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IDENTIFICATION OF KEY FACTORS INFLUENCING WATER QUALITY IN TWO SHALLOW LAKES

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ABSTRACT: *Water qualities of Lake Sanaruko and Teganuma in Japan have had the worst COD value of all the lakes in Japan over the past several years. In this study, the pollution mechanisms active in two lakes were studied by analyzing the data of aqueous environmental samples. It was observed that SS (Suspended Solid)-COD values correlated with Chl.a (Chlorophyll a) concentrations, which represent the population density of phytoplankton, and the growth of phytoplankton was accelerated by eutrophication in the lakes. Although Chl.a concentrations had some variations because the species of dominant phytoplankton vary seasonally, the COD values remained constant almost all year round, which suggested that the generation of phytoplankton occurs constantly, regardless of the temperature or season. The influent rivers mainly supply nitrogen and phosphorus, which caused eutrophication in both lakes. By comparing their average concentrations in the lake and in the rivers, it was presumed that the decrease of nitrogen concentration might occur by denitrification in both lakes; whereas, phosphorus might be released in small quantities from the bottom of both lakes. It was observed that the ratio of particulate matter SS-COD/Organic-N/Organic-P in both lakes had remained nearly constant, and that the concentration of phosphorus in the influent rivers had continued to decrease in Lake Sananruko. From these results, it is expected that the total COD will reach 5 mg/L after eight years in this lake. If the lake purification projects can be carried out more quickly, water quality will improve earlier than expected.*

KEYWORDS: lake eutrophication, pollution mechanism, suspended/soluble cod, chlorophyll a, n/p balance

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INTRODUCTION

Many shallow lakes are suffering from different pollution factors and need to be restored using different approaches. Major efforts have been made worldwide to improve the ecological quality, but the eutrophication remains as a main water quality management problem. Although good experience and expertise has increased worldwide during the last three decades, there is no single all-powerful solution for lake conservation. The plan for conservation of lake water quality consists of several countermeasures; among them, reducing external nutrient loading is usually the preferred method to improve water quality. The response of Lake Griffin located in central Florida, USA, indicates that the combination of external nutrient load reduction and bio-manipulation can result in sustained improvements in water quality in shallow subtropical lakes (Fulton *et al.*, 2015). The reduction was mostly due to improved sewage treatment, establishment of artificial rivers on the main flow in stream, and possibly the reduction of fertilization in the catchment. Nutrient load reduction led to substantial improvements in the lake. TN, TP, chlorophyll-a and the total biomass of phytoplankton have declined markedly (Jeppesen *et al.*, 2007-1,2). Phosphorus as the limiting nutrient for primary production is often the driver of the ecological deterioration of freshwater systems (Hupfer *et al.*, 2016; Smith *et al.*, 2009). There have been some successful cases of lake restoration where only external P loads were reduced. However, in some cases, the continued release of excess legacy P from lake sediment can continue to fuel algal blooms after external nutrient reduction (Welch *et al.*, 2001) and lead to recovery being delayed for decades or more (Hupfer *et al.*, 2016; Sas *et al.*, 1990; Chapra *et al.*, 1991). This is called P hysteresis and the ecological resistance to nutrient loading reduction (Mehner *et al.*, 2008). Additionally, there remain persistent doubts whether reducing external loading is an effective means of restoring water quality in large, shallow lakes which are potentially subject to frequent sediment resuspension (Bachmann *et al.*, 2000; Canfield Jr *et al.*, 2000; Nagid *et al.*, 2001; Bachmann *et al.*, 2003). Thus, the external load reduction was a necessary but not sufficient measure for the short-term (Chapra *et al.*, 1991). There have also been many case studies of restoring submerged macrophytes, or using other forms of biotechnology, for improving water quality in hypertrophic shallow lakes (Qiu *et al.*, 2001; Ha *et al.*, 2013). In some cases, the variation of climate also has influence in lake trophic status (Havens *et al.*, 2013). In Japan, to combat the water environmental deterioration, the central government has carried out a series of countermeasures. As a result of various measures taken by national and local governments, water quality has improved significantly (Otsuka *et al.*, 2005). Lake Sanaruko was the worst ranking COD value of national public water quality in Japan from 2001 to 2006. Lake Teganuma was the worst ranking value of national public water quality from 1974 to 2001. Both of the lakes had a significant improvement in water quality. Because of this, we choose these two lakes as the subject of our case study in order to learn more about key factors in water quality improvement. The pollution mechanisms active in both lakes were studied by analyzing the data of aqueous environmental samples, and the practical simulation models were proposed to express material balances of several constituents present in the lakes.

