

## RESEARCH PAPER

Yasuhiro Satoh · Mika Sasaki · Yasushi Miyamori  
Kotaro Sugawara · Tomoyuki Nishi · Megumi Nishizuka  
Koin Inamura · Yuko Yamagami

## Perturbations of a water column of Lake Onogawa by local heavy rainfall

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**Abstract** The perturbations of a water column at the deepest part of Lake Onogawa by a local heavy rainfall were analyzed. Mixing throughout the water column (18.8-m deep) was indicated by changes in the distribution of water temperature. This mixing perturbed the hypolimnetic seasonal distributions of dissolved components. All particulate components peaked at 10m, suggesting a center of inflowing water. Compared with background levels, particulate nitrogen (PN), particulate carbon (PC), particulate phosphorus (PP), and suspended solids (SS) increased from 16-fold for PN to 100-fold for SS. Soluble reactive phosphorus was the only dissolved component that formed a clear maximum at 10m, as did the particulate components. Assuming that SS consists mainly of mineral particles, SS can be classified into three categories: (1) A rapidly sinking fraction, the main body of the loaded SS, with a sinking rate exceeding  $1\text{ m day}^{-1}$  and radii exceeding  $2\text{--}3\text{ }\mu\text{m}$ . (2) A slowly sinking fraction with a sinking speed of about  $10\text{ cm day}^{-1}$  and radii of  $0.7\text{--}0.9\text{ }\mu\text{m}$ ; this fraction is calculated to be about 4% of the total loaded SS at most. (3) A fraction that was essentially retained in the water column. The maximum estimate of this fraction was 0.5% of the total.

**Key words** Heavy allochthonous load · Material distribution · Ventilation · SS sinking rate

### Introduction

An intensive study called the Biwako Transport Experiment (BITE'93) has clarified many aspects of the

limnological effects on Lake Biwa of energetic meteorological events of typhoons (e.g., special issue of *Jpn. J. Limnol.* 57: No. 4 (2)). Some of the effects observed in the shallow south basin of Lake Biwa stem from the same phenomenon, i.e., resuspension of sediments by turbulent mixing caused by a typhoon. Suspended solids, dissolved nitrogen, and dissolved phosphorus increased after a windy typhoon (Nakano et al. 1996; Robarts et al. 1998), resulting in increases of chlorophyll *a* (chl *a*), algal growth, hot-water extractable phosphorus, and so on (Seike et al. 1996; Nakano et al. 1996; Nagata et al. 1996; Sakamoto and Inoue 1996; Robarts et al. 1998). The concentration of chl *a* doubled, even in the deep north basin, probably because a supply of nutrients accumulated in the metalimnion during the intensive water mixing caused by a typhoon (Tanaka and Tsuda 1996). Other effects of the typhoon were also observed. After a rainy typhoon, highly turbid water from the Yasu River penetrated the north basin of Lake Biwa, resulting in a highly turbid thin layer at the seasonal thermocline (Tanaka et al. 1996).

Another sporadic meteorological event, a local heavy rainfall, has similar effects, as described by Tanaka et al. (1996). However, there have been extremely limited studies on the perturbation of water columns by local heavy rainfalls. During our regular observations of Lake Onogawa in Urabandai, Fukushima, we had a chance to record such events, since distributions of substances were perturbed by the heavy load of inflowing water. The present paper reports these perturbations.

