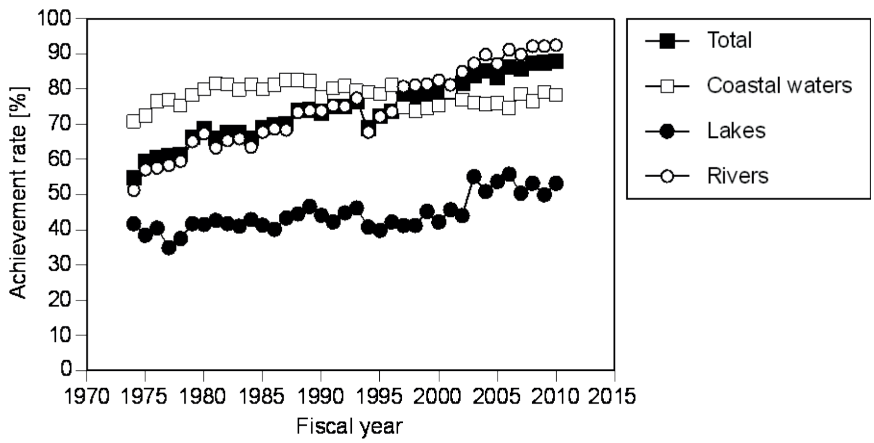

Fig. 2 Transition of achievement rates of environmental quality standards for water pollution (BOD for rivers and COD_{Mn} for both lakes and coastal waters). Data from the Ministry of the Environment (2012a).

The current framework for water pollution control

Figure 3 summarizes the current framework for water pollution control in Japan. The environmental quality standards for water pollution have been generated based on the Basic Environment Law for the protection of human health and conservation of the living environment (Ministry of the Environment, 2012b). The safety of drinking water is controlled by the Waterworks Act, which enforces drinking water quality standards for 50 parameters (Ministry of Health, Labour and Welfare, 2012). The Water Pollution Control Law defines the measures for adhering to the environmental quality standards by setting uniform effluent thresholds for 43 pollutants and regulations on total pollutant loads, as represented by chemical oxygen demand measured by the permanganate method (COD_{Mn}, Japanese Industrial Standards Committee, 2010), total nitrogen (TN), and total phosphorus (TP). Local governments can set stricter effluent standards than the generic thresholds stipulated under the Law. Sewers represent a pivotal system for the control of water pollution by domestic wastewater. Accordingly, the Sewerage Law sets special criteria such as technical standards for a sewage treatment plant and the corresponding effluent water quality discharged to the aquatic environment.

The environmental quality standards for water pollution are categorized into two basic groups: first, standards for human health and, second, those for conservation of the living environment. The former group contains 27 pollutants including heavy metals, organic solvents and inorganic ions. The latter group includes eight pollutants for lakes and reservoirs; pH, COD_{Mn}, suspended solids (SS), dissolved oxygen (DO), total coliforms, TN, TP, and total zinc. Different standards are assigned to each class of watershed, with this classification depending on the principal water use. Total zinc was added to the environmental quality standards for water pollution in 2003 for conservation of aquatic life (Ministry of the Environment, 2012b).

