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Original Article

Long-Term Dynamics of Freshwater Red Tide in Shallow Lake in Central Japan

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Abstract

Objective: The aim of this study is to clarify the long-term dynamics of the red tide occurring in Lake Kawaguchi.

Methods: The measurement of environmental factors and water sampling were carried out monthly at a fixed station in Lake Kawaguchi's center basin from April 1993 to March 2004. On June 26, 1995, the horizontal distribution of *Peridinium bipes* was investigated using a plastic pipe, obtaining 0~1-m layers of water column samples at 68 locations across the entire lake.

Results: *P. bipes* showed an explosive growth and formed a freshwater red tide in the early summer of 1995, when the nutrient level was higher than those in the other years, particularly the phosphate concentration in the surface layer. The dissolved total phosphorus (DTP) concentration was sufficient for *P. bipes* growth in that year. In the study of its horizontal distribution, *P. bipes* was found at all the locations. The numbers of cells per milliliter ranged from 67 to 5360, averaging 1094±987 cells/ml, with particularly high densities along the northern shore. Since then, *P. bipes* has annually averaged about 25 cells/ml in Lake Kawaguchi.

Conclusion: We observed that the red tide caused by *P. bipes* correlates with a high DTP concentration in Lake Kawaguchi.

Key words: freshwater red tide, Lake Kawaguchi, long-term dynamics, *Peridinum bipes*

Introduction

The deterioration in the quality of water in general and in that of drinking water specifically, because of anthropogenic pollution (1) and biological activities (2, 3), is occurring on a global scale (reviewed by Wetzel (4)). In many cases, the deterioration in the quality of water has caused a marked increase in the number of specific organisms in aquatic ecosystems (5–8). In recent years, the presence of the algae causing water bloom with progressive eutrophication in freshwater has become a social problem (9, 10). In Japan, water bloom, so-called freshwater red tide has recently been observed in many reservoirs; however, there have been few reports on water bloom in natural lakes (11–15). In most cases, freshwater red tide is caused by the dinoflagellate *Peridinium*, a well-known typical phytoplankton of red tide in reservoirs, lakes and ponds (9, 10). The degree of bloom of this species often reaches drastic proportions, discolouring the lake and creating a nuisance to water users. The bloom has important economic implications from the viewpoint of the intensive use of lakes for fishery (red tide causes large mortalities of fish and other freshwater organisms together with a decrease in the number of fish caught for months or more), for recreation, and above all as the main reservoir for drinking water. Moreover, a toxic freshwater bloom of *Peridinium polonicum* was reported in September 1962 in Lake Sagami, and the toxic substance glenodinine has been isolated from *P. polonicum* (16). This toxic freshwater bloom might have caused the deaths of domestic animals and wildlife in addition to human illness, thereby posing a threat to public health. In Lake Kizaki, which is a natural lake, *Peridinium bipes* (Dinophyceae) grew explosively and caused a freshwater red tide in the autumn of 1986. It was the first report on a freshwater red tide in a natural lake in Japan (17–19).

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In countries around the world, the few freshwater red tides of dinoflagellates reported in natural lakes have included those caused by *Peridinium cinctum* in Lake Kinneret in Israel (20–23), and by *Peridinium penardii* in Lake Clear in the USA (24). In many cases, the mass propagation of the dinoflagellate *Peridinium* results from eutrophication caused by nutrients such as nitrogen and phosphorus; however, some reports have indicated the roles of organic nutrients and trace elements, e.g., Ca, and much remains unclear (25, 26). Moreover, the physiological characteristics of the species and its relationships with other organisms (coaction) have also been considered (27–31).