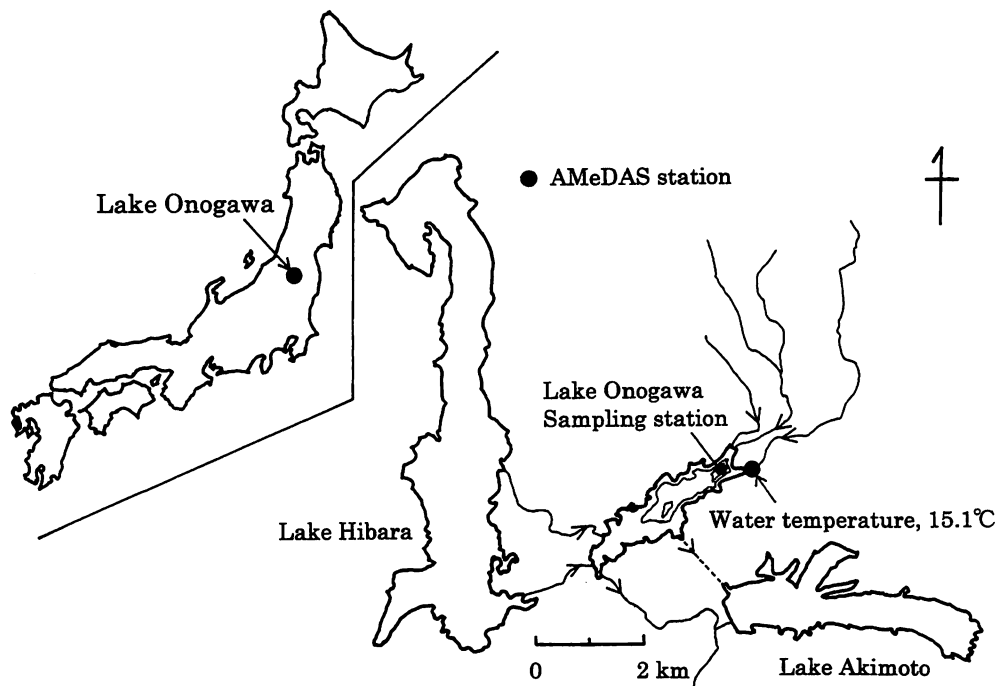
### Materials and methods

Lake Onogawa ( $37^{\circ}40'\text{ N}$ ,  $140^{\circ}06'\text{ E}$ ) is a dimictic dammed lake created by the volcanic eruption of Mt. Bandai in 1888. It lies 794 m above mean sea level and has a maximum depth of 21 m (Horie 1962). However, the water level fluctuates significantly because the lake water is used for hydroelectric power generation. The lake covers  $1.4\text{ km}^2$  (Horie 1962) and the water volume is about  $0.014\text{ km}^3$  (Satoh et al. 1995). The

Y. Satoh (✉) · M. Sasaki · Y. Miyamori · K. Sugawara · T. Nishi · M. Nishizuka · K. Inamura · Y. Yamagami  
Faculty of Science, Yamagata University, 1-4-12 Koshirakawa machi  
Yamagata 990-8560, Japan  
Tel. +81-23-628-4589; Fax +81-23-628-4510  
e-mail: hirosato@sci.kj.yamagata-u.ac.jp

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**Fig. 1.** Map showing sampling station. The isodepth lines in Lake Onogawa basin show 10 and 15m. The locations of inflowing water temperature measurement and the AMeDAS station are also shown



trophic status of the lake is thought to be on the boundary between meso- and eutrophic (Sato et al. 1996). It has several inflowing streams. Water from Lake Hibara, a sister lake created at the same time, flows into the lake through two streams on the southwest shore (Fig. 1). Water from the surrounding mountains flows into the lake by three streams on the northeast shore. Besides these five main inflows, some other minor inflows exist, including temporary ones, in which water flows for only limited times, such as during the snow-melt season or after rain. The water of Lake Onogawa flows out from two places: one is an artificial channel at the central part of the lake (dashed line in Fig. 1), which flows into Lake Akimoto by way of the Onogawa hydroelectric power station, and the other is the River Nagase on the southwest shore.

Water samples have been collected at a station in the deepest part of the lake (Fig. 1) about every 3 weeks in ice-free seasons since 1993. Some results obtained in 1998 are reported here, as examples of a year affected by sporadic local heavy rainfalls, and those obtained in 1997, as examples of a normal year. The results in Sato et al. (1996) also exemplify normal years. The sampling station is located adjacent to the three major water inflows. The distances from the three inflows are almost the same, about 500m. Water samples were collected with a 6-l Van Dorn sampler at about 2.5-m intervals from the surface to the bottom. An additional sample was taken from 1 m below the surface in 1998. Water samples for chemical analyses were transported to a field laboratory near the lake in heat-insulating boxes. The samples were filtered through preignited Whatman GF/F glass fiber filters (mean porosity,  $0.7\mu\text{m}$ ) within 1 to 3 h after sample collection. The filtrates were then frozen at the field laboratory, transported to Yamagata University, and kept frozen until they were chemically

analyzed. The filters, which were also frozen until analysis, were used for chemical analysis of particulate components. The physicochemical parameters analyzed and the methods used are summarized in Table 1. Meteorological data at the Wasezawa AMeDAS station on the Urabandai Plateau, which is the nearest station to Lake Onogawa (Fig. 1), were obtained from the Japan Meteorological Agency.