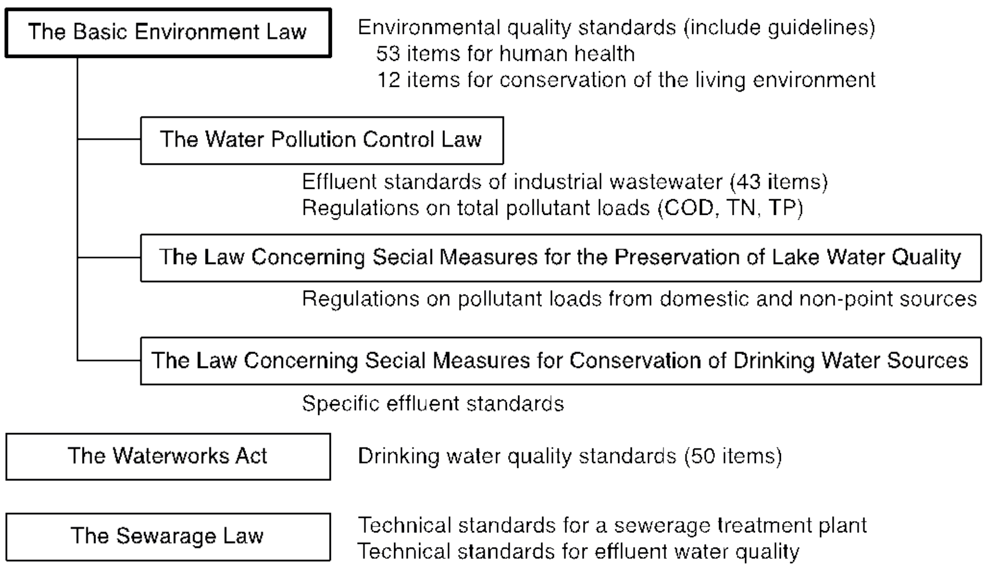

Fig. 3 Current framework for water pollution control and standards related to lakes.

OVERVIEW OF WATER QUALITY PROBLEMS IN JAPANESE LAKES

There are 1120 lakes and reservoirs with a surface area of more than 1 ha and a catchment area exceeding 1 km^2 in Japan. Of these, artificial lakes and reservoirs account for 82.4% (923 lakes). However, the stored water volumes of natural lakes amount to 131×10^9 m^3, which accounts for 89.4% of the total water volume (Society of Water Quality-Related Law, 1986). A number of environmental problems are widely observed in the world's lakes: (1) eutrophication, (2) contamination of water from toxic and hazardous substances, (3) acidification, (4) ecological disturbance by invasive species, and (5) climate change (World Lake Vision Committee, 2003). Japanese lakes also face these problems. Table 1 summarizes lake types in Japan. Eutrophic and mesotrophic

Table 1 Classification of major Japanese lakes.

Lake type	Lake number	Total area (km^2)
Eutrophic	158 (32.4%)	877.1 (36.5%)
Mesotrophic	82 (16.8%)	888.0 (37.0%)
Oligotrophic	131 (26.9%)	367.7 (15.3%)
Acidtrophic	20 (4.1%)	188.2 (7.8%)
Dystrophic	66 (13.6%)	35.8 (1.5%)
Siderotrophic	1 (0.2%)	43.6 (1.8%)
Others	29 (6.0%)	43.6 (1.8%)
Total	487 (100%)	2400.4 (100%)

lakes account for 49.2% of the total number and 73.5% of the total surface area (Environmental Agency, 1995). Thus, eutrophication is still a major issue in Japan, though significant organic pollution was observed during the period of high economic growth between 1954 and 1973.

In addition to eutrophication, contamination by micro-pollutants such as perfluorooctane sulfonate (Saito *et al.*, 2003), pesticides (Sudo *et al.*, 2004) and dioxins (Ikenaka *et al.*, 2005) are potential threats to lake environments. However, these contaminants remain at trace level and evidence of an actual influence on lake ecosystems by micro-pollutants is lacking at present. Lake acidification is a serious problem for many lakes in Northern Europe and Eastern North America (Jørgensen, 1993). However, it is not serious in Japan, in spite of the acid rain precipitation (Hara *et al.*, 1990), because Japanese soils have a high buffering capacity against acidic inputs (Sakamoto, 1991).

