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Long-Term Eutrophication in Mesotrophic–Eutrophic Lake Kawaguchi, Japan, Based on Observations of the Horizontal Distribution of Profundal Chironomid Larvae and Oligochaetes

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Abstract

Many researchers have used the species composition, relative abundance and distribution pattern of profundal benthic macroinvertebrate communities in particular, especially chironomid fauna, as indicators of the trophic state and pollution of lakes. In addition, compared with previous benthic macroinvertebrate data, it is expected that the process of eutrophication/oligotrophication of lakes can also be traced. Benthic macroinvertebrate distribution was studied in Lake Kawaguchi, Japan (maximum depth 16.1 m; mean depth 9.3 m), on 7 March 2025. The benthic animals identified were aquatic oligochaetes, chironomid larvae, shellfish and others. Differences among environmental factors and zoobenthos densities and rank correlation were analyzed using a non-parametric test. The mean density of oligochaetes, which was the dominant group, was 2457 ± 1247 individuals/m^2, followed by chironomid larvae at 816 ± 391 individuals/m^2. The larvae of *Propsilocerus akamusi* were the most abundant species at 669 ± 358 individuals/m^2, followed by *Chironomus plumosus* at 109 ± 114 individuals/m^2. Other chironomids (38 ± 75 individuals/m^2) were also captured. Benthic communities were collected at all sites, but each taxa had its own characteristics. Oligochaetes and *C. plumosus* were widely distributed throughout the lake, whereas the distribution of *P. akamusi* was skewed toward the western part of the lake. In comparison with previous studies, *P. akamusi* larvae were now found to be the most abundant chironomid species in this lake, accounting for an increased percentage of the chironomid community, while *C. plumosus* larvae had decreased in recent years. In addition, the higher levels of organic matter in the upper sediment layer of the lake suggest ongoing eutrophication. Previous studies classified Lake Kawaguchi as mesotrophic–eutrophic, but reconsideration of this classification is warranted given the above findings. We suggest that this lake be ranked as a eutrophic lake (chlorophyll-a concentration; ca. 0.05 mg/L) based on a long-term investigation of the changes in chironomid fauna.

Keywords: bathymetric distribution; benthic macroinvertebrate; benthos; Chironomidae; *Chironomus plumosus*; Oligochaeta; *Propsilocerus akamusi*

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1. Introduction

Benthic macroinvertebrates are taxonomically and functionally diverse and play crucial roles in the lake ecosystem structure and functions [1–3]. Recently, detailed studies of Chironomidae fauna can yield a reliable tool to evaluate the effects of climatic change and

anthropogenic disturbances over freshwater ecosystems [4]. Moreover, these macroinvertebrates are also good bioindicators for ecological monitoring and assessment due to their sensitivities to different environmental conditions [5–9].

Lake Kawaguchi is located at the base of Mt. Fuji on its northern slope (35°31′ N, 138°45′ E at the lake center; altitude above sea level 832 m; shore length 17.4 km; surface area 5.96 km^2; maximum depth 16.1 m; mean depth 9.3 m). According to Yamanashi Prefecture [10], Lake Kawaguchi underwent a period of strong eutrophication from the 1960s to the 1970s. Water pollution was rapidly increasing due to the increase in the human population and the development of cultivated land along its shores. In 1986, the local government introduced an extensive sewer treatment system. Aizaki et al. [11], using the modified Carlson's trophic state index based on transparency, total phosphorus and chlorophyll-a, ranked Lake Kawaguchi as mesotrophic–eutrophic in 1981. Yamanashi Prefecture [10] reported that the dominant species of the phytoplankton community showed a major change from the late 1980s to the late 1990s, i.e., at the end of the 1980s, *Microsystes aeruginosa*, *Asterionella formosa*, *Melosira granulate* and *M. islandica* were the dominant species, but Yoshizawa et al. [12] reported that by the end of 1990s *Preidinium bipes, A. formosa*, *Fragilaria crotonensis* and *Cyclotella* spp. had become dominant. In 1993, the Yamanashi Prefectural government [10] reported that transparency in the lake had decreased to about 3.5 m as a result of eutrophication. Hirabayashi et al. [13] reported explosive growth and water-bloom formation of *Peridinium bipes* in the early summer of 1995, a time when nutrient levels in the water, particularly phosphorus, were very high. Nakamura et al. [14] reported an analysis of the transparency, COD, TN, TP and chlorophyll-a based on the monthly surface water quality observation data from 1974 to 2013 of the Fuji Five Lakes by Yamanashi Prefecture. Although the surface water quality of Lake Kawaguchi had been growing significantly worse over time, a recovery trend was seen from 2002 to 2013.