## Results

### Rainfall

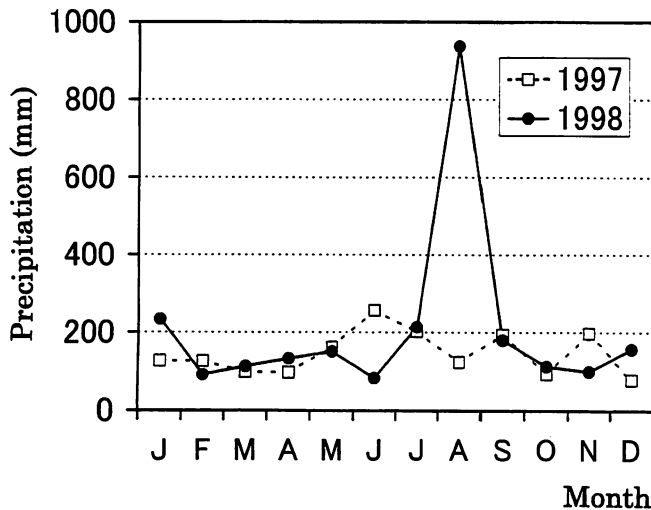
The precipitation in August 1998 was 937mm (Fig. 2), 7.6 times that in August 1997 (124mm). About half the normal annual total precipitation fell in only one month. We collected water samples on 7 August 1998. During the week prior to these sample collections, a total of 355mm of rain fell (Fig. 3). This amount is about equivalent to the total of 2 to 3 months of precipitation in normal months (Figs. 2 and 3). The next sampling date was 24 August. Between these two days, a second local heavy rainfall occurred, which lasted 6 days, from 12 to 17 August, with a total precipitation of 275mm. Another local heavy rainfall also occurred in late August (Fig. 3).

### Water temperature

The epilimnetic water of Lake Onogawa was colder and the hypolimnetic water was warmer in mid and late summer in 1998 than in 1997 (Fig. 4). Although no distinct epilimnion was observed on 16 July 1998, the lake was stratified as follows. The water temperature gradually decreased from

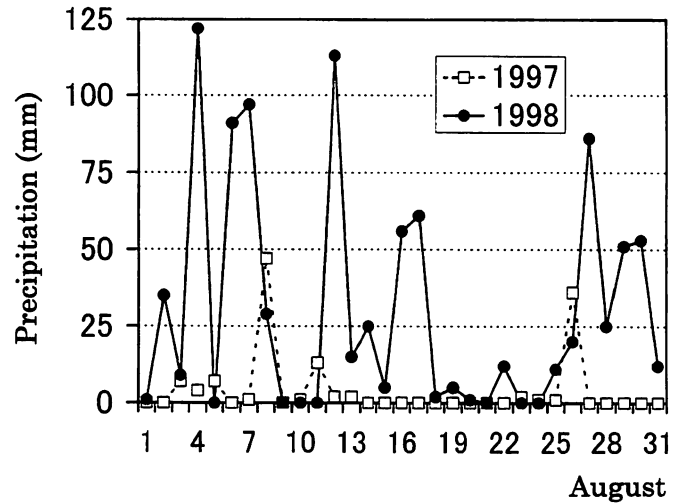
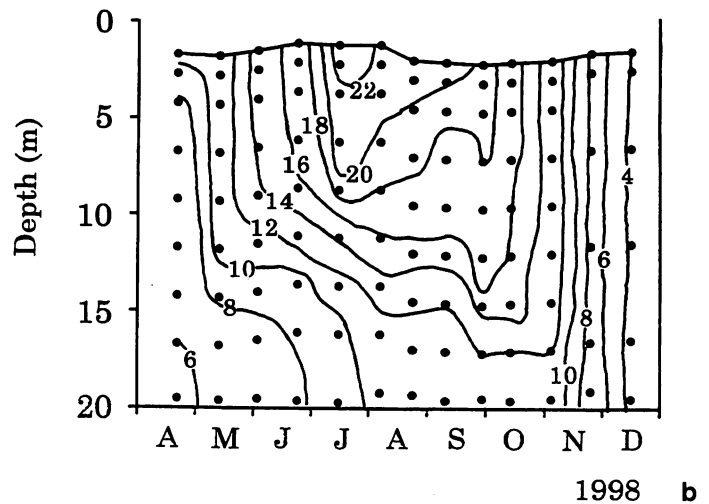
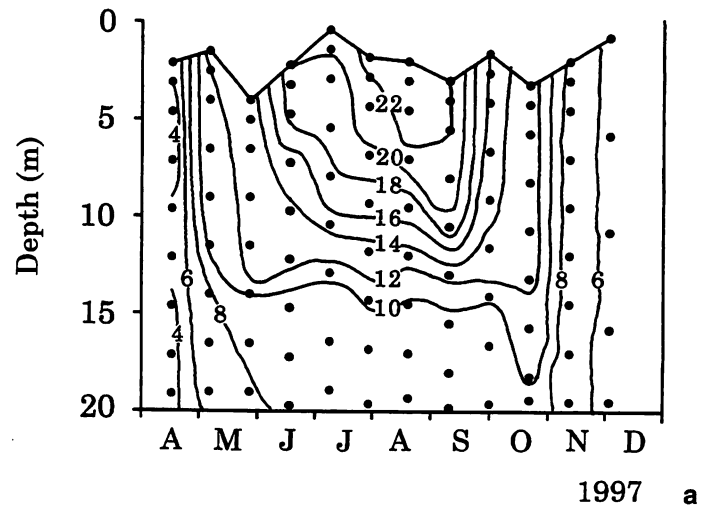
**Table 1.** Summary of physicochemical parameters analyzed and methods used