Lake Kawaguchi is one of the Fuji Five Lakes (i.e., L. Yamanaka, L. Kawaguchi, L. Sai, L. Shoji and L. Motosu), which are especially loved by Japanese people for their beautiful scenery (Fig. 1). More than 22 million tourists visit these lakes and Mt. Fuji annually (32). Recently, eutrophication has been occurring in Lake Kawaguchi (33). An explosive growth of *P. bipes* caused a freshwater red tide there in the summer of 1995. In this paper, we clarify the dynamics triggering the occurrence of red tide in Lake Kawaguchi. In addition, we report the results of monitoring *P. bipes* at the lake's center, with a discussion of the succession of *P. bipes* in association with changes in the lake's environment.

Study area

Lake Kawaguchi (the center of the lake, 35°31'N, 138°45'E; surface area, 5.96 km^2; maximum depth, 16.1 m; mean depth, 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 coming down from the northern mountain ranges. The lake has an inflowing river, i.e., the Terakawa River, but lacks outflowing rivers (Fig. 1). In its drainage basin, where porous volcanic deposits prevail, 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 its northeastern and southeastern shores. The lake is ice-covered from January to February and has a persistent thermocline in summer. Aizaki et al. (34) considered this to be a eutrophic-mesotrophic lake using the modified Carlson's trophic state index based on chlorophyll-a and total phosphorus concentrations and transparency.

Materials and Methods

1. Collection of P. bipes at monitoring station

The measurement of environmental factors and water sampling were carried out monthly, except during the ice-covered period, at a fixed location (10.0 m max. depth) in the center basin (Fig. 1) from April 1993 to March 2004. Water temperature was vertically measured with a thermometer at 1 m intervals from the surface to the bottom of the lake, and transparency was measured with a Secchi disk. Lake water was collected with a Van-Dorn sampler at depths of 0, 2, 6 and 9 m for the measurement of total nitrogen (TN), dissolved total nitrogen (DTN), total phosphorus (TP) and dissolved total phosphorus (DTP) concentrations (35). *P. bipes* samples were also collected at these water depths and fixed with a glutaraldehyde solution. Cells were counted under a microscope. The measurement of

