Distribution of Some Physicochemical Parameters and Trophic Status of Lake Onogawa*

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Abstract

The first data set of depth time profiles on some physicochemical parameters of Lake Onogawa over a two-year period is presented. Lake Onogawa is a dimictic lake. Hypolimnetic dissolved oxygen was not detected from August to October. This is different from Lake Hibara, a sister lake, where hypolimnetic oxygen was not exhausted in summer. Nitrate was depleted in the anoxic zone of Lake Onogawa, suggesting the operation of denitrification. Hypolimnetic ammonia consistently increased from spring to summer, while nitrate decreased during that same period. Based on the mass balance between ammonia and nitrate, apparent nitrification was not evident during this period. Chl. *a* concentration ranged from less than $3 \mu\text{g}\cdot\text{l}^{-1}$ to $48 \mu\text{g}\cdot\text{l}^{-1}$. It reached an annual maximum in early autumn. The Chl. *a* maximum was about 3 times greater than that of Lake Hibara. Mean transparency was about 3 m during the vernal and autumnal circulation periods and 5 m in the summer stratification periods. Mean concentrations of total phosphorus and Chl. *a*, and mean transparency in the circulation period indicate that the lake is oligotrophic, eutrophic and mesotrophic, respectively. The anoxic hypolimnion also indicates that the lake is eutrophic. Based on these facts, the lake is classified as on the boundary between meso- and eutrophic.

Key words : depth-time profiles, dammed lake, nutrients, nitrogen metabolism

1. Introduction

Lake Onogawa ($37^{\circ}40'\text{N}$, $140^{\circ}06'\text{E}$) is one of many lakes on the Urabandai Plateau, Fukushima Prefecture. They were formed at the time of the volcanic eruption of Mt. Bandai in 1888. The summit of the volcano, 1.7 km^3 in volume, was blown away by the eruption (MURAYAMA, 1973). Large scale mudflows caused by the eruption dammed the valleys of many rivers and formed a series of lake basins.

Limnological studies of Lake Onogawa have been limited. The earliest study involved the measurement of water temperature and water level by TANAKA (1904). YOSHIMURA (1935a, b, c) carried out the first comprehensive lim-

nological studies of the Urabandai lakes, including Lake Onogawa, though he sampled only in July and August. Subsequent studies, for which depth profiles of some physical and chemical parameters are provided, mainly focused on the plankton (WATANABE *et al.*, 1973) and benthos (KITAGAWA, 1974) during the summer months. Essentially, seasonal data on the limnology of this lake have been unavailable.

Here, we present the results of some physicochemical parameters of Lake Onogawa measured from spring to early winter of 1993 and 1994. This is the first data set to provide a basis for a discussion of hypolimnetic substance metabolism and trophic status of the lake.

2. Materials and methods

The altitude of Lake Onogawa is 794 m above

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mean sea level and the maximum depth is 21 m (HORIE, 1962). However, the water level significantly fluctuates because the lake water is used for hydroelectric power generation. The lake covers an area of 1.4 km² (HORIE, 1962) and the water volume is approximately 0.014 km³ (SATO *et al.*, 1995). Water samples were collected every 3 weeks from April to December 1993, and in 1994 from a fixed station (Fig. 1) with a 6 liter Van Dorn water sampler. Water samples from about 2.5 m depth intervals were kept in clean 4 liter polyethylene bottles which were stored in heat insulating boxes and transported to a laboratory at Yamagata University. The water samples were filtered through pre-ignited Whatman GF/F glass fiber filters (nominal porosity, 0.7 μ m) under reduced pressure (<100 mm Hg). The filtration was started within 5 hr and finished within 8 hr after sample collection. Aliquots of the filtrates were kept in clean polyethylene bottles and stored frozen prior to chemical analysis. Measured

Fig. 1. Map showing sampling station.

physicochemical parameters and the methods used are shown in Table 1.

When the concentration of nitrogen compounds in $\mu\text{g atom N}\cdot\text{l}^{-1}$ in this study is multiplied by 14.0, the atomic weight of nitrogen, the product is the concentration in $\mu\text{g N}\cdot\text{l}^{-1}$ or ppb. Likewise, when the concentration of phosphorus compounds in $\mu\text{g atom P}\cdot\text{l}^{-1}$ is multiplied by 31.0, the atomic weight of phosphorus, the product is the concentration in $\mu\text{g P}\cdot\text{l}^{-1}$ or ppb.