Parameter	Method
Water temperature	Thermistor thermometer
Suspended solids	Gravimetry
Particulate phosphorus	Molybdate blue method after persulfate digestion (Menzel and Corwin 1965)
Particulate carbon	CHN corder (Yanaco MT-3)
Particulate nitrogen	CHN corder (Yanaco MT-3)
Dissolved oxygen	Winkler method
Nitrate	Cadmium reduction with subtraction of nitrite (Strickland and Parsons 1972)
Ammonia	Phenol hypochlorite method (Sol6rzano 1969)
Inorganic carbon	Shimadzu TOC 5000
Total nitrogen	UV measurement after persulfate digestion (Otsuki 1981)
Soluble reactive phosphorus	Molybdate blue method (Strickland and Parsons 1972)

**Fig. 2.** Monthly precipitation at Wasezawa AMeDAS station of the Japan Meteorological Agency, the nearest station to Lake Onogawa, in 1997 (broken line) and 1998 (solid line)

23.5°C at the surface to 20.2°C at 7 m (Fig. 5). This layer was thought to be the epilimnion. The water temperature decreased sharply from 20.2°C at 7 m to 9.8°C at 15 m, indicating that this layer was the metalimnion. Below 15 m was the hypolimnion, with water temperature ranging from 9.8°C to 9.3°C. However, 3 weeks later, this stratification was partly destroyed. The water temperature decreased with depth at an almost constant rate of  $0.75^{\circ}\text{Cm}^{-1}$  from 21.4°C at 2 m down to 13.9°C at 12 m. The water temperature below 13 m was around 11°C, forming the hypolimnion. Thus, water temperatures down to 10 m decreased on average  $1.8 \pm 0.6^{\circ}\text{C}$ , and those at depths greater than 10 m increased on average  $1.5 \pm 0.3^{\circ}\text{C}$  on 7 August, as compared with those of the preceding observation on 16 July (Fig. 5).

The water temperature of an inflowing stream was 15.1°C at the point shown in Fig. 1 on 7 August 1998. This water

**Fig. 3.** Daily precipitation at Wasezawa AMeDAS station of the Japan Meteorological Agency, the nearest station to Lake Onogawa, in August 1997 (broken line) and 1998 (solid line)**Fig. 4.** Depth-time diagrams of water temperature ( $^{\circ}\text{C}$ ) of Lake Onogawa in (a) 1997 and (b) 1998

temperature corresponds to that at 10m depth (15.0°C, Fig. 4) in the water column of the lake on the same date.

### Dissolved components

Hypolimnetic dissolved oxygen decreases from spring to early summer, resulting in the formation of an anoxic layer in Lake Onogawa in late July or early August (1997 in Fig. 6), as has already been reported by Satoh et al. (1996). Nitrate also decreases in a similar way and is absent in the anoxic layer, probably due to denitrification (Satoh et al. 1996). These features were perturbed at the time of the local heavy rainfall in early August 1998. Depth-time diagrams of dissolved oxygen serve as examples (Fig. 6). The concentration of dissolved oxygen at the lowermost stratum increased 14 times, from 0.10mg l<sup>-1</sup> on 16 July to 1.43mg l<sup>-1</sup> on 7 August (Table 2). After that it began to decrease again, and finally an anoxic layer was formed in early September (Fig. 6). The formation of the anoxic layer in 1998 was delayed more than 1 month as compared with 1997. The same was true for nitrate. Nitrate concentration

increased about nine times in the same stratum (Table 2) and then decreased to 0 on 24 August (data not shown).

In contrast, hypolimnetic ammonia increases from spring to summer in this lake, as shown in 1997 (Fig. 7) and in Satoh et al. (1996). Hypolimnetic inorganic carbon also increases from spring to summer (data not shown). These

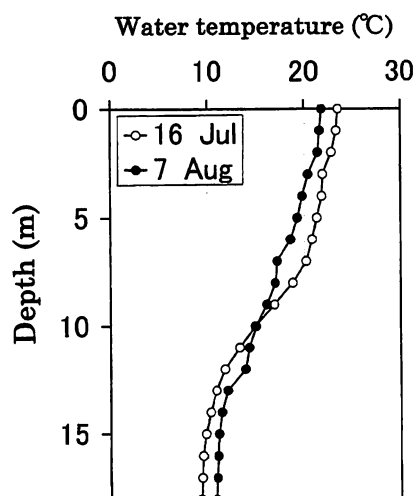


Fig. 5. Vertical distribution of water temperatures in Lake Onogawa on 16 July (open circles) and 7 August (solid circles) 1998