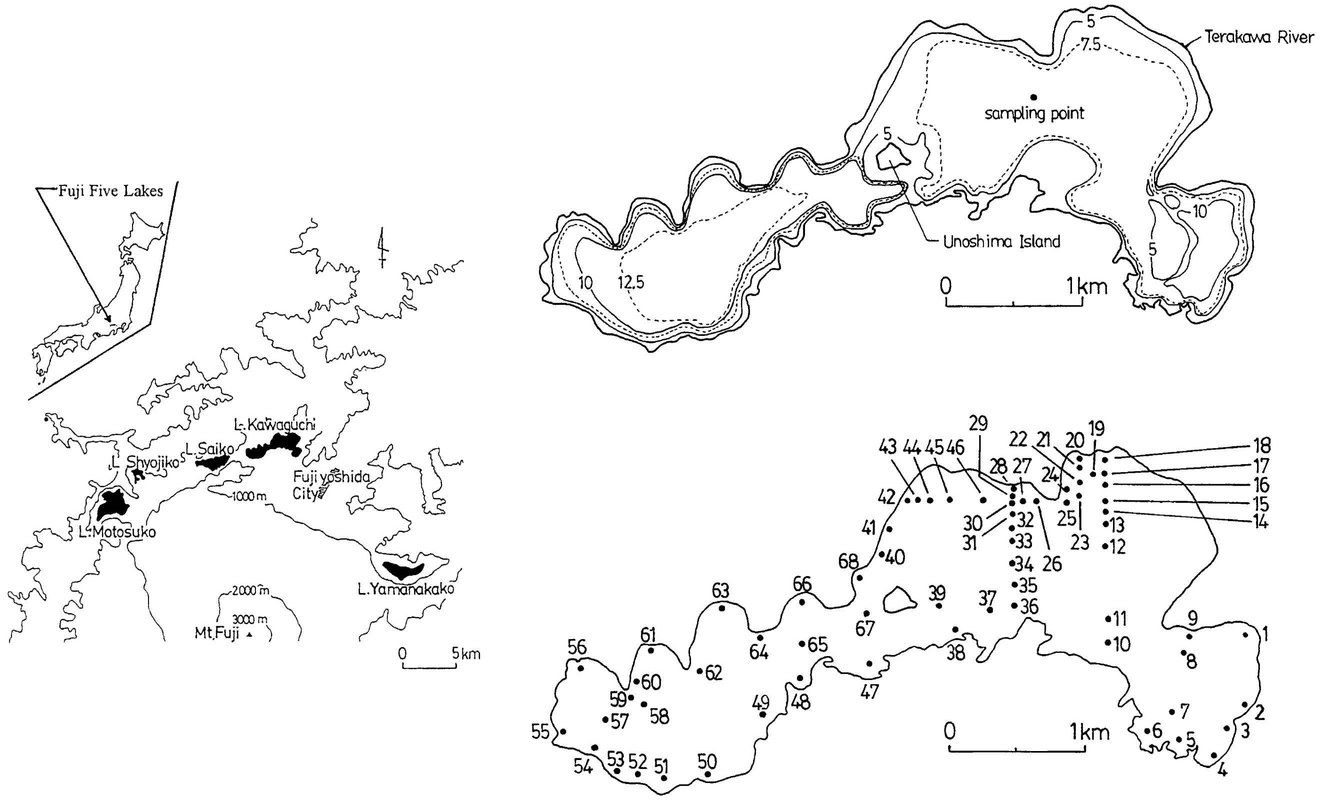

Fig. 1 Maps showing location of Lake Kawaguchi, isopleths of depth (m), and sampling stations in th lake.

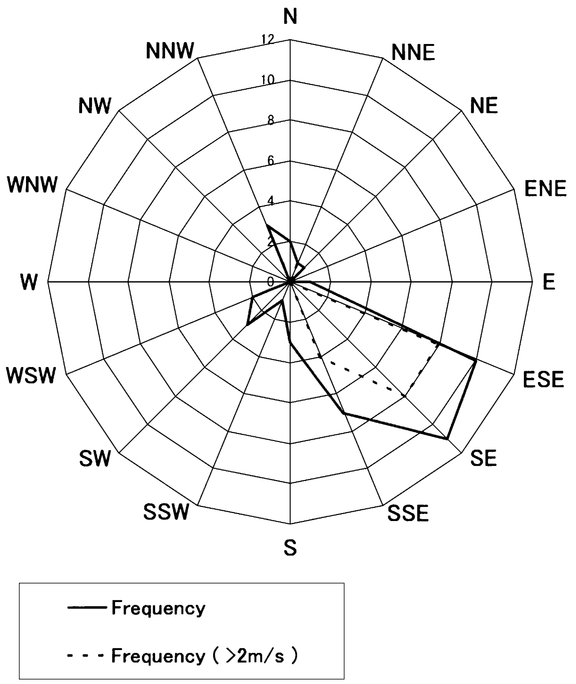

Fig. 2 Wind rose in Lake Kawaguchi from June 24 to June 25, 1995.

TN, DTN, TP and DTP concentrations was carried out monthly at the River Terakawa during the same investigation periods.

2. Horizontal distribution of P. bipes in surface water column

On June 26, 1995, the horizontal distribution of *P. bipes* was investigated using a plastic pipe (1 m in length, 3 cm in diameter), taking 0~1-m layers of water columns sample at 68 locations across the entire lake (Fig. 1). The water temperature, pH, electric conductivity and ORP (oxidation–reduction potential) of the 0~1-m layers of water column samples were measured with a thermometer and an electrode. *P. bipes* samples were also collected at these water depths and fixed with a glutaraldehyde solution, and then *P. bipes* cells were counted under a microscope in the laboratory. Data on wind direction and velocity (m/s) of the Kawaguchiko Meteorological Observatory Station were used from June 24 to June 25, 1995 (before 48-h investigation day). The wind velocity is shown in Fig. 2.