In comparison with micro-pollutant contamination and acidification, ecological disturbance by invasive species is a more serious problem in Japanese lakes. There are 2230 invasive species recognized in Japan (The Ecological Society of Japan, 2002). Some of these cause multiple problems like the alteration of fundamental ecosystems, changes in habitat conditions, excessive predation and herbivory, and competitive exclusion of indigenous species (Washitani, 2004). Alien fish including bluegill sunfish (*Lepomis macrochirus*), largemouth bass (*Micropterus salmoides*), and smallmouth bass (*Micropterus dolomieu*) are widely observed in many Japanese lakes. The basses and bluegill sunfish were introduced into Japan in 1925 and 1960, respectively (Azuma, 1992). The use of fishing tackle helped to spread their distribution throughout Japan. The absence of congeners with a similar food niche in Japanese lakes is thought to help the ecological release of these alien fish (Azuma, 1992). The alien fish have had substantial impacts on the populations of indigenous aquatic organisms due to their voracious appetites (Iguchi *et al.*, 2004; Kawamura *et al.*, 2006; Yonekura *et al.*, 2007). Water hyacinth (*Eichhornia crassipes*) is identified in the top 100 of the world's most invasive alien species (Lowe *et al.*, 2000). In addition to water hyacinth, water lettuce (*Pistia stratiotes*) and submerged macrophytes (*Egeria densa* and *Elodea nuttallii*) are widely observed in many Japanese lakes and rivers (Kadono *et al.*, 1997; The Ecological Society of Japan, 2002; Miyawaki & Washitani, 2004; Nagasaka, 2004). These plants overgrow indigenous plants by covering the water surface (water hyacinth and water lettuce) and the lake or river bed (*Eg. densa* and *El. nuttallii*). Furthermore, whole plants or shoot fragments of these species are washed ashore and give off an offensive odour during their decomposition. Dense colonies of the submerged macrophytes have been shown to significantly reduce the dissolved oxygen concentration in the bottom water (Haga *et al.*, 2006). To prevent the spread of invasive alien species, the Japanese government enacted the Invasive Alien Species Act in 2004, in which 105 species or genus were designated and regulated as invasive alien species (Ministry of the Environment, 2011).

Climate change is a new threat to lake water environment. The effects of lake warming are widely observed in Japanese lakes (Adhikari & Kumon, 2001; Ohtaka *et al.*, 2006; Hsieh *et al.*, 2010, 2011). Most Japanese lakes below the latitude of 35.5 degrees are categorized as trophic systems, which have a stratification period every year, whereas the remaining systems are categorized as temperate lakes, which have two stratification periods every year. Lake warming extends the stratification period in summer and shortens the stratification period in winter. As the result of changes in stratification periods, lake warming has the potential to alter the vertical transport pattern of nutrients and oxygen between the epilimnion and hypolimnion, which sometimes causes water quality deterioration (Komatsu *et al.*, 2007).

ENVIRONMENTAL PROBLEMS IN LAKE BIWA: A CASE STUDY

Background on Lake Biwa

Lake Biwa is located in Shiga Prefecture, which is in the centre of Honshu Island (Fig. 4), and is the largest lake in Japan. It has a surface area of 674 km^2, a volume of 27.5 km^3, a maximum depth of 104 m, a mean depth of 41 m, a catchment area of 3174 km^2 and a mean residence time of 5.5 years (International Lake Environment Committee, 1999). Lake Biwa is divided into two basins: south and north. The southern basin is shallow and small with a mean depth of 4 m and a volume of only 0.2 km^3, whereas the northern basin is deep and large with a mean depth of 43 m and a volume of 27.3 km^3; thus it stores most water. Lake Biwa is an ancient lake with endemic species of 15 fish, 29 shellfish, 3 insects, 4 crustaceans, 2 water plants, 5 phytoplankters, and 3 invertebrates (Nishino, 2007).

Lake Biwa is very important as a drinking water source for more than 14 million residents. Therefore, both national and local government have made efforts towards the preservation of the water environment of Lake Biwa. For instance, the Eutrophication-Control Ordinance for Lake Biwa was enacted in 1979 by the Shiga Prefectural government, in which the usage of phosphorous-containing detergents was prohibited for the first time. In addition, an advanced sewage treatment system, based on anaerobic-anoxic-oxic processes with the addition of coagulant and sand filtration, was installed. This system produces better quality effluent with a typical BOD of 0.8 mg/L, TN content of 4.4 mg-N/L, and TP content of 0.07 mg-P/L. As a result, pollutant loadings have drastically decreased over the past quarter of a century (Fig. 5). The annual mean BOD and TP concentration in Lake Biwa have also been improved (Fig. 6), against the background of accelerated eutrophication from the 1960s to 1970s (Hsieh *et al.*, 2010; Tsugeki *et al.*, 2010).