METHODOLOGY

Study sites

Lake Sanaruko is located in the western area of Hamamatsu, Shizuoka Prefecture. The average water depth is about 2 m (the maximum depth is 2.5 m). The lake area is 1.2 km^2. In the water system, there are three upstream rivers, Shin(nishi)kawa, Danzukawa, River and Gozendani Drainage, which flow into the lake; there are also three rivers, Kuryou, Sakai, and Higashi Kanda River, which flow into the Shinkawa River area. Along with the water effluent and tide, the water exchange between Lake Sanaruko and Lake Hamanako through Shinkawa River. Environmental deterioration began in 1960, which was caused by urbanization in the lake region. Water pollution increased rapidly. Not only did a high concentration of nitrogen and phosphorus flow into the lake from the upstream, but also, Lake Sanaruko is a brackish tidal lake affected by back-flow water from a river which is 13 km downstream of Shinkawa River. The lake map is shown in Fig. 1. Since 1999, the annual average of COD value reached 12 mg/L, and the COD value was the worst ranking value of national public water quality in Japan by 2006. After that, along with the continuously increasing sewer coverage area in the lake region, the amount of nutrients in upstream rivers has decreased. The COD value is no longer in the top five worst public water qualities in Japan.

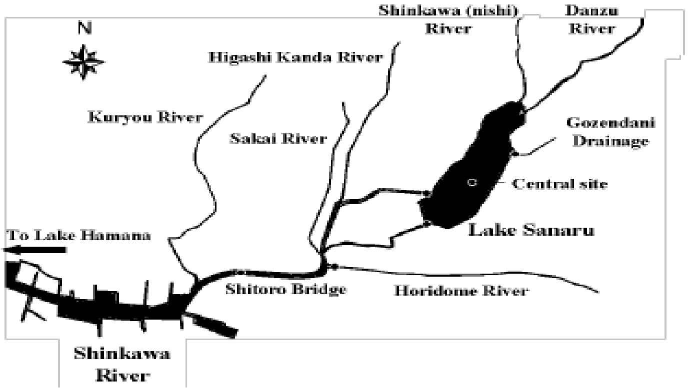

Figure 1. **A map around Lake Sanaruko.**

Lake Taganuma is located in Chiba Prefecture, Japan. The average water depth is about 0.86 m (the maximum depth is 3.8 m). The lake area is 4.02 km^2. Lake Teganuma receives river inflow from Ohori, Otsu and Somei-iriotoshi River, and the lake drains water out into Tone River through Teganuma River. Since the early 1970's, the influx of immigrating population from the Tokyo metropolitan area, however, resulted in the rapid eutrophication of the lake. Lake Teganuma had been listed as the environmentally worst lake in Japan for 27 years until 2001. Various researches have been conducted to study the physical, chemical and ecological aspects of the lake. For the improvement of water quality in Lake Teganuma, the North-Chiba Water Conveyance Channel was constructed in 2000, which transfer water from Tone River into the lake. The maximum amount of flow in water to the lake is 10 m^3/s. After that, the water quality drastically improved from its previous severe pollution levels. The lake map is shown in Fig. 2.

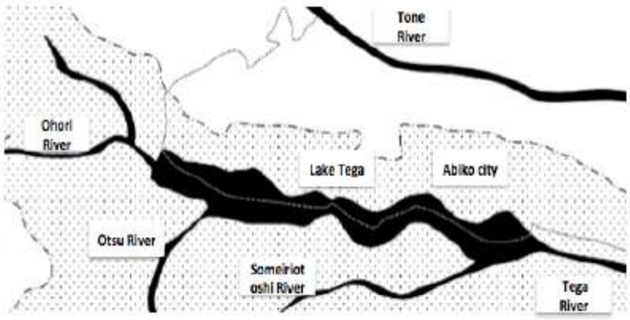

Figure 2. **A map around Lake Teganuma.**

Analysis of nutrient variation

Regular monitoring of lakes is important to determine their ecological state and development, and have key significance when deciding whether action should be taken to improve their quality (Søndergaard *et al.*, 2016). By using the water quality monitoring data, which has been taken in the both lakes and related waters region for many years (Hamamatsu city, 2015; Chiba prefecture, 2015; 2017), we attempted to elucidate the dominant factor of pollution in the lakes. The COD as an important pollution indicator of the water quality is quantitatively evaluated. For major water quality index, a monthly measurement is performed throughout the year; the other auxiliary items are measured every two or three months. The water samplings are taken at both lake's water surface. As a specific research method, first, the relationship between Chl.a concentration and SS-COD needs to be clarified. Then, as an important factor, how SS-COD with nitrogen and phosphorous has an affect on the growth of algae in the lake needs to be explained.