Results and Discussion

1. Annual changes in environmental factors (i.e., transparency, water temperature, and DTN and DTP concentrations) and number of P. bipes cells.

The transparency, which fluctuated between 1.8 and 8.1 m, was higher in summer and fall than in winter and spring, and showed different patterns between 1998 and 2000. Transparency decreased in 1994–1997 and 2001–2004, but increased in 1998–2000 (Fig. 3). The annual variation in the water temperature of the 0-m layer was high (minimum 1.7°C in February 1997, maximum 26.8°C in August 1995) compared with that of the bottom layer, where water temperature varied between 2.4°C in February 1994 and 23.5°C in August 1996. Stratification occurred and a thermocline developed at depths of about 6 m in the summer of every year, but the differences in water temperature between the 0- and 9-m layers were small in July and August of 1997, i.e., 3.6 and 3.7°C, respectively.

The mean TN and TP concentrations in all the layers during the investigation periods were 0.28±0.07 mg/L and 0.0149±0.0004 mg/L, respectively. The TN:TP ratio was about 20, suggesting that Lake Kawaguchi is either a mesotrophic or eutrophic lake with limited phosphorus (Table 1). Particularly from 1993 to 1997, the TN:TP ratio decreased from 25 to 12, showing progressive eutrophication due to the increasing phosphorus concentration. However, after that, the ratio was the same as that in 1993, i.e., ca. 20. On the other hand, the annual mean TN and TP concentrations in the Terakawa River were 1.25±0.34 mg/L and 0.0695±0.0375 mg/L, respectively, much higher than those at the monitoring station; the TN concentration was 4.5-fold higher and the TP concentration was 4.7-fold higher. The TP concentrations in the Terakawa River in 1995 and 1996 were ca. twofold higher than the annual mean TP concentration in the Terakawa River from 1993 to 2004 (Table 1). The DTN concentration in all the layers at the monitoring station was ca. 0.2 mg/L during the investigation periods. The DTN concentration, on the other hand, was several fold higher than that in 9-m layer in August 1995. In all the layers in

Table 1 Annual changes in TN and TP concentrations, and TN:TP ratio at monitoring station in Lake Kawaguchi and in Terakawa River

Year	Total nitrogen concentration (mg/L)		Total phosphorus concentration (mg/L)		TN:TP
	Lake center (n)	River Terakawa (n)	Lake center (n)	River Terakawa (n)	Lake center
1993	0.35±0.08 (48)	1.20±0.19 (12)	0.0140±0.0023 (48)	0.0478±0.0177 (12)	25.0
1994	0.29±0.06 (48)	1.31±0.39 (12)	0.0143±0.0019 (48)	0.0828±0.0445 (12)	20.3
1995	0.34±0.08 (44)	1.72±1.21 (11)	0.0187±0.0072 (44)	0.1549±0.1505 (11)	18.2
1996	0.22±0.03 (48)	1.56±0.48 (12)	0.0171±0.0036 (48)	0.1014±0.0511 (12)	12.9
1997	0.25±0.05 (48)	1.21±0.30 (12)	0.0200±0.0046 (48)	0.0980±0.0426 (12)	12.5
1998	0.41±0.13 (48)	1.22±0.42 (12)	0.0169±0.0043 (48)	0.0635±0.0185 (12)	24.3
1999	0.33±0.10 (48)	1.23±0.25 (12)	0.0127±0.0018 (48)	0.0660±0.0319 (12)	26.0
2000	0.26±0.05 (48)	1.10±0.48 (12)	0.0144±0.0040 (48)	0.0398±0.0227 (12)	18.1
2001	0.18±0.04 (48)	0.55±0.28 (12)	0.0077±0.0022 (48)	0.0329±0.0102 (12)	23.4
2002	0.20±0.03 (44)	0.93±0.28 (11)	0.0102±0.0023 (44)	0.0475±0.0303 (11)	19.6
2003	0.25±0.09 (40)	1.70±0.74 (10)	0.0092±0.0064 (40)	0.0300±0.0516 (10)	27.2
Mean±SD	0.28±0.07	1.25±0.34	0.0149±0.0004	0.0695±0.0375	19.8±5.9