Following an early study by Terao [15], a number of researchers have examined the biota of Lake Kawaguchi. However, its macro-benthic fauna has attracted less attention. In a review, Lindegaard [16] stated that researchers have used indicators including species composition and the relative abundance and distribution pattern of benthic macroinvertebrate communities, particularly chironomid fauna in the profundal zone, to assess the trophic state and pollution of lakes. Lake Kawaguchi has been changing biotically and environmentally since the mid-1990s, and this has affected the bottom fauna, especially the dominant chironomids. We examined the horizontal distribution of benthic macroinvertebrates in Lake Kawaguchi and compared chironomid fauna and density in this and past studies, and here, discuss changes in the chironomid community as they relate to the trophic status of the lake.

2. Materials and Methods

2.1. Study Site

Lake Kawaguchi was formed when lava flows from Mt. Fuji and other volcanoes dammed streams flowing down from the northern mountain ranges. These ranges have many porous volcanic deposits so that most of the runoff water flows underground, but there are surface streams as well. The lake is partly surrounded by cultivated land on its eastern shore and some towns and villages on the north-eastern and south-eastern shores. Ice covers the lake from January to February, and there is a persistent thermocline in summer [13].

Yamanashi Prefecture [17] reported an analysis of COD, chlorophyll-a, total nitrogen, total phosphate and the transparency based on the monthly surface water quality observation data for Lake Kawaguchi from 2000 to 2022 available online. We modified these data

and present them in Figure 1. COD, chlorophyll-a and TN were not significantly changed, but TP had tended to increase since 2018, while transparency has decreased recently.