RESULTS AND DISCUSSION

The water quality situation analysis

Figures 3 and 4 show the variation of the annual average COD in Lake Sanaruko and Lake Teganuma, respectively. Over the past years in Lake Sanaruko, a dredging of the lake bottom and a renovation project of the river (Shinkawa River) has been made as an effort to improve water quality. As people contemplate, these projects affect the annual fluctuation of COD in the lake**.** The period from 1975 to 2001 was one in which Lake Teganuma experienced its highest level of COD. Since 2001, COD started to decrease sharply. The influx of nutrients from the influent rivers such as Ohori River and Otsu River has decreased in recent years compared to the past. Because an artificial river called the North-Chiba Water Conveyance Channel was constructed in 2000, which transfer the water from Tone River water (with annual average TN, TP, and COD concentrations 2.7 mg/L, 0.1 mg/L, and 3.8 mg/L, respectively) flow into Lake Teganuma. This construction caused the flushing and dilution in Lake Teganuma, resulting in significant reduction of the nutrient load in the lake.

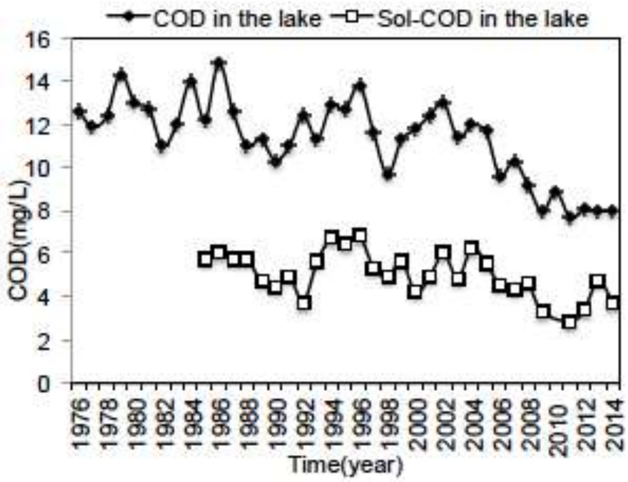

Figure 3. Annual average of COD in Lake Sanaruko.

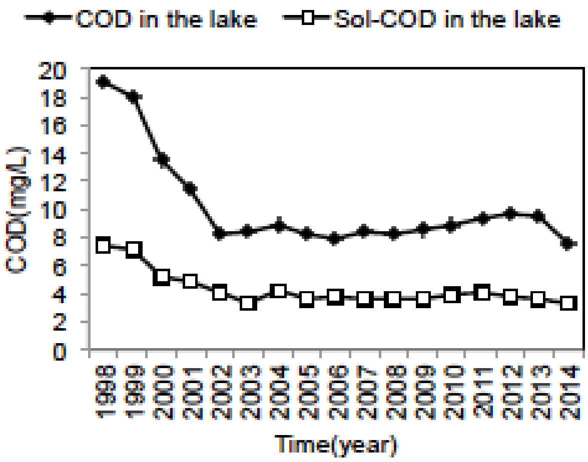

Figure 4. Annual average of COD in Lake Teganuma.

Similarly, TP and Chl.a have decreased in the recent years. Figures 5 and 6 show the annual average Chl.a concentration and TP in the two lakes. With TP decreased, the values of Chl.a in both lakes showed the same variations. However, the statuses of lakes are still in hypertrophic condition.

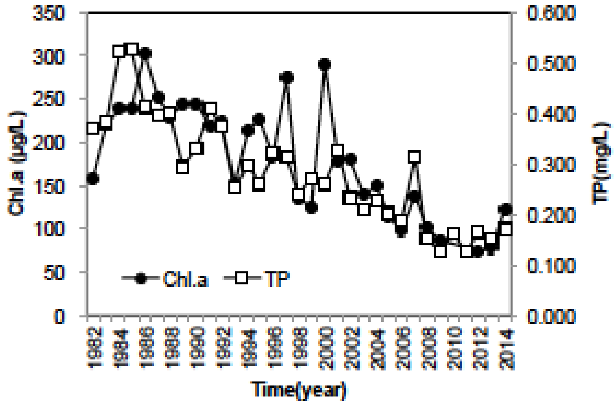

Figure 5. Annual average of TP and Chl.a in Lake Sanaruko.

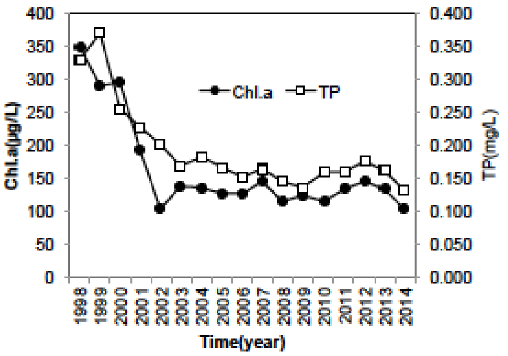

Figure 6. Annual average of TP and Chl.a in Lake Teganuma.