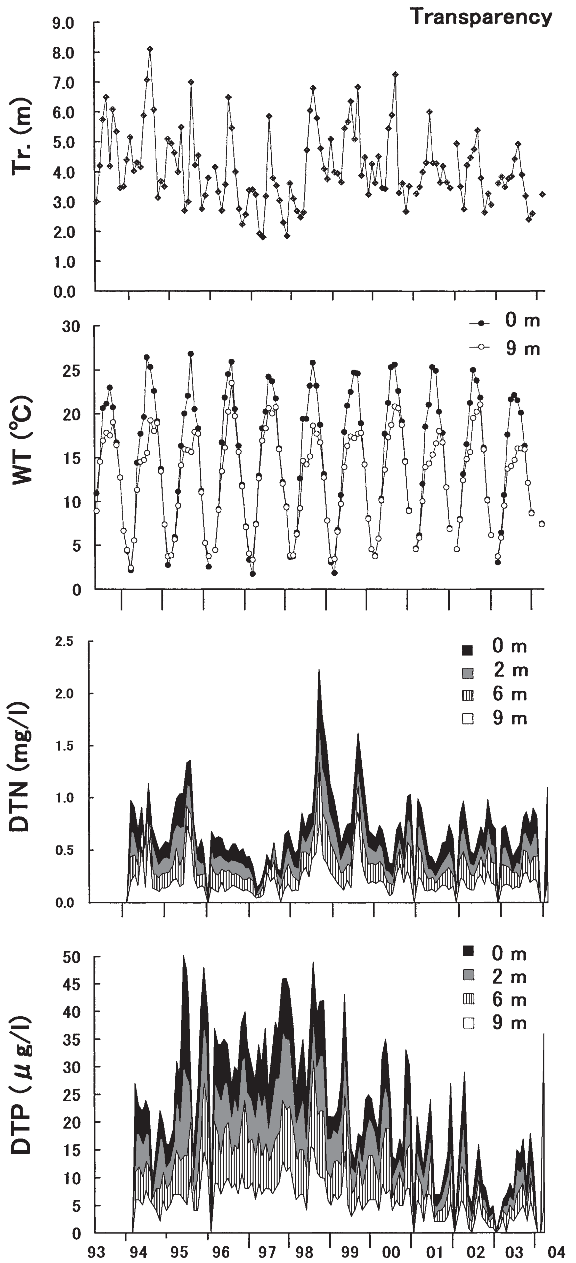

Fig. 3 Annual changes in transparency, water temperature (0 m and 9 m), and DTN and DTP concentrations at the monitoring station from April 1993 to March 2004. (Note: DTN and DTP concentrations from April 1994 to March 2004.)

