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Research Article

A long-term eutrophication process observed from the changes in the horizontal distribution of profundal oligochaete fauna in mesotrophic-eutrophic Lake Kawaguchi, Japan

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Abstract: The purpose of this study was to record the oligochaete fauna in Lake Kawaguchi and clarify their horizontal distribution. In addition, annual changes in the lake were recorded. Samples were collected between 5 March 1993 and 7 March 2006 by using a standard Ekman-Birge sampler at 22 stations, and multipoint sampling surveys were carried out. As a result of the study, a total of 8 species belonging to 6 genera and 3 subfamilies were identified. The average density of oligochaetes for the entire lake was 5247 ± 3873 ind m^{-2} and the average wet weight of oligochaetes was 25.5 ± 23.4 g m^{-2} in 1993, compared to 1075 ± 676 ind m^{-2} and 2.7 ± 1.7 g m^{-2}, respectively, in 2006. *Tubifex tubifex* had inhabited the entire lake bottom in 1993, but *Limnodrilus* spp. inhabited only the center of the lake in 2006. In recent years, the total number of oligochaetes has shown a tendency to increase, compared with the past record from the 1970s, suggesting that eutrophication is an ongoing process.

Key words: Aquatic oligochaetes, eutrophication, Lake Kawaguchi, horizontal distribution, *Tubifex tubifex*

Introduction

Aquatic oligochaetes play an important role in the material flows in lake ecosystems, especially in the detritus food chain (Brinkhurst and Jamieson, 1971). However, few studies on aquatic oligochaetes have been undertaken in Japan because of the difficulties in species identification.

The biota of Lake Kawaguchi has been studied by several researchers since Terao (1912). However, studies of the lake's macrobenthic fauna, especially aquatic oligochaetes, have been very few in number. Previous research on Lake Kawaguchi includes a descriptive study of benthic macroinvertebrates (Miyadi, 1932; Kitagawa, 1973). Since the middle of the 1990s, the biota and the environmental conditions of the lake have been changing (Yamanashi Prefecture, 2003), and it is suspected that such changes have affected bottom fauna, including the aquatic oligochaetes. The purpose of this study was to record the oligochaete fauna in Lake Kawaguchi and to clarify their horizontal distribution and annual changes in the lake.

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Study site

Lake Kawaguchi (35°31′N, 138°45′E at the center of the lake; surface area of 5.96 km^2; maximum depth of 16.1 m; mean depth of 9.3 m; altitude above sea level, 832 m) is located at the northern foot of Mt. Fuji. This lake was formed by lava flows from Mt. Fuji and related volcanoes, which dammed the streams draining the northern mountain ranges. The lake has an inflowing small stream, the river Terakawa, but lacks outflowing rivers. In its drainage basins, where porous volcanic deposits prevail, the runoff water mostly flows underground and only rarely as a surface stream. The eastern shore of the lake is partly surrounded by cultivated land. There are some towns and villages on the northeastern and southeastern shores. The lake is ice-covered from January to February and has a persistent thermocline in summer (Hirabayashi et al., 2007).

Materials and methods

On 5 March 1993 and 7 March 2006, multipoint sampling surveys were carried out using a standard Ekman-Birge grab (15 × 15 cm), and 3 replicate samples at 22 locations (5.4-13.2 m in depth) from a grid of 800 × 800 m were taken (Figure 1). The sampling points were determined by GPS. After sieving sediment through Surber nets (NGG 42, 418-μm mesh size), oligochaetes were picked up and counted using a binocular microscope (magnification of 10× and 20×), then put into glass bottles with a 10% formaldehyde solution for species identification. Individuals were wet-weighed, and the total numbers of individuals per species were determined. Specimens were mounted using Amman's lactophenol preparation method (Brinkhurst, 1971) and then identified using the Brinkhurst (1971) and Kathman and Brinkhurst (1999) keys. The samples from stations 3, 4, 5, 8, 10, and 11 in 1993 could not be identified because they had dried up, and only 16 sampling-point specimens for that year remained.