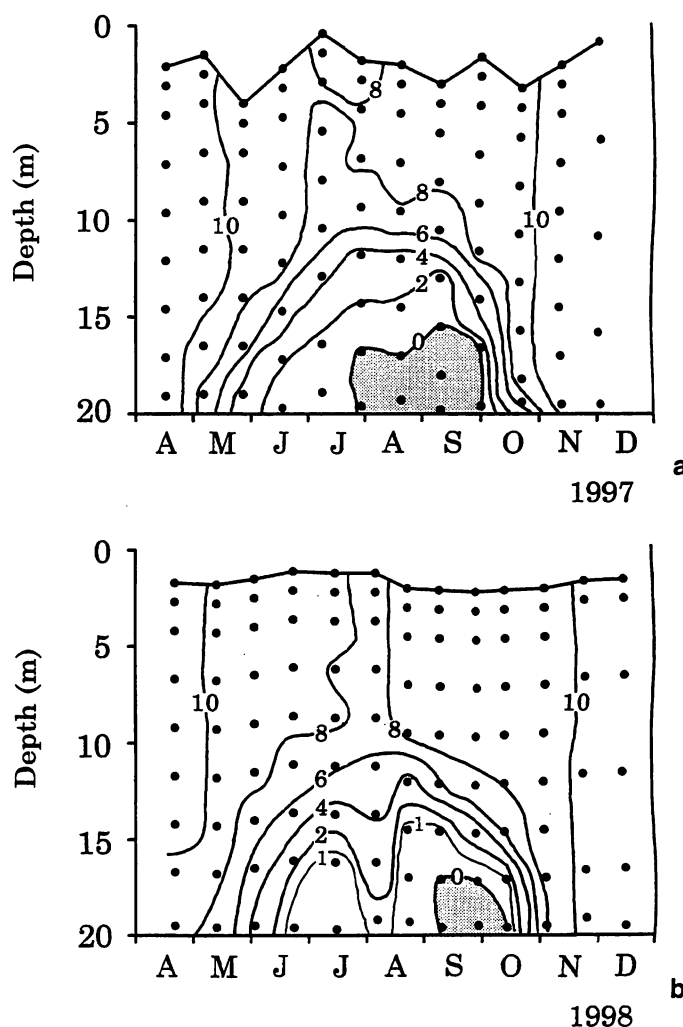
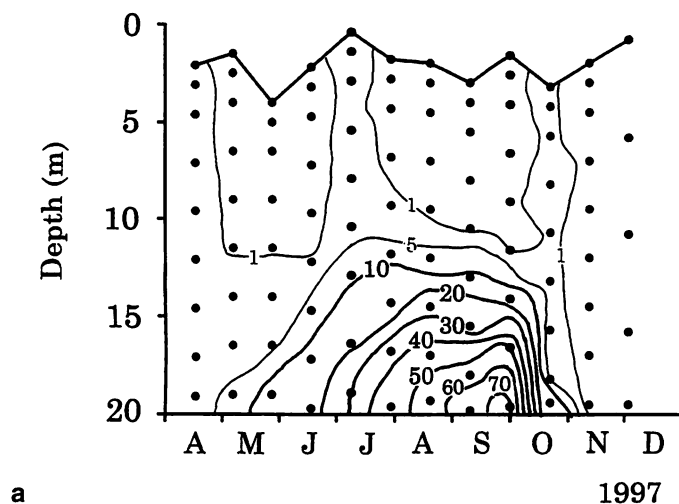


Fig. 6. Depth-time diagrams of dissolved oxygen (mg l<sup>-1</sup>) in Lake Onogawa from April to December in (a) 1997 and (b) 1998

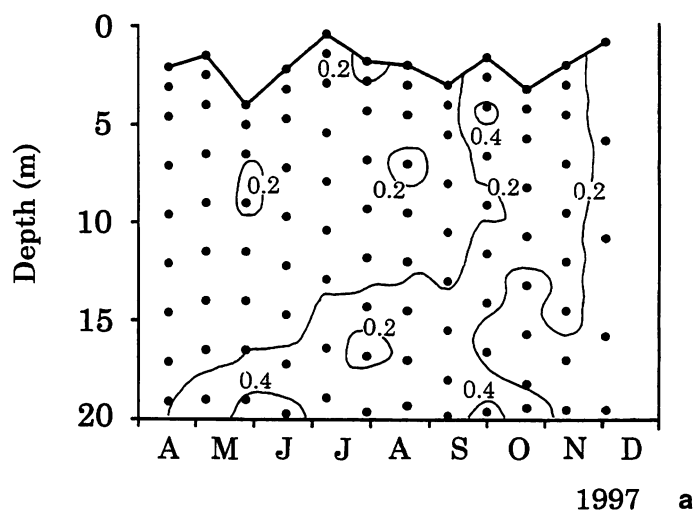
Table 2. Concentrations of dissolved oxygen (DO), nitrate, ammonia, inorganic carbon (IC), and soluble reactive phosphorus (SRP) on 16 July and 17 August 1998