The correlations between SS-COD with Chl.a during the years 2001 to 2014 are shown in Figs. 7 and 8. SS-COD is calculated by subtracting the Sol-COD from Total-COD. The variation is large, but certain correlations were observed in the annual average values. There is a roughly proportional relationship between SS-COD and Chl.a. One of the reasons may be that the dominant type of algae changes. Lake Teganuma has a better relationship between the two factors.

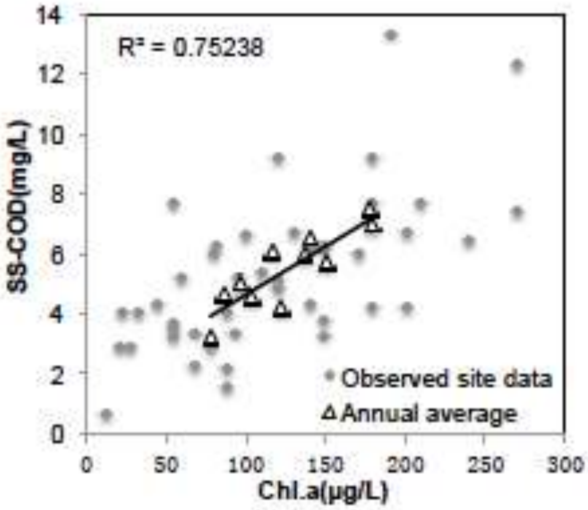

Figure 7. **The correlation between SS-COD and Chl.a in Lake Sanaruko.**

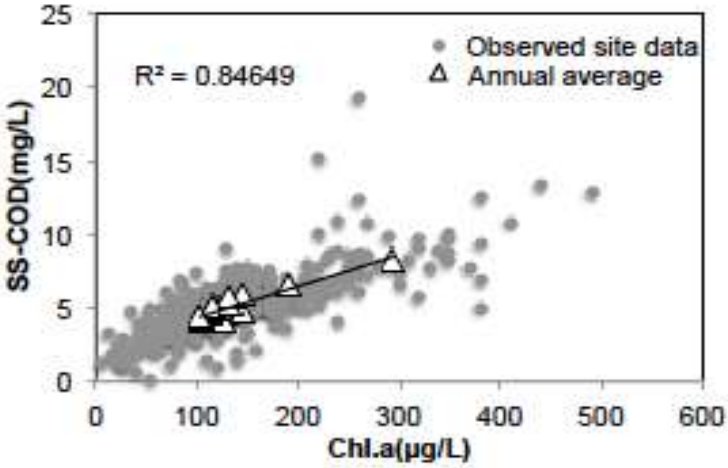

Figure 8. **The correlation between SS-COD and Chl.a in Lake Teganuma.**

Figures 9 and 10 show the transition of SS-COD concentration in the lakes from 2005 to 2014 for each month. It is impossible to view a particular seasonal trend according to changes over different years. However, looking at the monthly average line from late autumn to early winter in two lakes, during which there is little sunshine, SS-COD is small.