A sediment sample was collected with a core sampler (3 cm in inner diameter) at each station in order to analyze organic matter contents. Mud in the upper 3-cm layer of each core was oven-dried at 110 °C for 2 days and ignited in a muffle furnace at 550 °C for 3 h to determine the values of ignition loss (IL). The core sampler was also used to measure dissolved oxygen concentrations (DO) in the water at the mud-water interface. Water near the mud surface in the core sampler was carefully siphoned into a glass bottle. Dissolved oxygen concentration was determined by the Winkler method with azide modification. In addition, mud temperatures (MT) in the bottom sediments collected in the core sampler were measured with a thermistor thermometer.

Results

Table 1 shows the mean values, with standard deviations, of some environmental factors, as well as the oligochaete fauna measured in 1993 and 2006. The water depth and DO values were almost the same among the stations in both years investigated, due to the same period of spring overturns. Ignition loss was significantly different between 1993 and 2006 ($P < 0.01$, Wilcoxon U-test). Figure 2 shows the horizontal distributions of ignition loss of sediment in March 2006. The IL values of the sediment ranged from 4.2% to 19.8%. Most of the lake basin consisted of a soft bottom with organic matter contents higher than 14%. Sediment at station 3 contained the highest level of organic matter. In regions shallower than 6 m (i.e. station 6, the southern part of the lake), the sediment was generally sand and gravel with low values of loss on ignition. In regions deeper than 10 m, the bottom sediment consisted mainly of mud, with relatively high values of loss on ignition (12.0%-19.8%) (Figure 2).

In 1993, the average density of oligochaetes for the entire lake was 5247 ± 3873 ind m^{-2} and the average wet weight was 25.5 ± 23.4 g m^{-2}, compared to 1075 ± 676 ind m^{-2} and 2.7 ± 1.7 g m^{-2}, respectively, in 2006. Oligochaetes comprised only Naidinae, Rhyacodrilinae, and Tubificinae in the family Naididae in both years. In 1993, a total of 4 genera and 6 species belonging to 2 subfamilies were identified, including 2 species of Rhyacodrilinae and 4 species of Tubificinae. *Limnodrilus* was the most abundant genus. In order of abundance, 3 groups, *Tubifex tubifex* (Müller, 1774) (3072 ± 3513 ind m^{-2}, 54.8%), *Limnodrilus hoffmeisteri* Claparède, 1862 and *Limnodrilus claparedeianus* Ratzel, 1868 (1183 ± 1974 ind m^{-2}, 24.7%), and *Rhyacodrilus hiemalis* Ohtaka, 1995 (514 ± 350 ind m^{-2}, 10.6%), accounted for 90.1%