Divergent temporal trends in BOD and COD_{Mn}

As is shown in Fig. 6, COD_{Mn} in Lake Biwa began to increase again in 1984 and reached a plateau after 1998, whereas BOD has been steadily decreasing. A similar pattern is observed in other Japanese lakes, e.g. Lake Hachiro. Since the environmental quality standard for organic pollution

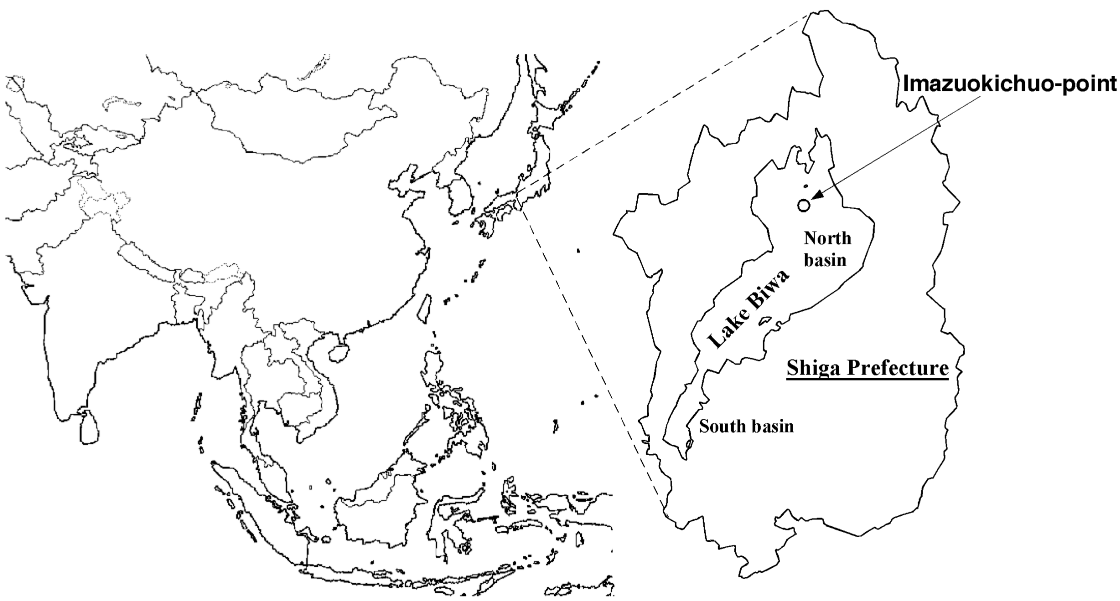

Fig. 4 The location of Lake Biwa.