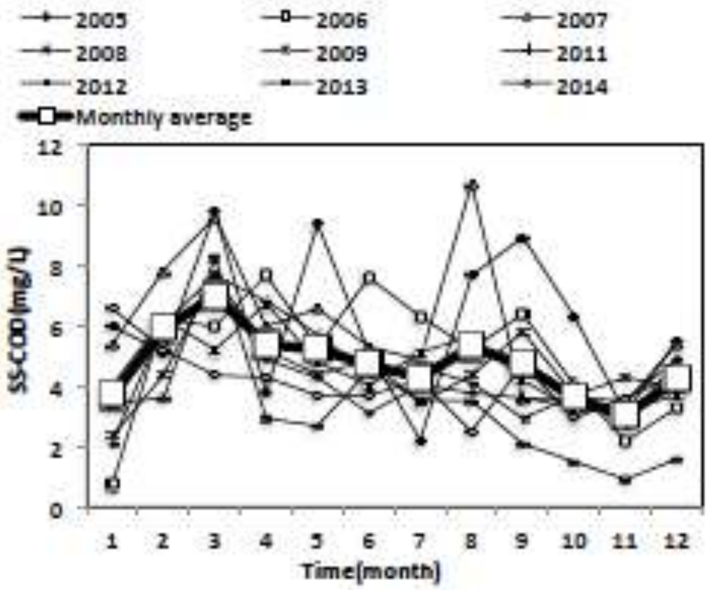

Figure 9. **Monthly change of SS-COD concentration in Lake Sanaruko.**

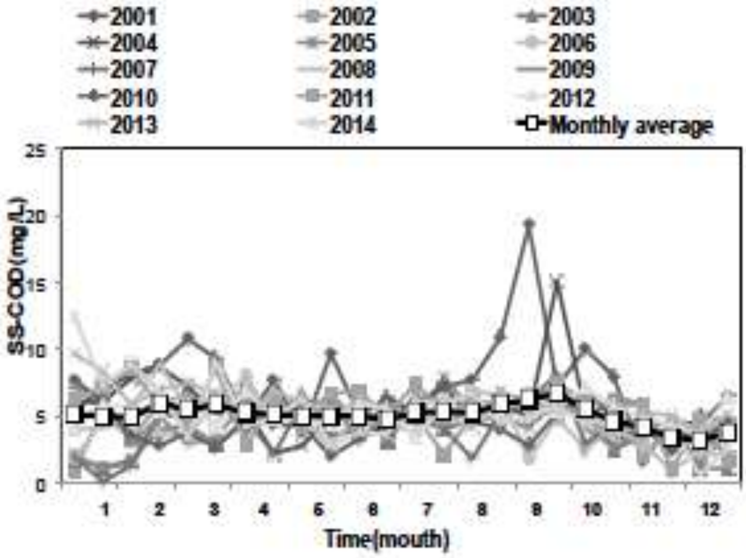

Figure 10. **Monthly change of SS-COD concentration in Lake Teganuma.**

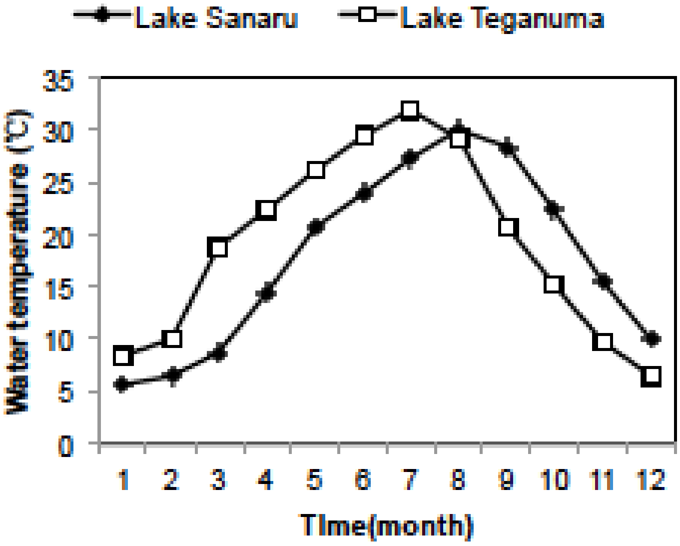

Figure 11. Monthly change of water temperature in Lake Sanaruko and Lake Teganuma.

Then, the seasonal change of water temperature in two lakes is shown in Fig. 11. From these figures we can see, SS-COD did not decrease conspicuously even in the lowest temperature period from January to March in Lake Sanaruko; on the contrary, average SS-COD shows the greatest value in March. In Lake Teganuma, SS-COD remain approximately the same year round with very little increase in September. Therefore, the generation rate of algae seems to not be dominated strongly by temperature. Some phytoplankton prefer cold water temperatures, and some prefer high temperatures.

We had known that after the water quality changed, the dominant species of phytoplankton in two lakes changed. In Lake Sanaruko, the dominant species of phytoplankton changed from Microcystis to Synechococcus sp. This reason may be attributed to Cl^- concentrations changing to high values after 2001 due to the excavation and dredging project implemented in the lake drainage. Furthermore, in Lake Teganuma, after 2000, the dominant species of diatoms, mainly Cyclotella sp., have been replacing blue-green algae, mainly Microcystis aeruginosa in Lake Teganuma. It could be concluded that the decrease in phosphorus concentration due to the river water dilution to Lake Teganuma would be interpreted as a minor factor for the transition of dominant species from M. aeruginosa to Cyclotella sp. (Amano *et al.*, 2010).

TN and TP in Lake Sanaruko and in the outflow river site Shitoro Bridge, average TN and TP in three influent rivers are shown in Figs. 12 and 13. From the figures, we can see TN and TP in the lake, especially TP showed a noticeable decreasing trend through the year, and this annual variable obviously correlated with the average nutrient concentration decrease in influent rivers. In addition, both TN and TP in

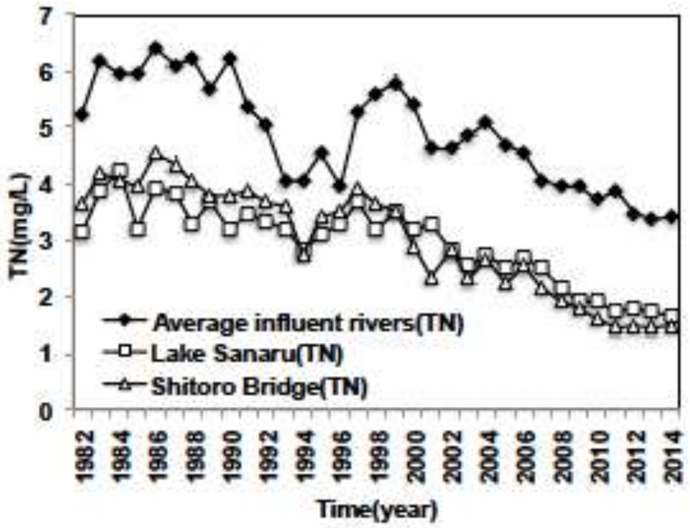

Figure 12. **Annual change of TN concentration in influent rivers, Lake Sanaruko, and outflow river.**