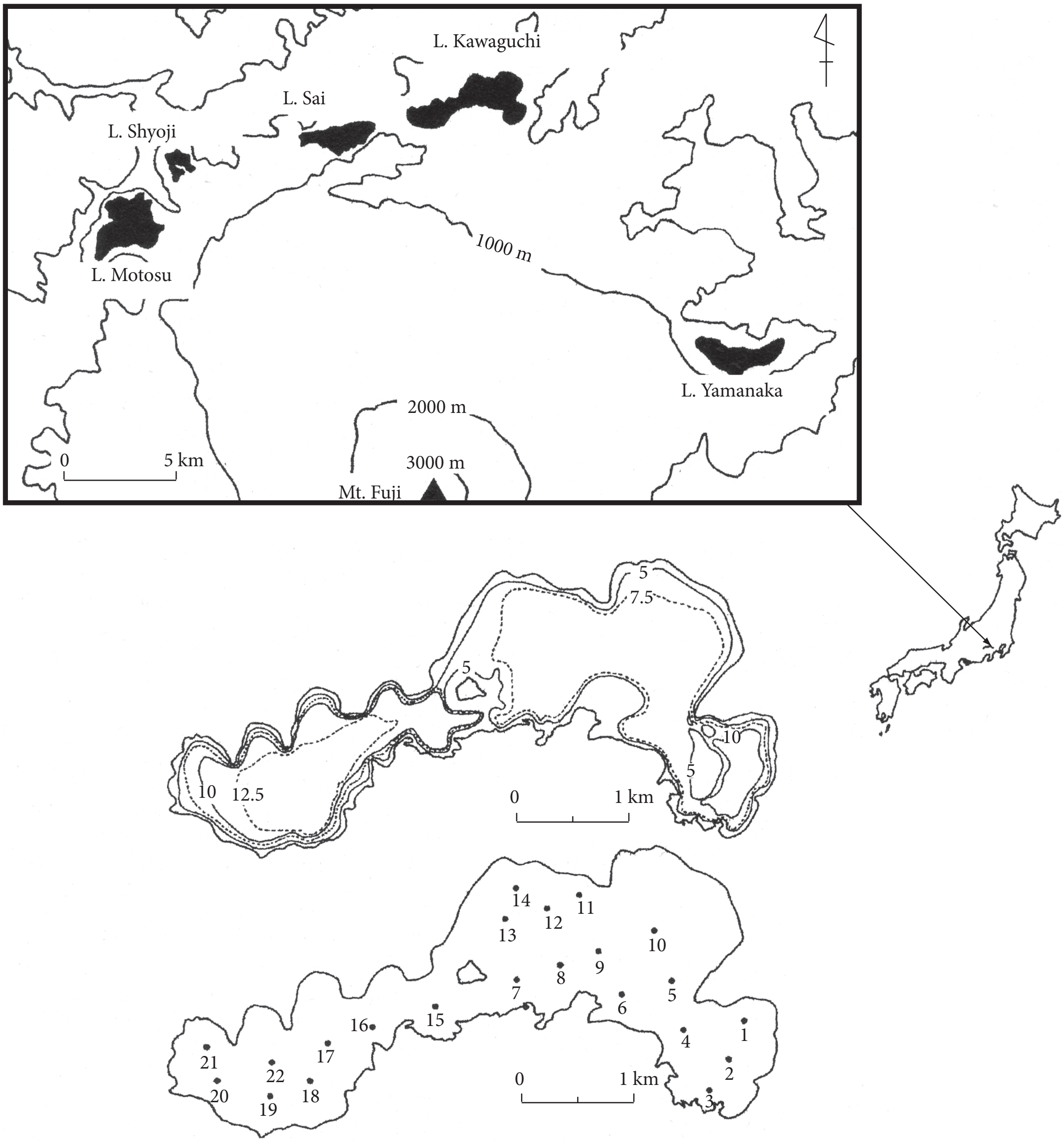

Figure 1. Location of Lake Kawaguchi, isopleths of depth (m), and sampling stations in the lake.

Table 1. Mean values and SDs of the environmental factors from the grid surveys.

Environmental factors	5 March 1993	7 March 2006
Number of sampling points	22	22
Depth (m)	10.6 ± 2.1	9.9 ± 2.2
Ignition loss (%)	10.4 ± 2.4[a]	15.8 ± 3.2[b]
Mud temperature (°C)	-	5.6 ± 0.6
Dissolved oxygen (mg/L)	10.8 ± 0.7	10.2± 0.5

a and b: difference is significant, $P < 0.01$ (Wilcoxon U-test)

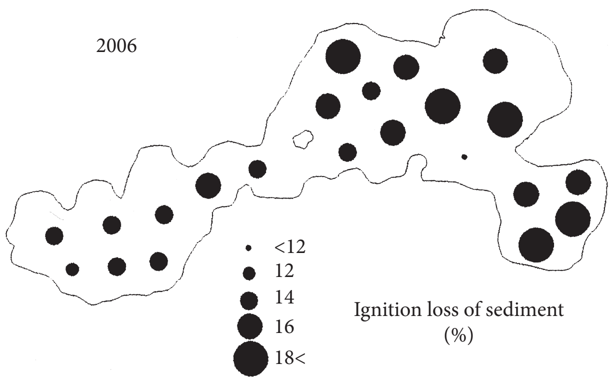

Figure 2. Horizontal distribution of ignition loss of the sediment in Lake Kawaguchi, March 2006.