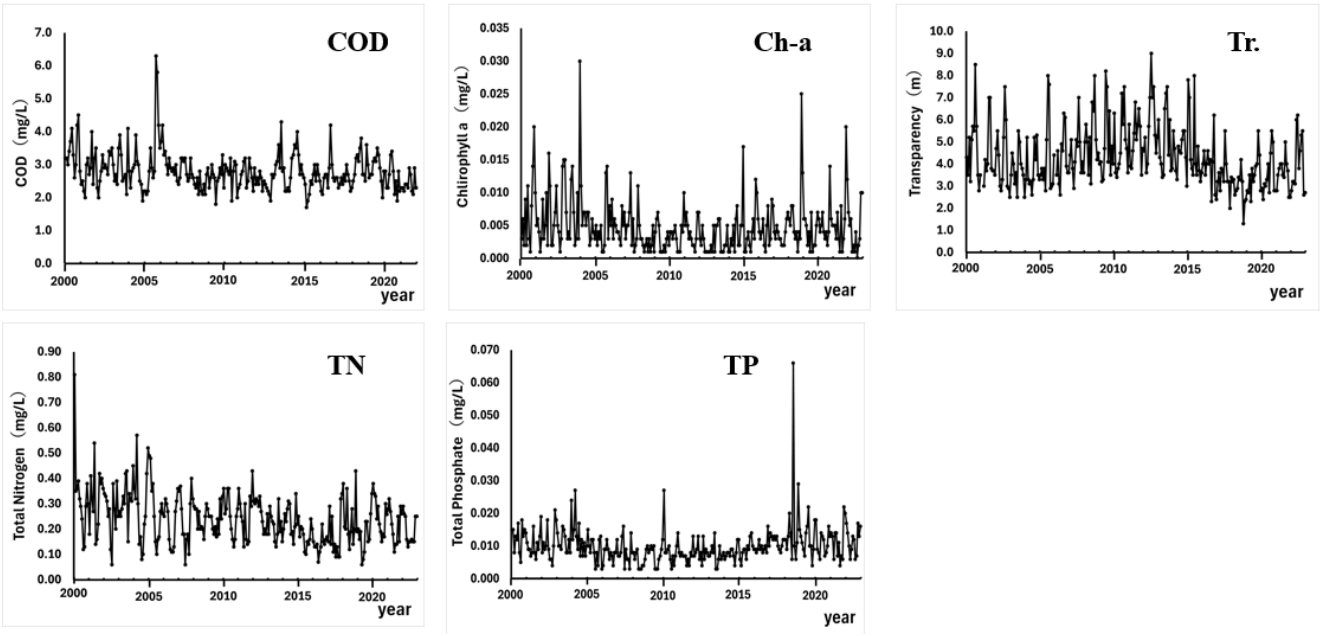

Figure 1. Annual changes in COD, chlorophyll-a, total nitrogen, total phosphate and transparency at the lake center from April 1998 to March 2023 in Lake Kawaguchi. Yamanashi Prefecture [17].

2.2. Methods

Chironomid larvae are most efficiently sampled from late autumn to early spring, when almost all stay near the sediment surface. The larvae of *P. akamusi* burrow deep into the lake bottom sediments, ca. more than 50 cm, to aestivate during the summer [18,19]. We conducted a multi-point sampling survey on 7 March 2025, using a standard Ekman-Birge grab (15 × 15 cm, Rigosha, Tokyo, Japan). Samples were taken at each of 20 locations (7.2–13.3 m depth) in a ca. 800 × 800 m grid (Figure 2). A global positioning system (GPS) was used to record the sampling sites. The sediment was sieved through a Surber net (NGG 38; 560 μm mesh size, Rigosha, Tokyo, Japan), after which benthic macroinvertebrates were separated out roughly and counted in the laboratory. The 560 μm mesh sieve might not have captured the first and second instar larvae of small chironomids and small oligochaetes completely. To verify, small chironomid larvae and oligochaetes were picked out from the sediment again and counted using a binocular microscope (magnification of 10× and 20×, Olympus, Tokyo, Japan), after which all samples were stocked in glass bottles with a 10% formaldehyde solution. To identify the obtained chironomids, we soaked some of the larvae in a 10% KOH solution (Wako Pure Chemical Industries, Ltd., Osaka, Japan), mounted them on slides with gum-chloral solution, and examined them under a microscope at 100×, 200× and 400× magnification. Identification was performed to the generic level using the keys of Cranston [20] and Wiederholm [21]. To identify them to the species level, the keys of Orendt and Spies [22] and Sasa [23] were used.

Samples of bottom sediment for use in organic matter analysis were collected with a core sampler (three cm inner diameter, Rigosha, Tokyo, Japan). The upper 3 cm layer of mud in each core was oven-dried at 110 °C for two days. Then, to determine the value of loss on ignition (IL), it was ignited in a muffle furnace at 550 °C for two hours. The dissolved oxygen concentrations (DO) in the water at the mud–water interface were also measured using the core sampler. The water near the mud surface in the core sampler (which remained above the sediment in the core sampler when it was pulled from the

water) was siphoned carefully into a glass bottle. The dissolved oxygen concentration was measured using Wikler's method with azide modification. A thermistor thermometer was used to measure the water temperature (WT) in the bottom sediment samples.