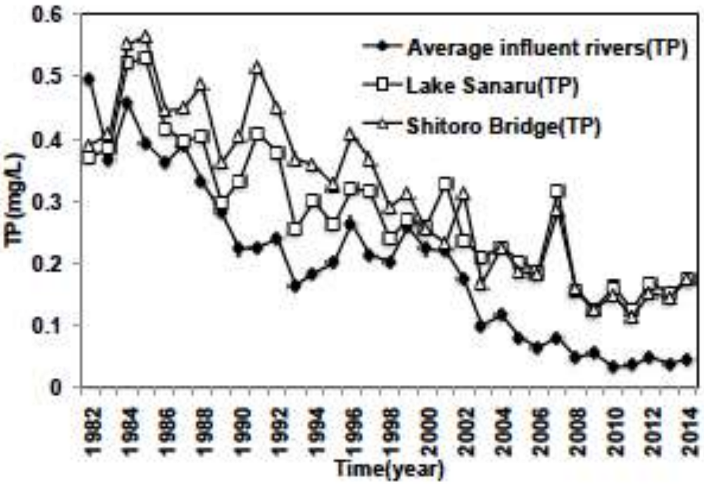

Figure 13. **Annual change of TP concentration in influent rivers, Lake Sanaruko, and outflow river.**

Outflow river site Shitoro Bridge are almost the same as in the lake. So N and P from the tide in a downstream river can be negligible. However, TN concentration in the lake is substantially less than the average TN in influent rivers. In contrast, TP concentration in the lake is higher than in influent rivers. In conclusion, the internal generation rate N is a negative value, and P is a positive value. Thus, the internal generation rate of N and P cannot be negligible in the water. The change of the P concentration in the lake is subject to the P concentration in influent rivers. In particular, the P concentration in influent rivers was extremely low in recent years. The inorganic P concentration in the lake has been under 0.05 mg/L since 2005. From the results and the data in Fig. 5, it can be inferred that the major cause of annual reduction of Chl.a concentration is the decrease in P concentration in the influent revers.

TN and TP in Lake Teganuma and the average TN and TP in three influent rivers are shown in Figs. 14 and 15. From the figures we can see that the TN and TP decreased slowly from 1998-2014 in the lake. However, the TN and TP decreased significantly from 2001 in influent rivers due to the water transfer project. TN concentrations in influent rivers are higher than in the lake, they had almost the same value when the water transfer project finished, after that, the TN in the lake was lower than the average TN in influent rivers. The TP concentration in rivers was much higher than in the lake, after the water transfer project, the TP in the lake was a little higher than in the influent rivers. In conclusion, the internal generation rate N is also a negative value similar to Lake Sanaruko, and P was a negative value before 2001, after that, this value became positive. Thus, the internal generation rate of N and P also occurred in Lake Teganuma. The change of the P concentration in the lake was not only subject to the P concentration in the influent rivers, but also subject to sedimentation before 2001. In particular, the P concentration in influent rivers decreased sharply in 2001. From the results and the data in Fig. 6, it can be deduced that the major cause of the annual reduction of Chl.a concentration is the decrease in the P concentration in the influent revers, as in the case of Teganuma.

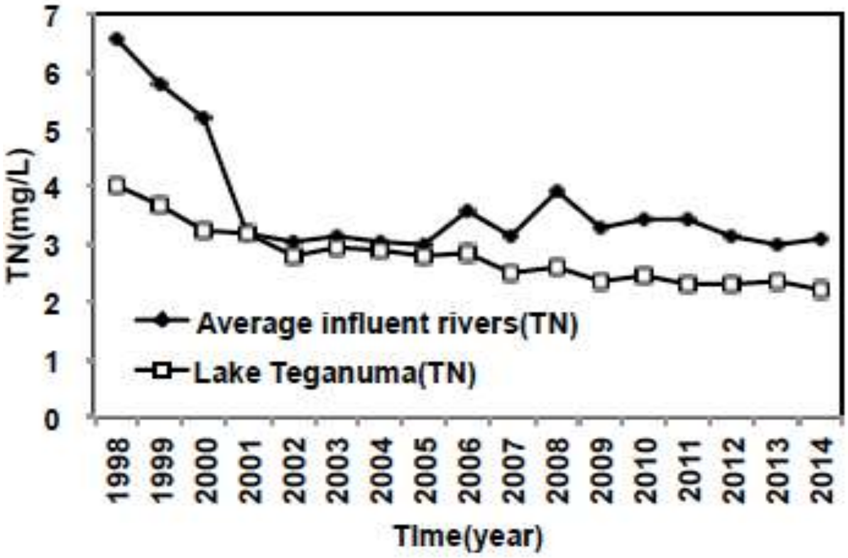

Figure 14. **Annual change of TN concentration in influent rivers, and Lake Teganuma.**