of the overall total individual numbers. It is extremely difficult to distinguish between immature worms of *L. hoffmeisteri* and *L. claparedeianus*. Consequently, immature specimens were recorded as *Limnodrilus* spp. Moreover, our specimens of *T. tubifex* could have occasionally included scarce immature individuals of some other tubificines with hair chaetae (Table 2). In 2006, a total of 6 genera and 7 species belonging to 3 subfamilies were identified, including 1 species of Naidinae, 3 species of Rhyacodrilinae, and 3 species of Tubificinae. *Limnodrilus* was also the most abundant genus. In order of abundance, 3 groups, *T. tubifex* (580 ± 395 ind m^{-2}, 54.0%), *L. hoffmeisteri* and *L. claparedeianus* (271 ± 394 ind m^{-2}, 25.2%), and *Bothrioneurum vejdovskyanum* Štolc, 1886, accounted for 91.1% of the overall total individual numbers. In 2006, the average density of *T. tubifex* was 2.1 times higher than that of *Limnodrilus* spp. and 2.6 times higher in 1993. However, the biomass of *T. tubifex* was 9.9 times greater than that of *Limnodrilus* spp. in 1993 and 0.65 times greater in 2006. The numerical dominance of *T. tubifex* and *Limnodrilus* spp. in oligochaete communities was 54.8% and 24.7% in 1993, and 54.0% and 25.2% in 2006, respectively. The density of *Limnodrilus* spp. and *B. vejdovskyanum* did not significantly vary between 1993 and 2006. The density of *T. tubifex* and *R. hiemalis*, however, decreased significantly during that period, by about one-fifth and one-seventh, respectively ($P < 0.01$, Wilcoxon U-test). The wet weight of *T. tubifex* and *R. hiemalis* also decreased significantly from 1993 to 2006 ($P < 0.01$, Wilcoxon U-test) (Table 2).

Figure 3 shows the horizontal distributions of the 4 dominant oligochaete species (*T. tubifex*, *Limnodrilus* spp., *B. vejdovskyanum*, and *R. hiemalis*) in 1993 and 2006. The population density of each oligochaete species differed among sampling stations and between sampling years. The most numerous

Table 2. Mean values and SDs of oligochaete data from the grid surveys.

Species name	5 March 1993				7 March 2006			
	Abundance (ind m^{-2})	%	Wet weight (g m^{-2})	%	Abundance (ind m^{-2})	%	Wet weight (g m^{-2})	%
Naidinae								
Slavina appendiculata (d'Udekem, 1855)	0	0.0	0	0.0	1 ± 3	0.06	0.1000 ± 0.0004	0.003
Rhyacodrilinae								
Bothrioneurum vejdovskyanum Štolc, 1886	472 ± 867	9.9	0.49 ± 0.90	1.9	128 ± 158	11.9	0.15 ± 019	5.6
Branchiura sowerbyi (Beddard, 1892)	0	0.0	0	0.0	17 ± 63	1.6	0.08 ± 0.29	2.9
Rhyacodrilus hiemalis Ohtaka, 1995	514 ± 350a	10.6	5.32 ± 350e	2.10	75 ± 71b	7.0	1.21 ± 1.11f	44.6
Tubificinae								
Tubifex tubifex (Müller, 1774)	3072 ± 3513c	54.8	17.84 ± 26.10g	70.0	580 ± 395d	54.0	0.50 ± 0.37h	18.4
Limnodrilus hoffmeisteri Claparède, 1862 *Limnodrilus claparedeianus* Ratzel,1868	1183 ± 1974	24.7	1.81 ± 3.04	7.1	271 ± 394	25.2	0.77 ± 1.03	28.5
Limnodrilus grandisetosus Nomura, 1932	6 ± 15	-	0.02 ± 0.06	0.1	0	0.0	0	0.0
Others	0	0.0	0	0.0	3 ± 7	0.24	0.004 ± 0.02	0.1
Total	5247±3873		25.47 ± 23.37		1075 ± 676		2.71 ± 1.73	