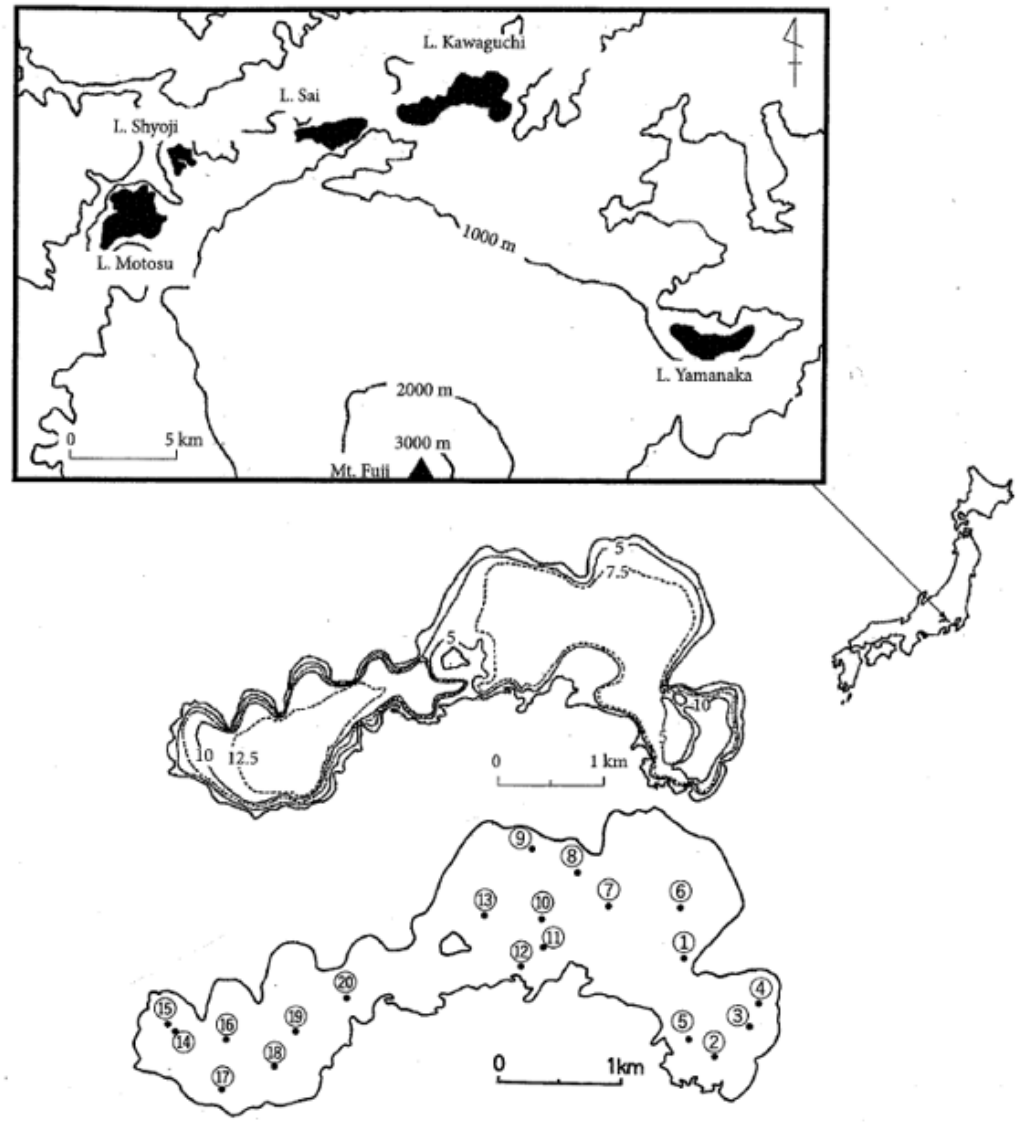

Figure 2. Maps showing location of Lake Kawaguchi, isopleths of depth (m) and sampling sites from ① to ⑳.

The results of a normality test indicated that our dataset did not have a normal distribution and did not have homoscedasticity. Therefore, a non-parametric test was used. Differences among environmental factors and zoobenthos densities were analyzed using Mann–Whitney's U-test. The Kendal rank correlation test was used to examine correlations between benthic macroinvertebrate densities and environmental variables including depth, IL, WT and DO, using the Nap Ver. 4 statistical package (Igaku-Shoin, Tokyo, Japan).