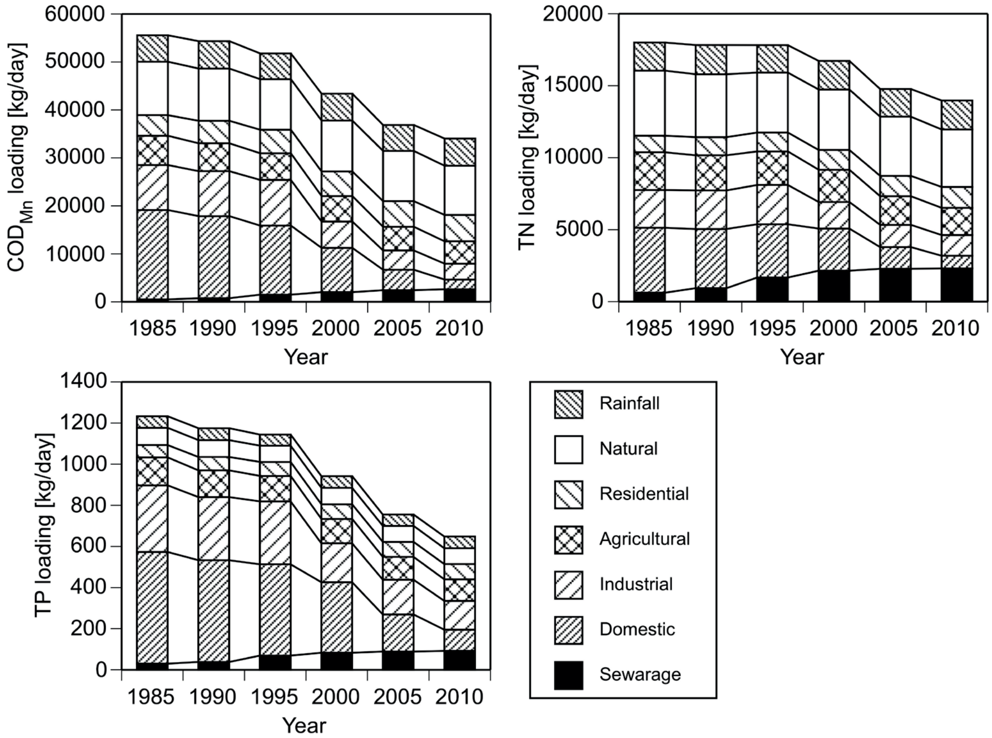

Fig. 5 Temporal trends in the loadings of BOD, TN, and TP to Lake Biwa (Shiga Prefecture, 2011).

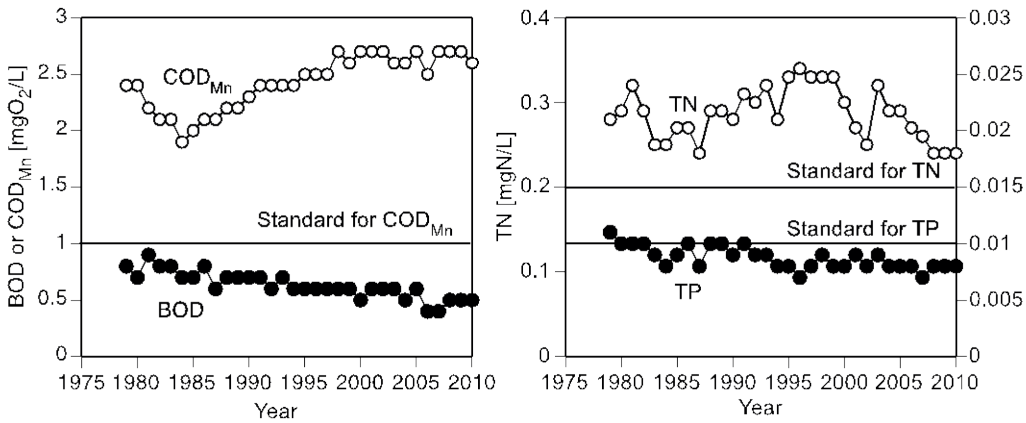

Fig. 6 Temporal trends in the water quality of the northern basin of Lake Biwa (Shiga Prefecture, 2011).

in lakes is currently set on the basis of COD_{Mn} in Japan, this trend is a serious issue for environmental administration. Many researchers have discussed the cause of this divergent trend in BOD and COD_{Mn} in Lake Biwa. From the viewpoint of mass balance, the four possible pathways for increasing COD_{Mn} in the lake are as follows:

(1) an increase in the organic loading from the lake watershed,
(2) an increase in autochthonous production of organic matter,
(3) a decrease in discharge of organic matter from the lake, and
(4) a decrease in the biodegradation rate of organic matter in the lake.