3. Results and discussion

3-1. Water temperature and dissolved oxygen

Lake Onogawa is a dimictic lake. The lake is

Fig. 2. Depth-time diagrams of water temperature ($^{\circ}\text{C}$) in 1993 (upper) and 1994 (lower).

Table 1. Measured parameters and methods used.

Parameters	Methods
Water temperature	Thermistor thermometer
Transparency	Secchi disk
Dissolved oxygen	Winkler method
Chl. <i>a</i>	SCOR/UNESCO (1966) after 90% acetone extraction
Total phosphorus	Molybdate blue method after persulfate digestion (MENTZEL and CORWIN, 1965)
Ammonia	Phenol hypochlorite method (SOLÓRZANO, 1969)
Nitrate	Cadmium reduction method (STRICKLAND and PARSONS, 1972)
Reactive phosphorus	Molybdate blue method (STRICKLAND and PARSONS, 1972)

covered with ice from January to March or April. The weather in 1993 and 1994 differed markedly. The air temperature was low and the precipitation was high in the summer of 1993. In contrast, the air temperature was high and the precipitation was low in the summer of 1994. The water temperature of Lake Onogawa reflects the difference in the weather. Vernal circulation continued longer in 1993 than in 1994, and autumnal circulation started earlier in 1993 than in 1994 (Fig. 2). The maximum water temperature was about 5°C higher in 1994 than in 1993 (19.6°C in 1993 and 24.6°C in 1994), and the hypolimnetic water temperature was about 1°C higher: between 8 and 9°C in 1993, and 9 and 10°C in 1994 (Fig. 2). The depth of the metalimnion was shallower in 1994 than in 1993: the bottom of the metalimnion was about 17.5 m in 1993 and 15 m in 1994. A longer circulation period probably resulted in the deeper metalimnion in 1993.

Dissolved oxygen in the epilimnion was slightly greater in 1994 than in 1993. The maxima were 114% at the surface on 21 October 1993 and 125% at 2.5 m on 27 August 1994 (Fig. 3). Dissolved oxygen was completely exhausted

in the hypolimnion from August to October in both years (Fig. 3). Sulfate was reduced to sulfide in the anoxic hypolimnion (data not shown).

Lake Hibara lies 1.2 km upstream of Lake Onogawa and is a sister lake of Lake Onogawa formed by the eruption of Volcano Bandai. Although hypolimnetic dissolved oxygen in Lake Hibara severely decreases in summer, it was never completely exhausted (SATO *et al.*, 1993). It is worthy of note that the two lakes, formed at the same time and with similar environments, show different hypolimnetic oxygen concentrations in summer. The difference in either productivity or water depth, or both, could be responsible for the different hypolimnetic oxygen concentrations. The maximum water depth of Lake Hibara is 31 m, while that of Lake Onogawa is 21 m (HORIE, 1962). The boundary between the meta- and hypolimnion of these two lakes lies about 15 m below the surface (Fig. 2, and SATO *et al.*, 1993). The thickness of the hypolimnion is roughly 5 m for Lake Onogawa and 15 m for Lake Hibara. Even if the productivity of the two lakes is the same, the hypolimnetic oxygen will be consumed faster in Lake Onogawa than in Lake Hibara. The annual maximum of Chl. *a* in Lake Onogawa ($33 \mu\text{g}\cdot\text{l}^{-1}$ in 1993 and $48 \mu\text{g}\cdot\text{l}^{-1}$ in 1994 shown in section 3-4) is two to three times greater than that in Lake Hibara ($15 \mu\text{g}\cdot\text{l}^{-1}$ in SATO *et al.*, 1993). The thinner hypolimnion and the higher productivity of Lake Onogawa compared with Lake Hibara may be the cause of the different hypolimnetic oxygen concentrations. Furthermore, the submerged grove shown by SATO *et al.* (1995) may accelerate the oxygen consumption in the water column of Lake Onogawa. The vegetation of the dammed valley of Onogawa was submerged as the valley filled with water and it remains on the lake bottom around the sampling station. The vast surfaces of these submerged trees were suggested as possible substrata for attached microbes. The respiration of these organisms could lead to a possible acceleration in oxygen consumption (SATO *et al.*, 1995).

Fig. 3. Depth-time diagrams of dissolved oxygen (%) in 1993 (upper) and 1994 (lower).