a-b, c-d, e-f, g-h: difference is significant, $P < 0.01$ (Wilcoxon U-test) species, *T. tubifex*, inhabited the entire lake bottom in both years, and this species was particularly abundant in the center and the western part of the lake, i.e. stations 13, 15, and 17, in 2006. However, in 1993, it was taken from the eastern part of the lake (stations 1 and 2). *R. hiemalis* had the widest distribution pattern in 2006 (except at station 1), especially in the western and northern parts of the lake, while *Limnodrilus* spp. was mostly found at the center of the lake. *B. vejdovskyanum* was most abundant in the western and southern parts of the lake. In 2006, the maximum number of *T. tubifex*, *Limnodrilus* spp., *B. vejdovskyanum*, and *R. hiemalis* reached 1615 ind m^{-2} at station 17 (depth: 11.8 m), 1644 ind m^{-2} at station 7 (depth: 8.4 m), 489 ind m^{-2} at stations 4 and 20 (depths: 9.3 m and 11.8 m), and 252 ind m^{-2} at station 20 (depth: 11.8 m), respectively. Another rare species, *Branchiura sowerbyi* Beddard, 1892, was found at stations 4-9 (depths of, less than 10 m, near the southeastern shoreline), and *Slavina appendiculata* (d'Udekem, 1855) was collected only at station 18 in 2006. On the other hand, in 1993, the maximum numbers of *T. tubifex*, *Limnodrilus* spp., *B. vejdovskyanum*, and *R. hiemalis* were 13,111 ind m^{-2} at station 2 (depth: 10.6 m), 5778 ind m^{-2} at station 13 (depth: 6.2 m), 3467 ind m^{-2} at station 9 (depth: 9.3 m), and 1111 ind m^{-2} at stations 10 and 21 (depths: 8.7 m and 10.6 m), respectively.

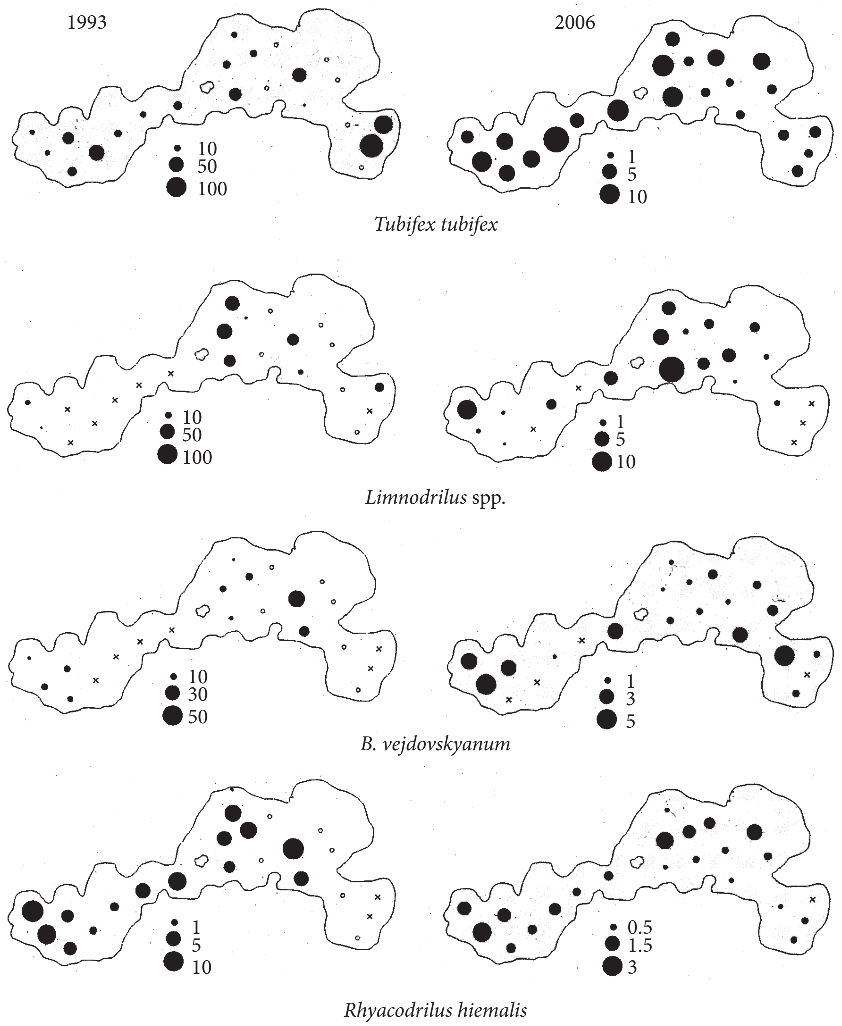

Figure 3. Horizontal distribution of the density of dominant oligochaetes in Lake Kawaguchi in 1993 and 2006. Dot size corresponds to the abundance at respective sampling points. All numbers must be multiplied by 100; x indicates a lack of oligochaetes. Note the different scales of abundance for 1993 and 2006.