3. Results

Among environmental factors, the mean values and standard deviations were 10.0 ± 1.9 m for water depth (ranging from 7.2 m to 13.3 m), 5.4 ± 0.4 °C for WT and 9.6 ± 0.6 mg/L for DO, respectively. The differences in DO and WT were small among the sampling sites, indicating that the spring cycle period had begun. The content of organic matter in the sediment's surface layer (IL) was $16.4 \pm 2.0\%$ (ranging from 12.9% to 19.9%)

for the entire lake, which was relatively high. The lake basin consists mostly of soft bottoms with more than 15% organic matter content. The inlets in the eastern part (sampling sites 1, 2 and 3) and western part (site 15) of the lake had the highest levels (Figure 3).

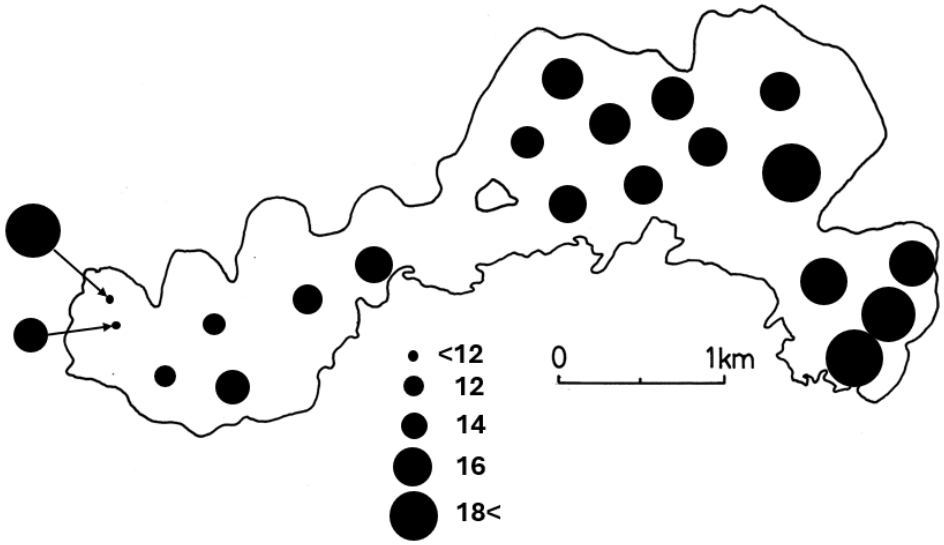

Figure 3. Horizontal distribution of organic matter content in the sediment surface layer of Lake Kawaguchi, March 2025.

The benthic animals identified in this survey were aquatic oligochaetes, chironomid larvae, shellfish and others. The mean density of oligochaetes, which was the dominant group, was 2457 ± 1247 individuals/m^2, followed by that of total chironomid larvae at 816 ± 391 individuals/m^2. Chironomidae species belonging to two subfamilies, Chironominae and Orthocladiinae, were identified. The larvae of *Propsilocerus akamusi* were the most abundant species of the chironomid fauna at 669 ± 358 individuals/m^2, followed by *Chironomus plumosus* at 109 ± 114 individuals/m^2. Other chironomids (38 ± 75 individuals/m^2) were also captured. Benthic communities were captured at all stations, but each taxa had its own characteristics.

Figure 4 illustrates the bathymetric distribution of the density of oligochaetes and chironomid larvae, which were collected at all sampling sites. Oligochaetes were present at higher densities in the western part of the lake (sampling sites 14, 15 and 17) and at the center of the lake (sites 7, 9 and 12). The densities differed between the sites, with the maximum density of 5200 individuals/m^2 (sampling site 12; 8.4 m depth) measured about 250 m from the south shore of the lake. Chironomid larvae also inhabited the entire lake bottom, with higher densities in the eastern and western parts of the lake (sampling sites 2 and 20). *P. akamusi* had the widest depth distribution (from 7.2 to 13.3 m in depth), followed by *C. plumosus* (from 7.4 to 13.3 m in depth) (Figure 4). The maximum density of *P. akamusi* was as high as 1422 individuals/m^2 (sampling site 2; 10.0 m depth), measured about 150 m from the south-eastern shore of the lake, followed by sites 19 and 20, with the same value of 1289 individuals/m^2 in the center of the lake. The distribution of *P. akamusi* was skewed toward the western part of the lake. The maximum density of *C. plumosus* was as high as 444 individuals/m^2 (sampling site 8; 9.0 m depth), measured about 250 m from the northern shore of the lake. At sampling sites 2, 3, 5, 10 and 11, *C. plumosus* was not collected from the bottom samples.