3-2. Ammonia and nitrate

Low concentrations of ammonia (less than $1 \mu\text{g atom N}\cdot\text{l}^{-1}$) were occasionally recorded from the surface down to about 10 m (Fig. 4). Utilization of ammonia by phytoplankton probably caused this low ammonia layer. Ammonia clearly accumulated with time below 10 m from late spring to autumn in both years (Fig. 4). The maximum concentration was higher in 1994 ($80 \mu\text{g atom N}\cdot\text{l}^{-1}$) than in 1993 ($65 \mu\text{g atom N}\cdot\text{l}^{-1}$). The difference in summer weather in both years (section 3-1) probably resulted in the difference in ammonia concentrations: fine weather in 1994 might have favored primary productivity in the epilimnion resulting in a high organic load to the hypolimnion, and the higher water temperatures might have accelerated the decomposition of this organic matter. In order to understand the year-to-year fluctuations in hypolimnetic ammonia accumulation, further observations are needed on a long-term basis.

The maxima of ammonia concentration in both years are 8-10 times greater than the maximum in Lake Hibara in 1991 (SATO *et al.*, 1993). Two factors are possibly causing this higher accumulation of ammonia in Lake

Fig. 4. Depth-time diagrams of ammonia ($\mu\text{g atom N}\cdot\text{l}^{-1}$) in 1993 (upper) and 1994 (lower).

Onogawa. 1) The higher productivity of the lake as suggested by the Chl. *a* level (section 3-4) may have resulted in a higher input of organic matter to the hypolimnion. 2) Another factor is the difference in the concentrations of dissolved oxygen in the hypolimnion. SATO *et al.* (1993) have suggested that a dissolved oxygen level of about $0.6\text{--}0.7 \text{ mg}\cdot\text{l}^{-1}$ is critical in impeding efficient nitrification. Above that level of dissolved oxygen, ammonia is in dynamic balance between production from deamination of organic matter and utilization for nitrification and microbial uptake. Below that critical level, ammonia is in dynamic balance between deamination and microbial uptake, with the result that ammonia will accumulate. Hypolimnetic dissolved oxygen in Lake Hibara reached that critical level in mid September, while in Lake Onogawa it did so in early August. Thus, the elapsed time below the critical concentration of dissolved oxygen is much longer in Lake Onogawa than in Lake Hibara.

The concentration of nitrate during the spring circulation in both years differed markedly: $16\text{--}18 \mu\text{g atom N}\cdot\text{l}^{-1}$ in 1993, $6\text{--}8 \mu\text{g atom N}\cdot\text{l}^{-1}$ in 1994 (Fig. 5). One possible reason for this difference is the variation in the year-to-year

Fig. 5. Depth-time diagrams of nitrate ($\mu\text{g atom N}\cdot\text{l}^{-1}$) in 1993 (upper) and 1994 (lower).

nitrate input via inflowing waters during the snowmelt season, though further study is needed to explain this phenomenon.

Nitrate disappeared in the hypolimnion from late July or early August to late October in both years (Fig. 5). The depth and time of this nitrate disappearance coincided with an absence of the dissolved oxygen (Fig. 3), suggesting that denitrification was occurring. The concentration of nitrate in the lower hypolimnion began to decrease from mid-June 1993 and from late June 1994 (Fig. 5), when the water still contained about $3 \text{ mg} \cdot \text{l}^{-1}$ (30%) of dissolved oxygen (Fig. 3). These facts indicate that denitrification had probably started at the lake water-sediment interface, or in the lake sediment before dissolved oxygen in the water column was exhausted.

Nitrification appeared to be absent in this lake based on the mass balance between ammonia and nitrate. SATOH *et al.* (1993) showed that a clear decrease in ammonia coincided with a clear increase in nitrate in the hypolimnion of Lake Hibara in early summer, a fact which may indicate nitrification. In Lake Onogawa, on the other hand, the hypolimnetic

ammonia gradually increased during the two stratification periods (Fig. 4). Hypolimnetic nitrate gradually decreased in the stratification period of 1993, though it increased slightly in the lower metalimnion in 1994 (Fig. 5). Thus, nitrification on the basis of mass balance in this lake was not apparent. However, these facts do not necessarily suggest that nitrification did not occur in the lake. If the rates of ammonification and denitrification exceed the rate of nitrification, the concentration of ammonia would gradually increase and the concentration of nitrate would gradually decrease.

The metalimnetic nitrate maximum was clear in the summer stratification period, especially in 1993. This vertical structure could be formed as follows: the epilimnetic nitrate decreased due to utilization by primary producers, and the hypolimnetic nitrate decreased due to denitrification, resulting in a relatively high concentrations in the metalimnion.