Table 3 shows the correlation matrix for variables in the density of oligochaetes (*T. tubifex*, *Limnodrilus* spp., *R. hiemalis*, *B. vejdovskyanum*, *B. sowerbyi*, and *S. appendiculata*) as well as such environmental factors as water depth, DO, MT, and IL, in March 2006. The water depth showed a negative correlation with MT ($r = -0.68$, $P < 0.05$). The density of *T. tubifex* was closely related to the density of *R. hiemalis*. The density of *R. hiemalis* and DO showed a positive correlation. On the other hand, the density of *B. sowerbyi* and water depth, the density of *B. sowerbyi* and IL, and the density of *T. tubifex* and MT showed negative correlations.

Discussion

Although there have been some reports on aquatic oligochaete fauna in Japanese lakes, almost no reports have been made regarding mesotrophic-eutrophic lakes. This is the first report on the horizontal distribution of aquatic oligochaete fauna in Lake Kawaguchi. A total of 6 genera and 8 species belonging to 3 subfamilies were identified, including 1 species of Naidinae, 3 species of Rhyacodrilinae, and 4 species of Tubificinae (Table 2).

According to Hirabayashi et al. (2007), 2 naidine species, *Uncinais uncinata* (Ørsted, 1842) and *Pristina aequiseta* Bourne, 1891, were only collected from the shallower area, especially the sandy-mud bottom, of Lake Kizaki. Both species typically inhabit an aquatic plant zone (Brinkhurst and Jamieson, 1971). According to Nagasaka (2004), patchy *Elodea nuttallii* cover was observed in the shallower regions of Lake Kizaki as in Lake Kawaguchi, and the vertical growth limit of this species was approximately 6 m. In the present study we were unable to collect these species in Lake Kawaguchi. In regions shallower than 5 m, however, there were many kinds of submerged plants and a dominant species, *E. nuttallii* (Nagasaka et al., 2002), which provided important habitats for oligochaetes. Thus, it is necessary to investigate the distribution of aquatic oligochaetes in more detail in the shallower regions of this lake.

Similar oligochaete communities, in which *T. tubifex* and *L. hoffmeisteri* predominate, have been reported in the profundal zone of Japanese lakes. These lakes include mountainous lakes such as Lake Yunoko (1475 m above sea level; Ohtaka and Iwakuma, 1993; under the name of *Tubifex* sp.), Lake Ozenuma (1665 m above sea level; Ohtaka et al., 1998; under the name of *Tubifex* sp.), Lake Kizaki (764 m above sea level; Hirabayashi, 2007); deep lakes such as Ikeda (120 m in depth; Ohtaka et al., 2006), the north basin of Lake Biwa (103.8 m in depth; Ohtaka and Nishino, 1999); and high-latitude lakes such as Lake Akan (Ito, 1980) and Lake Onuma (Ito, 1978) in Hokkaido, in northern Japan. However, the composition of oligochaete fauna is not similar in typical shallow eutrophic lakes in central Japan, such as Lake Suwa (759 m above sea level; Yasuda and Okino, 1987), or in the littoral zone, the south basin, or the attached lakes of Lake

Table 3. Correlation matrix for the environmental variables and densities of oligochaetes in March 2006.