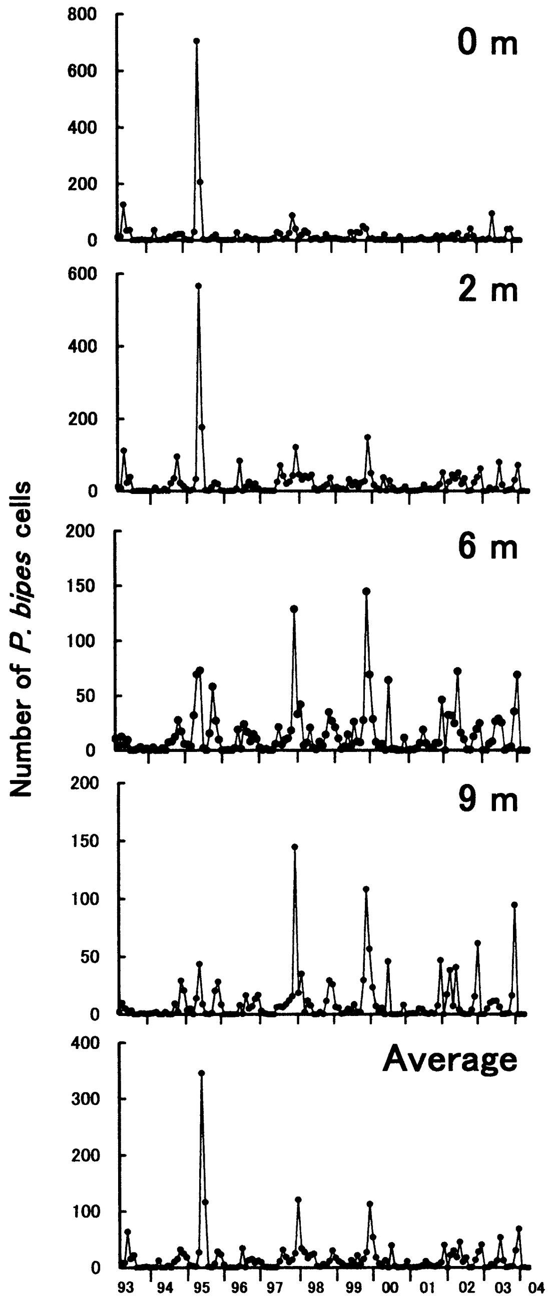

Fig. 4 Annual changes in number of *P. bipes* cells per milliliter at the monitoring station from April 1993 to March 2004.

October 1998 and September 1999, the DTN concentration was 0.8 mg/L at 9 m (Fig. 3). DTP concentration showed a rapid increase from 1994 to 1995, maintaining a high value from 1995 to 1999, but then decreasing after 2000. During the investigation periods, the maximum concentration of DTP was 0.02 mg/L at 0 m in June and July 1995. These concentrations were threefold higher than the annual mean DTP (0.006 mg/L).

Figure 4 shows the annual changes in the number of *P. bipes* cells at the monitoring station (0, 2, 6, and 9 m). During the investigation periods, the maximum number of *P. bipes* cells per milliliter was 705 in the 0 m layer (mean cell number in all layers, 346 cells/ml) in June 1995, when they caused a freshwater red tide. Since then, *P. bipes* has maintained about 25 cells/ml, but with several small peaks in January 1998 (120.6 cells/ml) and December 1999 (113.2 cells/ml).

The dinoflagellate *Peridinium* was earlier reported to be present in this lake in 1971 (33). The freshwater red tide of May 1982 was also caused by *Peridinium*, with high densities along the northern shore of this lake, showing the same pattern as that in our previous study (33). There have been many reports on the relationship between environmental factors (particularly certain nutrients) and the dramatic growth of *Peridinium* so as to cause a freshwater red tide (reviewed by Ishida (36)). Hata (14, 37) reported that NO_3-N and PO_4-P are used as nitrogen and phosphorous sources, respectively. According to Watanabe (38), NO_3-N is used as the nitrogen source for *P. penardii*, but urea is effective for mass propagation. Ikeda et al. (39) later reported that phosphorus is the primary growth-limiting factor controlling the annual frequency of red tide blooms of *P. bipes* in reservoirs on the basis of the results of an AGP (algal growth potential) assay. On the other hand, Nishibori et al. (40) reported that *P. bipes* can use NO_2^-, NO_3^-, NH_4^+, and urea-N at low concentrations. The half-saturation constant for nitrogen was within 50–65 µg of N/L, and the specific growth rate was highest at 0.5–1.3 mg of N/L. However, a higher concentration of nitrogen (5 mg of N/L) is needed to reach the maximum cell yield. Moreover, the optimum concentrations of phosphorus, nitrogen, calcium and magnesium for *P. bipes* growth were compared with those for other blooming freshwater phytoplankton. The optimum concentrations of phosphorus and calcium for *P. bipes* were lower than those of other types of blooming phytoplankton.