Depth (m)	DO (mg l <sup>-1</sup> )		NO <sub>3</sub> <sup>-</sup> (μM)		NH <sub>3</sub> (μM)		IC (μM)		SRP (μM)	
	16 Jul	7 Aug	16 Jul	7 Aug	16 Jul	7 Aug	16 Jul	7 Aug	16 Jul	7 Aug
0	8.06	7.86	2.4	4.1	0.92	0.51	221	219	0.04	0.87
1	8.01	7.99	2.2	4.1	0.68	0.47	230	ND <sup>a</sup>	0.05	0.66
2.5	8.07	7.95	2.3	3.7	0.95	0.21	226	ND	0.04	0.92
5	7.99	7.94	2.7	4.5	1.15	0.19	244	174	0.05	1.54
7.5	8.26	7.31	3.5	4.9	0.99	2.16	248	220	0.07	3.38
10	6.22	5.72	5.1	4.7	3.22	6.19	323	ND	0.11	4.23
12.5	3.23	4.06	6.3	4.1	11.9	9.10	444	406	0.08	3.54
15	0.65	2.29	3.2	3.6	20.4	16.9	585	502	0.21	2.73
17.5	0.10	1.43	0.3	2.8	30.5	19.5	777	567	0.13	1.84

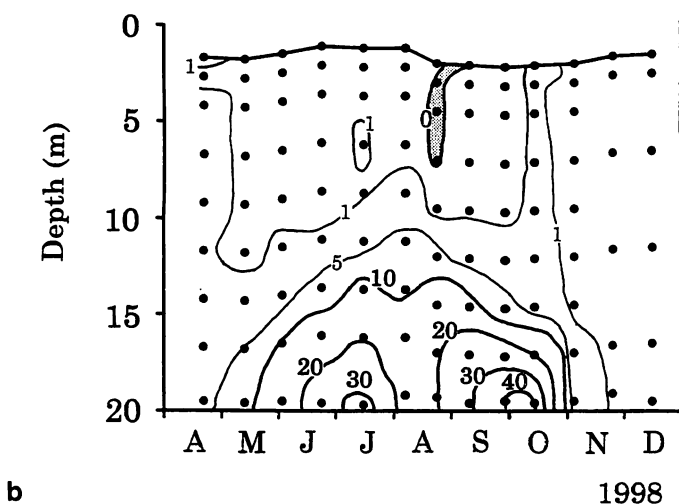
<sup>a</sup>ND, no data



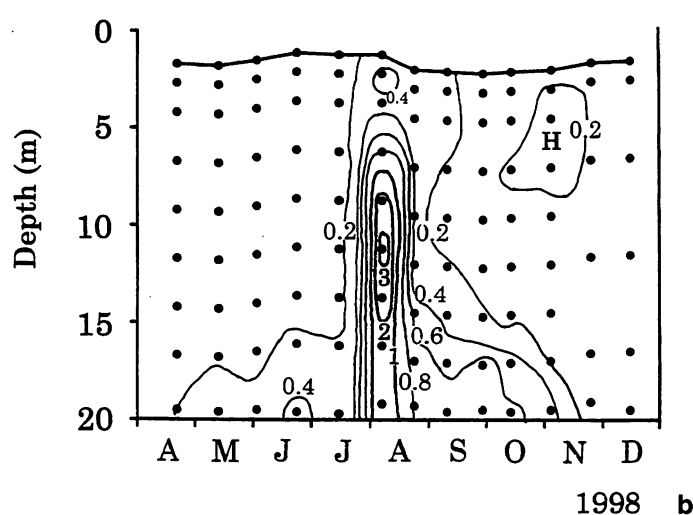
a



1997 a



b



1998 b

**Fig. 7.** Depth-time diagrams of ammonia ( $\mu\text{M}$ ) in Lake Onogawa from April to December in (a) 1997 and (b) 1998