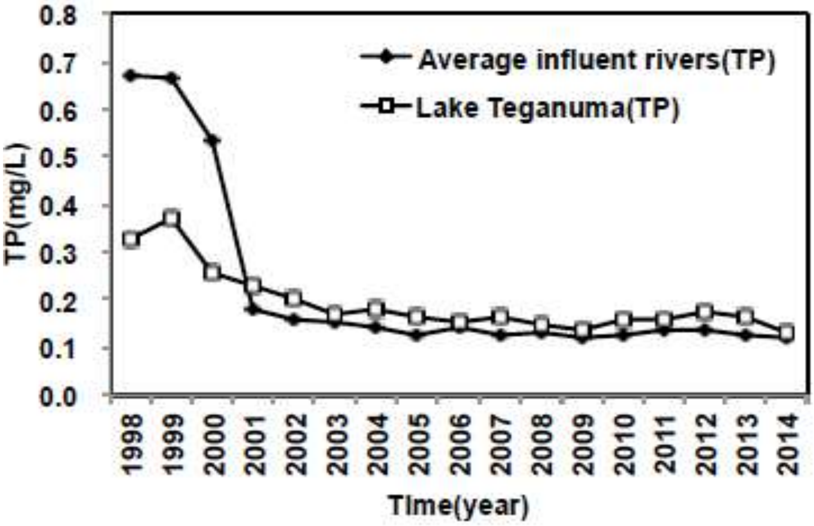

Figure 15. **Annual change of TP concentration in influent rivers, and Lake Teganuma.**

The ratio of SS-COD/organic nitrogen/organic phosphorus in the lake and water quality prediction

Organic N and P as constituents of algae can be considered to be supplied from the inorganic N and P in the influent rivers. However, we cannot ignore the effect of internal generation in the lake. Algae bodies hold a large portion of N and P in the form of organic matter. Therefore, the ratio of SS-COD, the Organic N concentration (TN minus inorganic N), and the Organic P concentration (TP minus inorganic P) in two lakes are calculated and shown in Figs. 16 to 18.

In Lake Sanaruko, the annual variation of the organic N/SS-COD ratio and the organic P/SS-COD ratio vary widely, but there is a constant average value shown in the following relationship.

SS-COD/Organic N/Organic P=1/0.27/0.033 ≒ 30/8.1/1 **(1)**

The Redfield ratio in phytoplankton is found to be C/N/P = 41/7.2/1. The relationship of SS-COD (here is COD$_{Mn}$) and SS-TOC in the lake is given in Fig. 17 from an actual measurement.

SS-TOC / SS-COD = 1.25 **(2)**

Place result (2) into (1)

SS-TOC/Organic N/Organic P = 38/8.1/1 **(3)**

From the equation (3), C/N/P in Lake Sanaruko is almost the same as the Redfield ratio. Thus, SS-COD in the lake can be attributed to algae.

As Fig. 12 shows, TP followed a decrease tendency in recent years. PO_4-P changed in a small range of 0.01-0.03 mg/L since 2006. If we want COD in the lake to reach the target of 5 mg/L, under current conditions after ten years, TP = 0.043 mg/L, we suppose that the organic P is 0.04 mg/L, from (1), SS-COD corresponding to this value is given as 1.2 mg/L. On the other hand, in Fig. 9, the Sol-COD in the lake also decreased. Thus, it is possible to assume that the total-COD = 3.52 +1.2 = 4.72 mg/L if the Sol-COD =3.52 mg/L. In fact, Sol-COD would have had to reach 3.8 mg/L by now. From the trend line prediction, it will decrease very little after ten years. Sol-COD is rather difficult to lower, even if TP in the lake decreased by half of what it was before.

In Lake Teganuma, the annual variation of the organic N/SS-COD ratio and the organic P/SS-COD ratio remained almost consistent.