However, the probability of pathways (1) and (3) is thought to be low because the COD_{Mn} loading is decreasing (Fig. 5) and an increase in COD_{Mn} discharge has been reported (Kishimoto, 2008). In relation to pathway (2), attempts have been made to estimate the areal primary production at Imazuokichuo Point, which is near the deepest zone of the northern basin of Lake Biwa, on the basis of physiological parameters for various phytoplankters, phytoplankton census data, and existing environmental data from 1981 to 2008 (Kishimoto *et al.*, 2012). Surprisingly, the areal primary production was estimated to have increased, whereas the chlorophyll concentration has tended to decrease (Fig. 7). Two factors can explain this result. Firstly, the decrease in chlorophyll, (i.e. of phytoplankton), increases transparency, which enhances the thickness of the euphotic layer and compensates for a decrease in primary productivity by the low phytoplankton population. Secondly, the shift of phytoplankton to smaller species like cyanobacteria in Lake Biwa (Kishimoto *et al.*, 2013) has induced an increase in the primary production due to higher specific productivity (Kagami & Urabe, 2001). In our estimation, the average abundance of cyanobacteria from 2000 to 2008 was 15%, but the corresponding average contribution ratio to total primary production amounted to 76% (Fig. 7).

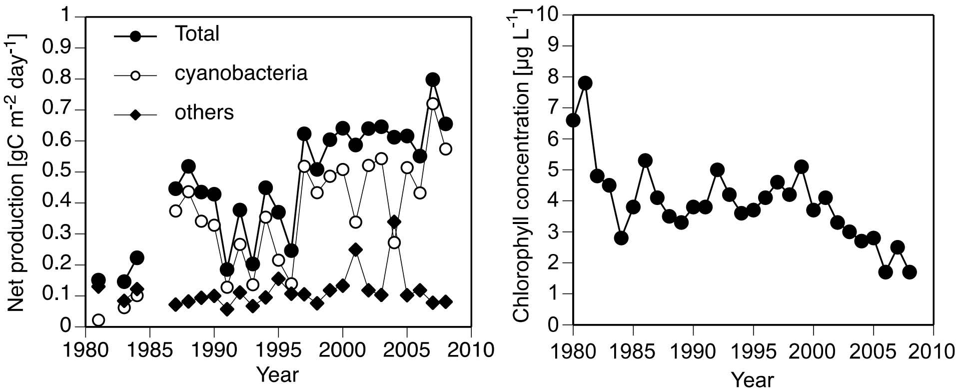

Fig. 7 Temporal trends in estimated areal primary production and chlorophyll concentration at Imazuokichuo-point of Lake Biwa.

The above discussion suggests that the change in autochthonous production of the lake may play an important role in the COD_{Mn} increase observed in Lake Biwa. However, an increase in organic matter should accompany an increase in both COD_{Mn} and BOD, which differs from the observed trends (Fig. 6). In this context, the possibility of accumulation of recalcitrant organic matter has been raised (Imai, 2002). Here we should discuss the possibility of pathway (4) for an explanation of the divergent trends in BOD and COD_{Mn}. When a part of the water body in Lake Biwa is considered as a control volume, the following mass balance equation can be established:

$$V\frac{dC}{dt} = L_{in} - L_{out} - kCV \quad (1)$$

where, C is the organic matter concentration, L_{in} is the organic load to the control volume, which contains an influent load and an autochthonous production rate, L_{out} is missing load except biodegradation, k is a pseudo-first order biodegradation rate constant, V is the control volume, and t is time. When a steady state is established, equation (1) is transformed into:

$$C = \frac{L_{in} - L_{out}}{kV} \quad (2)$$

Thus, organic matter concentration is inversely proportional to k, when $(L_{in}-L_{out})/V$ is constant. In Lake Biwa, phosphorus is a limiting nutrient for heterotrophic bacteria (Gurung & Urabe, 1999). Furthermore, TP concentrations have decreased temporally, as shown in Fig. 6. Accordingly, it is possible that the severe phosphorus limitation has reduced the biodegradation rate of organic matter by bacteria. Kishimoto & Ueno (2011) demonstrated that this hypothesis is viable with respect to the increasing trend in COD_{Mn}. Consequently, an increase in autochthonous production and a deterioration of biodegradation rate in tandem are possible explanations for the divergent temporal trends of BOD and COD_{Mn} in Lake Biwa.