**Fig. 8.** Depth-time diagrams of soluble reactive phosphorus (SRP) ( $\mu\text{M}$ ) in Lake Onogawa from April to December in (a) 1997 and (b) 1998

trends were perturbed at the time of the local heavy rainfall. Depth-time diagrams of ammonia in 1997 and 1998 serve as examples for this group (Fig. 7). Accumulated hypolimnetic ammonia at the level of  $11.9\mu\text{M}$  (12.5 m) to  $30.5\mu\text{M}$  (17.5 m) on 16 July decreased to  $9.10$  to  $19.5\mu\text{M}$  on 7 August (Table 2). The same was true for inorganic carbon (Table 2). After the perturbation, ammonia began to increase again and reached the annual maximum of  $52.9\mu\text{M}$  on 14 October (Fig. 7). The level of the annual maximum in 1998 was about 70% of that in 1997 (Fig. 7). Soluble reactive phosphorus (SRP) increased throughout the water column. The concentrations of SRP in the water column on 7 August were from 13 (at 1 m and 15 m) to  $48$  (at 7.5 m) times greater than those on 16 July (Table 2). SRP was the only dissolved component that formed a clear maximum at 10 m after the local heavy rainfall (Table 2 and Fig. 8).

#### Particulate components

Particulate components, such as suspended solids (SS), particulate carbon (PC), particulate nitrogen (PN), and

particulate phosphorus (PP), more or less increased throughout the water column and peaked at 10 m on 7 August 1998 (Table 3). SS increased 100-fold at 10 m, from  $1.5\text{mg l}^{-1}$  on 16 July to  $157\text{mg l}^{-1}$  on 7 August (Table 3). Likewise, at the same depth, PC, PN, and PP increased 17-, 16-, and 31-fold, respectively. Among these, the depth-time diagrams of suspended solids in 1998 (Fig. 9, no data in 1997), and particulate phosphorus in 1997 and 1998 (Fig. 10) are shown as examples.

## Discussion

### Water temperature and dissolved components

The changes in the distribution of water temperatures before and after rainfalls (Fig. 5) indicate intensive vertical water mixing due to the local heavy rainfalls. Although we have no data on the fluxes of inflowing water to Lake Onogawa, the precipitation data (Fig. 3) suggest that a huge amount of water entered the lake prior to and during the



which constituted a part of PP and hydrolyzed in the water column, resulting in parallel maxima of SRP and PP (Figs. 8 and 10, respectively). The fact that no dissolved component except SRP shows parallel maxima to the particulate components strongly supports the latter origin. Regardless of its origin, the increase of SRP in a lake after a local heavy rainfall is worthy of note in view of primary productivity, since phosphorus is the most probable factor limiting primary productivity in many lakes (e.g., Wetzel 1983).

Nitrate increased by 0.4 to 2.5  $\mu\text{M}$  in the water column of Lake Onogawa except for the 10- and 12.5-m layers after local heavy rainfalls (Table 2). The concentration of nitrate plus nitrite also increased by 0.4 to 5.4  $\mu\text{M}$  in the water of the south basin of Lake Biwa after a rainy typhoon (Seike et al. 1996). Based on the results from Lake Nakanoumi (Seike et al. 1990), Seike et al. (1996) concluded that this increase was caused by the increased river discharge containing a high concentration of nitrate plus nitrite after the rainy typhoon. The increase in nitrate in Lake Onogawa was a little smaller than that observed in Lake Biwa. The watershed of Lake Biwa contains urban and cultivated areas as well as a mountain area, whereas the watershed of Lake Onogawa is mainly in a mountain area. This difference in the nature of the watershed might affect the nitrate concentrations of the inflowing water after heavy rain.

### Particulate components

The next sampling date after 7 August was 24 August. Between these 2 days, another local heavy rainfall occurred, which lasted 6 days, from 12 to 17 August, with a total precipitation of 275 mm (Fig. 3). An input of particulate components into the lake might also have occurred during this local heavy rainfall. However, depth-time diagrams show no evidence of a heavy load of particulate components in the water column at this time (Fig. 9). This local heavy rainfall stopped 1 week before the sampling on 24 August. On the other hand, the sampling date of 7 August was within a local heavy rainfall period, which lasted 7 days, from 2 to 8 August (Fig. 3). These facts suggest that the main body of the loaded SS may have sunk within 1 week.

Gravitational sinking of a small particle in a fluid obeys Stokes' law:

$$v = 2gr^2(\sigma - \rho)/(9\eta) \quad (1)$$

where  $v$  is sinking speed,  $g$  is gravitational acceleration,  $r$  is the radius of the particle,  $\sigma$  is the density of the particle,  $\rho$  is the density of the fluid, and  $\eta$  is the viscosity of the fluid. Assuming that (1) the sinking of the loaded particulate components in the water column obeyed Stokes' law, (2) the particulate components were mainly of minerals having a density ( $\sigma$ ) of 2–3  $\text{g cm}^{-3}$  (National Astronomical Observatory 1991), (3) these particles would have sunk from 10 m to depths below 17.5 m in 7 days, (4) the viscosity of water ( $\eta$ ) was  $1.3 \times 10^{-2} \text{ g cm}^{-1} \text{ s}^{-1}$  (a value at 10°C), and (5) the density of water ( $\rho$ ) was  $1 \text{ g cm}^{-3}$ , the minimum radius of such particles is calculated to be about 2–3  $\mu\text{m}$ . The