SS-COD / Organic N / Organic P=5.21 / 1.07 / 0.14 ≒ 37 / 7.6 / 1 **(4)**

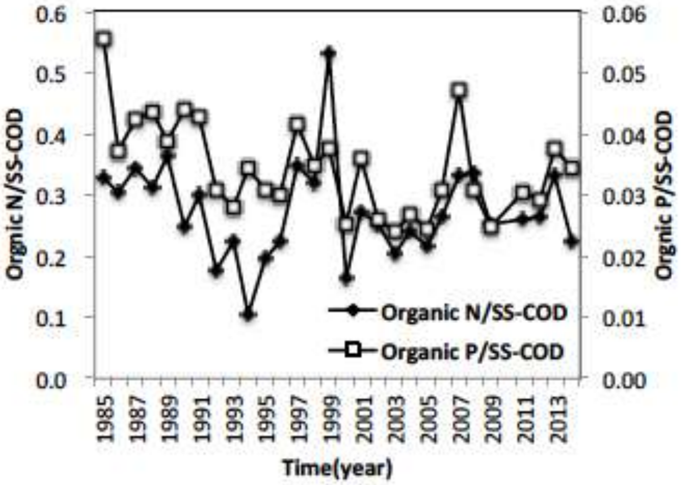

Figure 16. **Annual change of organic N and organic P to SS-COD ratios in Lake Sanaruko.**

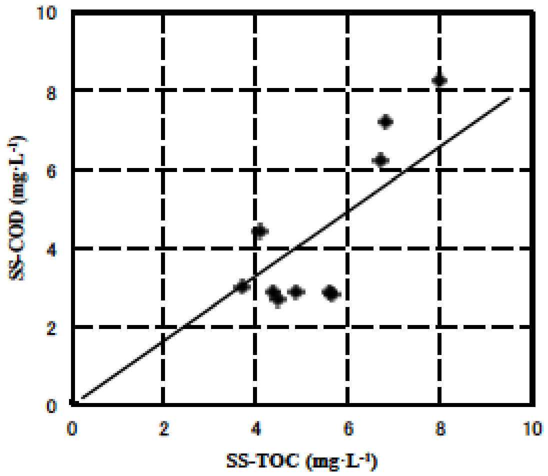

Figure 17. **The correlation between SS-COD and SS-TOC in Lake Sanaruko.**

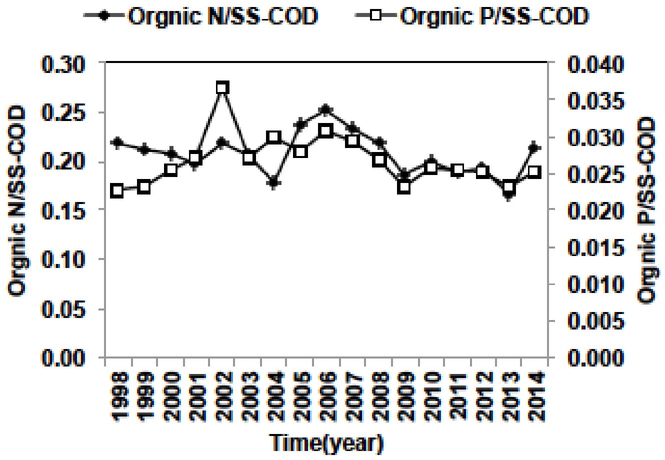

Figure 18. **Annual change of organic N and organic P to SS-COD ratios in Lake Teganuma.**

Using the relationship of SS-TOC / SS-COD = 1.25 in Lake Sanaruko. The result as follows:
SS-TOC / Organic N / Organic P = 46 / 7.6 / 1 **(5)**
Compare with Redfield ratio, SS-COD in the lake can be attributed to algae. Because of human interference, it is difficult to predict water quality in Lake Teganuma. If we can calculate how much pollution needs to be solved in the lake, it will help us to know what method would be best suited for water purification in the lake. In our other paper, we will focus on quantifying pollution.

CONCLUSION

The water pollution mechanism of Lake Sanaru and Lake Teganuma based on the observation data has been clarified. Chl.a concentration that represents the concentration of algae has a roughly proportional relationship with SS-COD in the lake. The dominant phytoplankton varies seasonally, which causes proportional variations between SS-COD and Chl.a. The nitrogen concentrations in the two lakes were less than the average compared to the influent rivers. It is assumed that there is nitrogen removal in the two lakes. On the other hand, the phosphorus concentrations in the influent rivers became extremely small recently, and Chl.a in the two lakes also decreased. Phosphorus is considered to dominate the growth of algae in the two lakes. According to the observation data in the lake, the ratio of SS-COD/organic P/organic N kept a nearly constant value. The annual decline trend of P concentration in the lake attributed to the decrease of P in the influent rivers. Without taking any special measures, in Lake Sanaruko, COD concentration is expected to become less than 5 mg/L after 10 years.

Future Research

We will develop a simple and practical simulation model based on material balances around a lake on several constituents contained in water, and the sensitivity of parameters will be checked for the future prediction of water quality.

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