	DO	Mud temp.	IL	*S. appendiculata*	*T. tubifex*	*Limnodrilus* spp.	*B. vejdovskyanum*	*B. sowerbyi*	*R. hiemalis*
Depth	0.02	−0.68**	0.09	0.34	0.23	−0.31	0.05	−0.49*	0.07
DO		−0.34	−0.12	0.03	0.21	−0.14	0.23	0.01	0.51*
Mud temp.			0.25	−0.25	−0.43**	0.07	−0.15	0.11	−0.07
IL				−0.11	−0.13	0.06	−0.40	−0.79**	−0.14
S. appendiculata					0.07	−0.15	−0.18	−0.06	−0.05
T. tubifex						0.30	0.02	−0.24	0.49*
Limnodrilus spp.							−0.03	−0.06	0.01
B. vejdovskyanum								0.23	0.27
B. sowerbyi									−0.24

DO: dissolved oxygen, mud temp.: mud temperature, IL: ignition loss
*P < 0.05, **P < 0.01

Biwa (Ohtaka and Nishino, 1995, 2006), which are devoid of *Tubifex* species (Ohtaka and Iwakuma, 1993). Ohtaka and Kikuchi (1997) reported that *Limnodrilus* species, *R. hiemalis*, *Aulodrilus* species, and *B. sowerbyi* predominate in the profundal zones of these lakes. Although Lake Suwa, Lake Kizaki, and Lake Kawaguchi are at similar elevations, water temperature in the profundal zone rises to more than 20 °C in Lake Suwa during the summer (Yasuda and Okino, 1987), but less than 10 °C in Lake Kizaki. According to Hirabayashi et al. (2007), the average water temperature in the profundal zone of Lake Kawaguchi from 1993 to 2004 was less than 15 °C during the summer. Takada et al. (1992) and Narita (2006) reported that *R. hiemalis* burrows deep into the sediment (20-90 cm) and estivates during the summer in order to escape high temperatures. Thus, the bottom water temperature could be one of the most important factors in determining oligochaete composition.

The benthic macroinvertebrates of Lake Kawaguchi have been studied by various researchers (Miyadi, 1932; Kitagawa, 1973). We compared our results with previous data (collected during winter) on oligochaetes reported by Kitagawa (1973) in an attempt to clarify the relationship between eutrophication and the density of oligochaetes in Lake Kawaguchi (Table 4). Ohtaka and Iwakuma (1993) pointed out that Kitagawa (1973) may have recorded every oligochaete species as *Tubifex* sp. If the species described by Kitagawa as *Tubifex* sp. indeed represented total oligochaetes, a noticeable change has occurred in the mean density of total oligochaetes. Therefore, according to the present study, the density of total oligochaetes is tending toward an increase, in contrast with Kitagawa's studies. According to Yamanashi Prefecture authorities (1993), the extent of transparency has decreased since 1971 to about 3.5 m, due to the progression of eutrophication. According to Aizaki et al. (1981), this lake is ranked as a mesotrophic-eutrophic lake, using the modified Carlson's trophic state index based on chlorophyll-*a*, total phosphorus, and transparency. Recently, Hirabayashi et al. (2007) reported that *Peridinium bipes* showed explosive growth and formed a water-bloom in the early summer of 1995 when the nutrient levels in the water were very high, particularly the phosphate concentration. Moreover, Hirabayashi et al. (2008) recently found that *Propsilocerus akamusi* (Tokunaga, 1938) larvae were the most abundant chironomid species in Lake Kawaguchi, and the percentage of *P. akamusi* in the chironomid communities has increased. In general, *P. akamusi* larvae have dominated the eutrophic lakes of Japan (Iwakuma et al., 1988).

To summarize, in recent years, the total number of oligochaetes shows a tendency toward increase, in contrast to Kitagawa's studies. The increased levels of organic content in the upper sediment of Lake Kawaguchi suggest that eutrophication is an ongoing process. Although this lake was classified as mesotrophic-eutrophic in previous studies (Aizaki et al., 1981; Yamanashi Prefecture, 1993), this classification should be reconsidered in light of the circumstances mentioned above.

Table 4. Change in dominant oligochaetes in Lake Kawaguchi.

	Kitagawa (1973)	Present study	
	17 February 1973	5 March 1993	7 March 2006
Number of sampling points	12	22	22
Mean depth (m)	10.9 ± 3.3	10.6 ± 2.1	9.9 ± 2.2
Ignition loss of sediment (%)	no data	10.4 ± 2.4	15.8 ± 3.2
Total abundance of oligochaetes (ind m^{-2})	139 ± 156	5247 ± 3873	1075 ± 676

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