existence of mineral particles having radii greater than 2–3  $\mu\text{m}$  seems to be quite realistic. After a rainy typhoon, Tanaka et al. (1996) measured the size of particles collected from a highly turbid layer formed at the seasonal thermocline in the north basin of Lake Biwa. The diameter of the particles peaked at 6  $\mu\text{m}$  (3  $\mu\text{m}$  in radius), which corresponds to the lower limit of the present estimate. Probably particles greater than 6  $\mu\text{m}$  in diameter had already sunk before the inflowing water reached their sampling station.

The isopleths of 4 and 6  $\text{mg l}^{-1}$  of the SS concentration deepened with time from 7.5–10 m in late August to around 15 m in early November (Fig. 9). The average SS concentration throughout the water column before August is calculated as  $1.51 \pm 0.53 \text{ mg l}^{-1}$  ( $n = 45$ ). Assuming that this average represents a normal level of SS, the level of 4–6  $\text{mg l}^{-1}$  is still significantly higher than the normal level. These isopleths did not reach the bottom until autumnal complete circulation started in November. This suggests that although the main body of the SS loaded by the flood sank very rapidly to the bottom within a week, a small amount of slowly sinking SS was also contained in the flood water. Assuming that the slowly sinking particles sank from 7.5 to 15 m in 2 months along the 4  $\text{mg l}^{-1}$  isopleth, the radii of such particles are calculated to be about 0.7–0.9  $\mu\text{m}$  according to the same method as described above. Since the peak concentration of SS was 157  $\text{mg l}^{-1}$  (Fig. 9), 4  $\text{mg l}^{-1}$  and 6  $\text{mg l}^{-1}$  correspond to 2.5% and 3.8% of the total SS, respectively. These should be maximum estimates, because the particles in this fraction might also be supplied by the local heavy rainfalls in mid and late August (Fig. 3).

Even excluding the slowly sinking fraction mentioned above, the concentrations of SS did not reach similar levels to those before the local heavy rainfalls until autumnal complete circulation began in November (Figs. 4 and 9). The average concentration of SS in the layer overlying the isopleth of 4  $\text{mg l}^{-1}$  in September and October is  $2.28 \pm 0.73 \text{ mg l}^{-1}$  ( $n = 27$ ), whereas that in the whole water column before August was  $1.51 \pm 0.53 \text{ mg l}^{-1}$  ( $n = 45$ ), as mentioned above. These two averages are significantly different ( $P = 0.01$ ). The excess SS, which is the difference between these two averages, may be a fraction of the particles derived from the loaded SS and retained in the water column for a long time. The concentration of the excess SS was  $2.28 - 1.51 = 0.77 \text{ mg l}^{-1}$ . This is about 0.5% of the total SS. In a similar sense as mentioned above for the slowly sinking fraction, 0.5% is also the maximum estimate.

In conclusion, the present study showed that inflowing water from a local heavy rainfall could perturb a whole water column of a moderate-sized lake. Some remarkable features of the perturbation are as follows: (1) Water mixing caused by inflowing water, which is suggested by changes in the depth profiles of water temperature, resulted in changes in the seasonal depth distributions of substances. One of the prominent changes is that oxygen was supplied to the depths, and the formation of anoxic conditions was postponed by more than 1 month. This, in turn, resulted in less accumulation of ammonia in the hypolimnion as compared with that in the normal year. (2) SRP increased in the whole water column and peaked at 10 m, where all

particulate components peaked. There are two possible origins of this increase in SRP. One is that SRP per se was contained in the inflowing water, and the other is that SRP originated from the easily hydrolyzable particulate fraction, which constituted a part of PP and hydrolyzed in the water column. Though the latter seems to be more probable, the increase of SRP in the lake water after a heavy rainfall is worthy of note, regardless of its origin from the viewpoint of primary productivity. (3) Assuming that the loaded SS mainly consists of minerals, SS is divided into three classes. The first class is a rapidly sinking fraction, the main body of the loaded SS, with a sinking rate exceeding 7.5 m per 7 days, or  $1 \text{ m day}^{-1}$ , whose radii are estimated to be greater than  $2\text{--}3 \mu\text{m}$ . The second class is a slowly sinking fraction with a sinking speed of 7.5 m per 60 days, or  $10 \text{ cm day}^{-1}$ . The radii of this fraction are estimated to be  $0.7\text{--}0.9 \mu\text{m}$ . This fraction is calculated to be about 4% of the total loaded SS at most. The third is a fraction that was retained for a long time in the water column. A maximum estimate of this fraction is 0.5% of the total loaded SS.

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