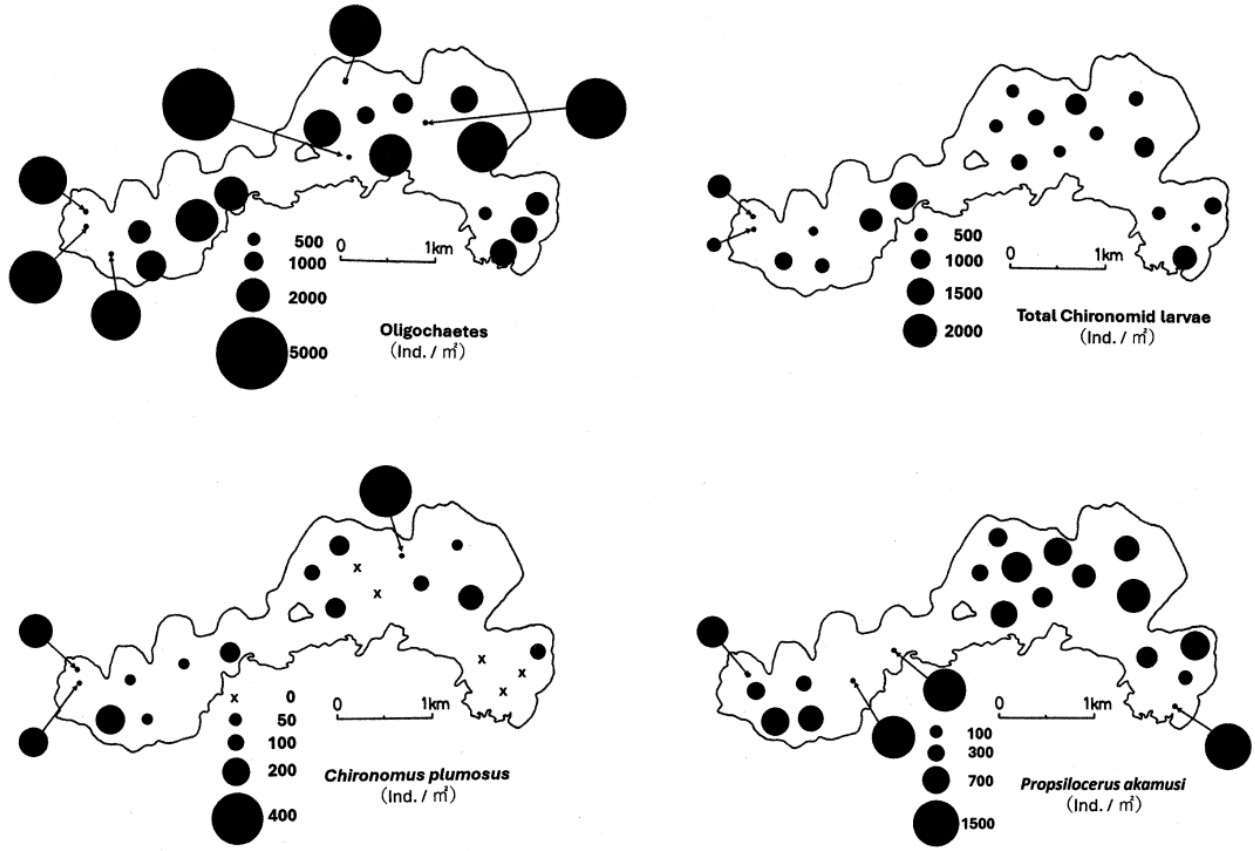

Figure 4. Bathymetric distribution of the density of oligochaetes, total chironomid larvae, *C. plumosus* and *P. akamusi* in lake Kawaguchi on 7 March 2025. Dot size corresponds to abundance at each sampling site. Multiply all numbers by 100. x indicates no chironomid larvae.