A comparison was made of nutrient and *P. bipes* trends in Lake Kawaguchi. During the investigation period from June to July 1995, a marked occurrence of red tide was observed in the 0-m and 2-m layers. Moreover, it was shown that the highest DTP concentration in these layers was 0.02 mg/L, nearly threefold higher than the mean concentration of 0.006 mg/L observed during the 11-year survey period (Fig. 3). Moreover, the TN and TP concentrations in the Terakawa River were respectively 4.5- and 4.7-fold higher than those in Lake Kawaguchi's water (Table 1). In addition, the annual mean TP concentration in 1995, when freshwater red tide was observed, was ca. twofold higher than the annual mean concentration from 1993 to 2003 (Table 1). It is assumed that the inflow from the Terakawa River is the most important source of phosphorus supplied to Lake Kawaguchi.

2. Horizontal and vertical distributions of P. bipes in Lake Kawaguchi

Figure 5 shows the vertical distribution of *P. bipes* and isopleths of water temperature, dissolved oxygen concentration, pH, electric conductivity and ORP at the monitoring station on June 26, 1995. The water temperature and dissolved oxygen concentration decreased from the 4-m layer to the bottom layer. On the other hand, the pH and electric conductivity from the surface to the bottom was constant. The irradiance was ca. 0% at the 2 m depth and the transparency was 2.3 m. Almost all the *P. bipes* cells were distributed in the upper layers, i.e., 0 and 2 m (94.7% of total number of cells); a few cells were distributed in the 6- and 9-m layers. According to the data on water temperature and dissolved oxygen concentration, stratification was formed on June 26. *P. bipes* cells grew and proliferated on the surface layer. As a result, transparency decreased and because the compensation depth became shallower, more and more *P. bipes* cells accumulated in the surface layer where it was assumed to be more advantageous for photosynthesis (Fig. 5).

On the basis of data from the investigation of the horizontal distribution of environmental factors at the 68 stations, water temperatures ranged from 19.3°C at Sts. 52 and 55 to 20.3°C at Sts. 14 and 15 with a mean±SD of 19.8±0.3°C; pHs ranged from 8.4 at St. 68 to 9.1 at St. 11 with a mean of 8.7±0.2; electric conductivities ranged from 116.7 µm hos/cm at St. 61 to 123.1 µm hos/cm at St. 14 with a mean of 120.4±2.0 µm hos/cm; and ORPs ranged from 153 mV at St. 14 to 172 mV at St. 57 with a mean of 163.7±4.0 mV. These environmental levels were almost the same among the stations. *P. bipes* was found in all stations. The numbers of *P. bipes* cells per milliliter ranged from 67 (St. 40) to 5360 (St. 28), averaging 1094±987 cells/ml, with high densities along the northern shore (Fig. 6). According to the wind rose (Fig. 2), from June 24 to June 25, 1995, there was a high frequency of wind blowing from east-southeast to south-southeast (wind force of more than 2 m/s). From the horizontal distribution, it was confirmed that there were a large number of *P. bipes* cells in the shallow northern estuary portion near the Terakawa River, which is the only inflowing river (Fig. 6). From this and the fact that the sites where previous red tides were observed nearly coincided with the northern shore in this study, it is presumed that the