3-3. Reactive and total phosphorus

The concentration of reactive phosphorus was up to $0.4 \text{ } \mu\text{g atom P} \cdot \text{l}^{-1}$ in both years (Fig. 6). It was almost the same level to that of Lake

Fig. 6. Depth-time diagrams of reactive phosphorus ($\mu\text{g atom P} \cdot \text{l}^{-1}$) in 1993 (upper) and 1994 (lower).

Fig. 7. Depth-time diagrams of total phosphorus ($\mu\text{g atom P} \cdot \text{l}^{-1}$) in 1993 (upper) and 1994 (lower).

Hibara ($0.35 \mu\text{g atom P}\cdot\text{l}^{-1}$ in SATOH *et al.*, 1993). Reactive phosphorus accumulated slightly in the lower hypolimnion in summer.

The concentration of total phosphorus ranged from less than 0.3 to $0.7 \mu\text{g atom P}\cdot\text{l}^{-1}$ in 1993 and to $0.9 \mu\text{g atom P}\cdot\text{l}^{-1}$ in 1994 (Fig. 7). The level of total phosphorus was similar to that in Lake Hibara where it ranged from less than 0.2 to $0.8 \mu\text{g atom P}\cdot\text{l}^{-1}$ (SATO *et al.*, 1993). Total phosphorus also accumulated slightly in the lower hypolimnion. The surface maximum of total phosphorus in October in both years (especially 1994) coincided with that of Chl. *a* (Fig. 8).

3-4. Chl. *a*

The concentration of Chl. *a* in the epi- and metalimnion ranged from 0.7 to $33 \mu\text{g}\cdot\text{l}^{-1}$ in 1993 and 1.0 to $48 \mu\text{g}\cdot\text{l}^{-1}$ in 1994 (Fig. 8). As has been mentioned (section 3-1), the maximum concentration of Chl. *a* in this lake was two to three times greater than that in Lake Hibara. The annual maximum was recorded at the partial circulation period in both years (Figs. 2 and 8). According to a report from Fukushima Prefecture (1991), the dominant species of phytoplankton in September of 1989 was

Peridinium sp. The annual maxima in early autumn of 1993 and 1994 might also be formed by *Peridinium* sp. After that, the concentration of Chl. *a* was maintained at the relatively high level of 9 – $15 \mu\text{g}\cdot\text{l}^{-1}$, indicating an autumnal bloom of phytoplankton (Fig. 8). The dominant species of phytoplankton in November of 1989 were *Peridinium* sp. and *Melosira* sp. (Fukushima Prefecture, 1991). *Peridinium* sp. and diatoms also probably formed the autumnal bloom in 1993 and 1994. Depth-time diagrams for Chl. *a* did not indicate the occurrence of vernal blooms in this lake (Fig. 8). Further studies on the seasonal succession of phytoplankton in Lake Onogawa are required.

3-5. Transparency

The transparency of Lake Onogawa varied between 2.7 m in April and 6.3 m in September 1993, and between 2.1 m in October and 7.3 m in August 1994 (Table 2). The mean transparency in the summer stratification period (June to early September) was about 5 m, and vernal and autumnal circulation periods were about 3 m in both years (Table 2). Epilimnetic nutrients decreased to the level of oligotrophy in summer (Figs. 4, 5 and 6), probably resulting in the observed low level of Chl. *a* (Fig. 8), which in turn resulted in the high transparency. The situation is similar to that found in Lake Hibara (SATO *et al.*, 1993). Since this lake lacks a vernal bloom of phytoplankton (see 3-5), the low transparency observed in spring might be caused by allochthonous inorganic solids contained in inflowing snowmelt water.

3-6. Trophic status

We judged the trophic status of Lake Onogawa to be on the boundary between meso- and eutrophic. The anoxic hypolimnion indicates that the lake is eutrophic. By using the criteria of FORSBERG and RYDING (1980), the concentration of Chl. *a*, total phosphorus, and transparency indicate that the lake should be eutrophic, oligotrophic and mesotrophic, respectively.

The circulation period is the proper season to determine the trophic status of lakes based on material concentrations (SAKAMOTO, 1962). The

Fig. 8. Depth-time diagrams of Chl. *a* ($\mu\text{g}\cdot\text{l}^{-1}$) in 1993 (upper) and 1994 (lower).

Table 2. Transparency of Lake Onogawa in m in 1993 and 1994.