The influence of lake warming

After 1990, progressive lake warming began to be observed in Lake Biwa (Nakamuro *et al.*, 2008; Hsieh *et al.*, 2010). In response to this trend, Lake Biwa has recently encountered the problem of declining dissolved oxygen levels near the lake bottom (Fig. 8). This is caused by excessive consumption of dissolved oxygen in response to the extended stratification period and a decrease in oxygen supply associated with vertical convection in winter (Hosoda, 2009). The prolonged exposure of sediments to low DO conditions may change the redox state of sediments and affect biogeochemical cycles within the lake as evidenced by the release of phosphate and additional reduced compounds, including ferrous iron, ammonium, methane and hydrogen sulfides (Yoshimizu *et al.*, 2010). In addition to depletion of dissolved oxygen supply, lake warming has induced the succession of the phytoplankton community from large to smaller species (Kishimoto *et al.*, 2013). This succession has, in turn, caused an increase in primary production.

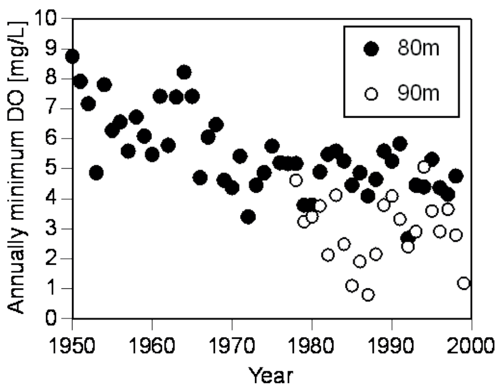

Fig. 8 Temporal trends in annual minimum dissolved oxygen at a depth of 80 and 90 m in Lake Biwa (Nishino & Ohtaka, 2002).

The problem of invasive alien species

Lake Biwa has encountered threats from the typical invasive alien species for Japan. For example, 10 alien fish are recognized in Lake Biwa. Bluegill sunfish and largemouth and smallmouth basses have had serious detrimental impacts on endemic species like *Gnathopogon caerulescens* and *Gymnogobius isaza*, which are currently endangered (Nakai, 2007; Nishino, 2007). The submerged macrophyte, *El. nuttallii*, is widely observed in the southern basin of Lake Biwa and recently the presence of *Eg. densa* increased in the lake (Hamabata & Kobayashi, 2002; Hamabata, 2005). These macrophytes can cause problems for the screw propellers of fishing boats. Therefore they need to be harvested every year to permit the safe passage of boats.

FUTURE PERSPECTIVE

Eutrophication of Japanese lakes is a major issue at present and will remain a serious problem in the future. Continued efforts to reduce pollutant loads will be urgently needed to improve the lake eutrophication problem. In particular, improved measures for diffuse pollution and small-scale wastewater control will need to be reinforced. In this regard, promising measures might include optimization of fertilizer application rates for agricultural emissions control, the installation of soil infiltration zones for collecting and intercepting roadway runoff (Wada *et al.*, 2011), and the installation of small-scale wastewater treatment systems (Johkaso systems, Sankai *et al.*, 1997).

Cyanobacterial and picoplankton blooms are currently observed in Japanese lakes (Nakanishi & Sekino, 1996) and pose serious threats to water supply systems. These blooms may result from the significant increase in the N/P ratio observed for lake waters. These issues mean that the development of an economical nitrogen-removal technology currently represents an urgent priority for helping to improve lake ecosystem quality.

Lake warming will potentially be more serious in the future and this has the potential to alter vertical mass transport patterns, the redox state of sediment, and ultimately lake ecosystems. These changes may occur suddenly. However, we currently have little knowledge of the lake warming issue. Therefore, limnological studies on warming and the continued monitoring of lake environments need to be reinforced in Japan and elsewhere in the world.

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