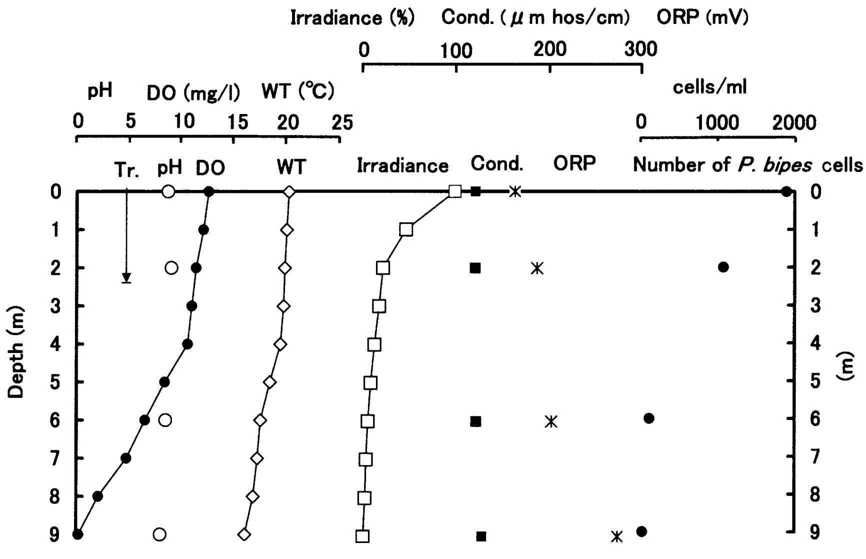

Fig. 5 Vertical distribution of *P. bipes* (cells/ml) and isopleths of water temperature, dissolved oxygen concentration, pH, electric conductivity and ORP at monitoring station on June 26, 1995.

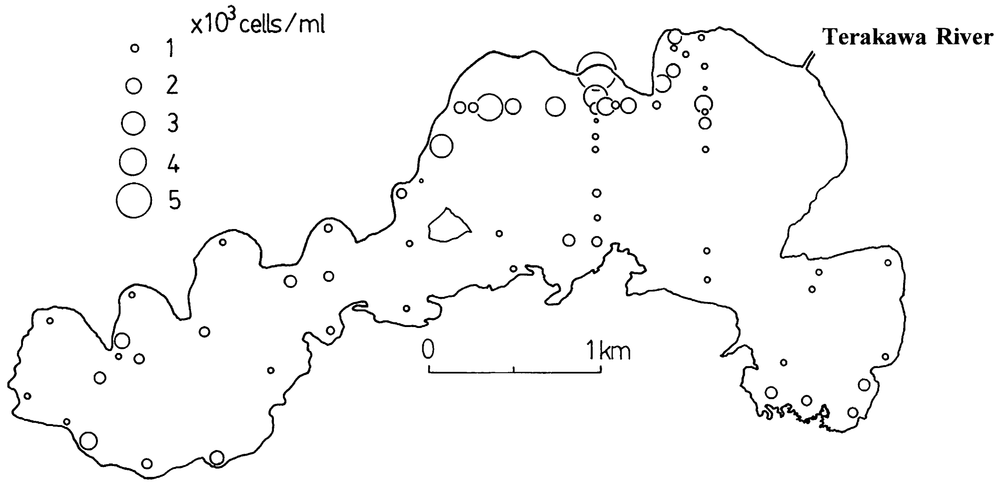

Fig. 6 Horizontal distribution of *P. bipes* in Lake Kawaguchi on June 26, 1995.

phenomenon observed in this study is a recurring one. In addition, from June 24 to June 25, 1995, the wind blew with a high frequency from southeast, and possibly more *P. bipes* cells accumulated at the surface layer of the northwest shoreline under this wind condition. Moreover, the configuration of the shelf, which is relatively shallow even in the middle of the lake, may also be widespread throughout the littoral zone on the lake's north shore. According to Kida et al. (17), the excystment of *Peridinium* cysts occurred under cool (5–15°C), light (more than 1500 lux) and aerobic conditions in laboratory experiments. It is supposed that the initiation of bloom results from the excystment of cysts in the bottom sediment of the littoral region. In Lake Kawaguchi as well, the inflowing Terakawa River is a source of phosphorus, and it is considered that the north shore of the lake is the section in which the bottom configuration is suitable for excystment.

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