1993			
Date	Transparency	Date	Transparency
30 Apr.	2.7	9 Sept.	6.3
27 May	3.1	30 Sept.	3.5
18 June	5.2	21 Oct.	3.2
9 July	5.1	11 Nov.	3.3
30 July	4.7	2 Dec.	3.1
19 Aug.	5.6	24 Dec.	3.0
Stratification period	5.4 ± 0.6		
Circulation period	3.1 ± 0.2		
1994			
Date	Transparency	Date	Transparency
26 Apr.	3.9	27 Aug.	6.2
12 May	4.1	16 Sept.	5.0
7 June	5.3	6 Oct.	2.1
23 June	4.1	27 Oct.	3.1
12 July	4.9	17 Nov.	3.1
5 Aug.	7.3	8 Dec.	4.0
Stratification period	5.2 ± 1.8		
Circulation period	3.4 ± 0.8		

mean concentrations of total phosphorus and Chl. *a* from the surface down to 6 m (twice the transparency) in April, May (vernal circulation), October, November and December (autumnal circulation) were calculated. A mean transparency in the same period was also calculated. The mean concentrations of total phosphorus were $0.42 \pm 0.09 \mu\text{g atom P} \cdot \text{l}^{-1}$ in 1993 and $0.29 \pm 0.16 \mu\text{g atom P} \cdot \text{l}^{-1}$ in 1994. The concentration of total phosphorus was less than $0.48 \mu\text{g atom P} \cdot \text{l}^{-1}$ ($15 \mu\text{g} \cdot \text{l}^{-1}$), the critical concentration between oligo- and mesotrophy by FORSBERG and RYDING (1980), indicating that the lake is oligotrophic. However, the concentration in 1993 was very close to FORSBERG and RYDING's critical value. Similarly, Chl. *a* was $10 \pm 7 \mu\text{g} \cdot \text{l}^{-1}$ in 1993 and $10 \pm 10 \mu\text{g} \cdot \text{l}^{-1}$ in 1994. Chl. *a* was greater than $7 \mu\text{g} \cdot \text{l}^{-1}$, which is the critical concentration between meso- and eutrophic, suggesting that the lake is eutrophic. Transparency was 3.4 ± 1.8 m in 1993 and 3.1 ± 0.2 m in 1994. Transparency was greater than 2.5 m but less than 4.0 m, a mesotrophic range.

Based on these facts as well as the results of dissolved oxygen, we classified the lake as on the boundary between meso- and eutrophic.

A sister lake, Lake Hibara is classified as on the boundary between oligo- and mesotrophic (SATO *et al.*, 1993). It is interesting that two lakes having the same age and lying in a similar environment have a different trophic status. One possible reason is the difference in water depth. Future analyses of, for example, organic contents and diatom species successions of sediment cores may be helpful in understanding the history of the changes in the trophic status of these lakes.

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摘 要

小野川湖の物理学的, 化学的諸因子の
分布と栄養状態

2 年間に渡り, 小野川湖の物理学的, 化学的諸因子の分布を明らかにした。これらは, 小野川湖の深水層における物質代謝と同湖の栄養状態を論じることのできる, 初めてのデータ・セットである。

小野川湖は 2 回循環湖で, 深水層の溶存酸素は 8 月から 10 月になくなった。小野川湖と同時に形成された松原湖では, 無酸素層は形成されない。水深, 栄養状態等の違いによるものと考えられる。更に, 小野川湖の湖中林が酸素消費を促進している可能性もある。硝酸塩は, 無酸素層で枯渇し, 脱窒が示唆された。深水層のアンモニアは春から夏にかけ一貫して増加し, 他方硝酸塩はこの期間減少する。アンモニアと硝酸塩の間の物質収支に基づく, この湖では見かけ上硝化は起こらない。アンモニア生成速度と脱窒速度が硝化速度を上回れば, 実際には硝化が起こっている, 今回の観測結果のようになるだろう。クロロフィル *a* の濃度は $3\sim 48\mu\text{g}\cdot\text{l}^{-1}$ で, 初秋に年間の最大値に達する。秋期循環期のクロロフィル *a* の最大値は, 松原湖の約 2-3 倍である。春と秋の循環期の透明度の平均値は 3m で, 夏の成層期の平均値は 5m であった。循環期の全リンの濃度は貧栄養の範囲, クロロフィル *a* 濃度は富栄養の範囲, 透明度は中栄養の範囲であった。また, 夏季成層期の深水層が無酸素状態になることより, この湖は富栄養であると示唆される。以上より, 小野川湖の栄養状態は中栄養と富栄養の境界にあると判断した。

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