Table 1 presents correlation matrices of the densities of oligochaetes (Oli), total chironomid larvae (T-Ch), *P. akamusi* (PA), *C. plumosus* (CP), and environmental factors. The *P. akamusi* density was positively correlated with total chironomid density.

Table 1. Correlation matrix of benthic macroinvertebrate densities and environmental variables in Lake Kawaguchi on 7 March 2025, based on Kendall's rank correlation.

	Depth	**WT**	**DO**	**IL**	**T-Ch**	**Cp**	**Pa**	**Oli**
Depth	-	−0.74	−0.25	−0.41	0.30	0.03	0.35	−0.03
WT		-	0.04	0.41	−0.24	−0.27	−0.16	−0.11
DO			-	−0.08	−0.41	−0.02	−0.48	−0.08
IL				-	0.20	−0.01	0.20	−0.14
T-Ch					-	0.38	0.93 **	0.05
Cp						-	0.06	0.27
Pa							-	−0.02
Oli								-

** $p < 0.01$. DO, dissolved oxygen concentration; IL, ignition loss (organic matter content); WT, water temperature; Oli, density of oligochaetes; T-Ch, density of total chironomids; Cp, *Chironomus plumosus*; Pa, *Propsilocerus akamusi*.

4. Discussion

Species composition and the relative abundance and distribution pattern of benthic macroinvertebrate communities, particularly in the profundal zone, have been used by many researchers as indicators of the trophic state and pollution of lakes (reviews by Brinkhurst [24]; Lindegaard [16]). Chironomid fauna and chaoborids have been used in trophic classifications of Japanese lakes [25–27]. According to Iwakuma et al. [28],

C. plumosus and *P. akamusi* are common in eutrophic lakes in Japan. An attempt was made to compare the results of this study with previous Lake Kawaguchi studies [29–32] (Table 2), but the different sampling seasons among the reports, especially between ours and Miyadi [29] and Kitagawa [30], makes discussion of the long-term change in chironomid fauna in this lake difficult. On the other hand, our survey and the Hirabayashi et al. [31,32] surveys were conducted in the same season and with the same methods. Thus, the results can be simply compared.

Table 2. Changes in dominant chironomid fauna, Lake Kawaguchi.

	Miyadi [29]	**Kitagawa [30]**	**Hirabayashi et al. [31]**	**Hirabayashi et al. [32]**	**Present Study**
	2 May 1931	**17 February 1973**	**5 March 1993**	**7 March 2006**	**7 March 2025**
No. of sampling points	16	12	22	22	20
Mean depth (m)	10.1 ± 1.3	10.9 ± 3.2	10.6 ± 2.1	9.9 ± 2.2	10.0 ± 1.9
Ignition loss of sediment (%)	-	-	10.4 ± 2.4	15.8 ± 3.2	16.4 ± 2.0
Total Chironomid density (Ind./m^2)	429 ± 317	885 ± 384	1256 ± 661	474 ± 418 *	816 ± 391
C. plumosus (Ind./m^2)	75 ± 102	593 ± 258	341 ± 182	97 ± 96 *	109 ± 114
(%)	17.4	66.9	27.2	20.5 *	13.3
P. akamusi (Ind./m^2)	0	259 ± 149	634 ± 280	335 ± 257	669 ± 358
(%)	0	29.2	50.5	70.7	82.0
Oligochaeta (Ind./m^2)	1258 ± 500	139 ± 150	5489 ± 2769	1135 ± 717	2457 ± 1247
(%)	74.6	13.6	81.4	70.5	75.1

* According to Hirabayashi et al. [32], many pupae were collected, indicating an imminent emergence period of *C. plumosus* and possibly causing underestimate of *C. plumosus* abundance.

The results of this study show that the mean value of organic matter in the upper sediment layer has increased since Hirabayashi et al. [31]. Compared to 2006 (19 years ago; [32]), the density of *C. plumosus* was almost the same, whereas there was a decrease of one third compared with 1993 (32 years ago; Hirabayashi et al. [31]). Moreover, comparative analysis revealed a decrease in the percentage of *C. plumosus* larvae in the chironomid community since Kitagawa [30], i.e., 13.3% in the present study. However, the density of *P. akamusi* had doubled since 2006, whereas compared to 1993, the density of *P. akamusi* was almost the same. The percentage of *P. akamusi* larvae in the chironomid community increased over time, from 29.2% (1973) and 50.5% (1993) to 70.7% (2006) and 82.0% (2025). In this study, *P. akamusi* larvae were the most abundant chironomid species. The density of oligochaetes had doubled since 2006 but was less than half compared with 1993. No noticeable change has occurred in the percentage of oligochaetes among the benthic macroinvertebrates since 1931, except in 1973, ranging from 70.5% to 81.4%. According to Yamanashi Prefecture [10] and Yoshizawa et al. [12], the dominant species in the phytoplankton community showed major changes from the late 1980s to the late 2000s. Lindegaard [16] reported that the factors determining the chironomid assemblages in lakes involved an interaction primarily between the quality and quantity of food and the summer oxygen conditions. The available food originates exclusively from precipitating organic matter produced in the photic zone. Food is more abundant in eutrophic lakes and within the tube. Thus, larvae of the *C. plumosus* type (e.g., *P. akamusi* and *C. plumosus*) often dominate in a shallow eutrophic lake such as Lake Kawaguchi. Devai and Moldovan [33] were able to correlate the chironomid fauna with a trophic gradient measured as the organic content in the sediment of the shallow Hungarian Lake Balaton: the higher the proportion of larvae of the *C. plumosus* type (in this case, *Chironomus balatonicus*), the higher the carbon content in the sediment. Recently, the chironomid community has had an increased percentage of *P. akamusi* larvae and a decreased percentage of *C. plumosus*. Increased organic matter in the upper sediment layer

is also seen. Iwakuma and Yasuno [19] report that high temperature and low oxygen concentrations are unfavorable for *C. plumosus* larvae. However, mature *P. akamusi* larvae can withstand anoxic conditions, especially during the summer, by burrowing deep into the sediment to aestivate [18]. Zou et al. [34] reported *P. akamusi* presented extremely low fuel consumption at a state of estivation when the larvae dwelt in deep sediment and conducted anaerobic respiration, with ethanol as a major metabolite, to withstand long-term anoxic conditions. Additionally, the abundance of *P. akamusi* correlated positively with most nutrient-related variables, indicating that this species can serve as sentinel organisms of nutrient enrichment. Nakamura et al. [14] reported that the water quality of Lake Kawaguchi had been recovering since 2002, but the fact that the percentage of *P. akamusi* larvae, which is an indicator species of eutrophication [28], in the chironomid community has increased from 1993, suggests increased eutrophication of this water body.

5. Conclusions

To summarize, in recent years, the most abundant chironomid species in Lake Kawaguchi has been *P. akamusi* larvae, which is an indicator species of eutrophication [28], and the chironomid community has shown an increased percentage of *P. akamusi* and a decreased percentage of *C. plumosus* larvae. In addition, the increased levels of organic matter in the upper sediment layer of Lake Kawaguchi suggest ongoing eutrophication. Although previous studies classified this lake as mesotrophic–eutrophic [10,11], reconsideration of this classification is warranted given the findings of this study. We suggest that this lake be ranked as a eutrophic lake based on the long-term investigation of the changes in chironomid fauna.

Author Contributions: Conceptualization, K.H.; methodology, K.H.; software, K.H.; validation, K.H.; formal analysis, M.T.; investigation, K.H. and M.T.; resources, K.H.; data curation, K.H.; writing—original draft preparation, K.H.; writing—review and editing, K.H.; visualization, K.H. and M.T.; supervision, K.H.; project administration, K.H. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Primary data (COD, chlorophyll-a, total nitrogen, total phosphate, transparency) of Lake Kawaguchi (Water quality data) are available from downloading. Yamanashi Prefecture, Japan: Water quality data in the Fuji Five Lakes. https://www.pref.yamanashi.jp/taiki-sui/sokutei.html, accessed on 20 October 2025.

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Conflicts of Interest: The authors declare no conflicts of interest.

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