Characteristics of Autochthonous Deposition and Resuspension of Sediments in the Takahamairi Bay of Lake Kasumigaura

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Abstract

Deposition rates were measured by means of sediment traps at five stations in hypertrophic Takahamairi Bay of Lake Kasumigaura for the selected periods of 1981–1986. Separation of deposited fluxes into autochthonous and sediment resuspension components was attempted on the basis of chlorophyll *a* concentration for the tracer. Even at the central station of the bay, the average daily flux of autochthonous matter was $4\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ compared with $46\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ of resuspension. There was a time lag of one or two months between the peak of primary production and that of autochthonous deposited flux, which resulted in a surprising increase in chlorophyll *a* concentration of lake water in mid-summer. Calculated autochthonous deposited rates of carbon, nitrogen, and phosphorus in backwater regions and near the inflow river mouth were much higher than those at offshore due to the contamination of allochthonous matter. In regard to the resuspension rates, a logarithmic decrease against water depth and significant correlations with some meteorological conditions were observed. The sum of autochthonous and allochthonous deposited fluxes exceeded the accumulation rates in sediments estimated both by the mass balance method and the sediment dating method by a factor of 8–17 for nitrogen and 2–10 for phosphorus, both of which were much larger than the ratios observed in other lakes. The shallowness of this lake greatly influenced these ratios because of the large resuspension rate followed by rapid decomposition in lake water and high activity of benthos.

Key words : autochthonous deposition, resuspension, sediment trap, nutrient cycle.

1. Introduction

Deposition of particulate matter is one of the fundamental processes governing lake nutrient cycles (Lastein, 1976; Bloesch *et al.*, 1977). Although the theoretical aspects of sinking mechanisms of particles are complex and poorly understood, data on bulk particle flux provide insight into the lake ecosystem. Some aspects of the deposition process were studied with sediment traps in the Takahamairi Bay of Lake Kasumigaura. Our aims here are: (1) to separate the deposited flux into autochthonous and sediment resuspension components, (2) to explain the factors influencing autochthonous deposition and resuspension fluxes, (3) to compare the autochthonous deposited rates with primary production rates and the net sedimentation rates estimated both by the mass balance method and by the sediment dating method.

2. Study sites and methods

Lake Kasumigaura (surface area 171km^2 ; maximum

depth 7.3m ; mean depth 4.0m) is a shallow hypertrophic lake composed of three basins (Fig. 1). The

Fig. 1. Sampling stations in the Takahamairi Bay of Lake Kasumigaura.

Takahamairi Bay (surface area 23km^2 ; mean depth 3.2m) is one of the basins known to be highly eutrophic. There is one main river named the

River Koise at the north-west end (inflow about $3\text{m}^3\cdot\text{s}^{-1}$. Before the river mouth, River Sanno and River Amano joint River Koise).

At one station in the backwater region of River Koise (Sta. 1) and four stations in the lake (Sta. 2,3,4,5), deposition rates were measured for the three periods of July 1981–October 1982, August 1983–October 1983, and April 1985–May 1986. Two parallel cylindrical traps (25cm high, 5.3cm dia.) in a frame (Fukushima *et al.*, 1984) were exposed with a simple mooring system using an anchor and sub-surface buoys. The traps were set 0.5–1m off the bottom. Traps were exchanged at intervals of 1–7day from July to August and biweekly from September to June, the supernatant water drained, and two samples of deposited matter (DM) were combined into one mixed sample for analysis.

For several selected periods, we checked (1) trapping efficiencies with various sediment traps of different size and shape, (2) the effect of exposure intervals on mineralization in traps, (3) the vertical difference in fluxes and compositions of deposited matter. As to (1), the cylindrical type was recommended as in the previous works (Gardner, 1980; Bloesch and Burns, 1980), and the differences of trap size (0.5, 1.5, 2.0 times as large as standard type) had a negligible effect on trapping efficiency (Fukushima *et al.*, 1984). As to (2), the time intervals used in this study were thought to be appropriate to neglect the mineralization in the traps (Fukushima *et al.*, 1984). The last problem (3) will be discussed in the following section.

Dry weight (DW) at 80°C and chlorophyll *a* (Chla) were analyzed on a Whatman GF/C glass-fiber filter. The concentration of Chla was determined by the UNESCO method (UNESCO, 1966). After the residual of the sample was freeze-dried, particulate organic carbon (POC) and nitrogen (PON) were measured with a CHN analyzer (Yanagimoto MF3). Digested by potassium peroxodisulfate, the particulate phosphorus (PP) was determined with an auto-analyzer (Technicon Type-2). Concentrations of some metals such as Ti, Al and Fe in selected DM were measured by the Takamatsu method (1978) using X-ray fluorescence spectrometry (ORTEC TEFA MODEL-6111).

In addition to the sediment trap program, we obtained water samples at all five stations. The suspended solids (SS), Chla, POC, PON, and PP were also measured by nearly the same method as DM. After being filtrated by nuclepore filter and

digested by hydrofluoric acid and nitric acid, concentration of some metals in seston were determined by inductivity coupled plasma emission spectrometry (Jarrell-Ash Atomcomp Model-975, Okamoto and Fuwa, 1984). Sediment cores were collected over 20 times at each station, and the samples of 5mm on the surface were analyzed by the same method as DM.

3. Results and discussion

3-1. Separation of deposited matter

Evaluating the settling process of the particulate matter in view of the nutrient cycles in lakes, it would be necessary to separate DM by origins and to count each component quantitatively. In a shallow lake of soft water, DM collected in sediment traps is mainly composed of autochthonous (bio-seston and detritus), allochthonous matter, and resuspended sediments. Two methods have been proposed for the separation of DM. The first is to collect one component during the period when other components would not be expected (Watanabe and Hayashi, 1971; Fuhs 1973). The second is to use the tracer's concentration which should be considerably different from the components. Organic matter (Gasith, 1975; Fallon and Brock, 1980), benthic animal (Lastein, 1976), and Ti (Matsunaga, 1982; Fukushima *et al.*, 1988) have been examined for the tracer. Since the first method involves the difficulty in determining whether there is a calm period or not, we chose the second one.

Applying the second method, several prerequisites are thought to be necessary (Fukushima *et al.*, 1988). The most important and most carefully examined problem is that one tracer could separate DM into only two components. Annual amounts of deposition observed from July 1981–June 1982 were 27.8×10^4 , 4.0×10^4 , and $1.4 \times 10^4 \text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ at Sta. 1, 3 and 5, respectively. Against these values, the sediment accumulation rate in the central basin was estimated to average $600\text{--}800 \text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ by several methods (Otsubo *et al.*, 1984). Since the primary production rate was $615\text{--}751 \text{gC}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ for 1982–1983 in the Takahamairi Bay (Takamura *et al.*, 1984), the autochthonous deposited flux would be on the order of $100 \text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$, taking into account the POC content of autochthonous matter, respiration, and mineralization in the settling process. These figures indicate that the resuspension rate is much larger than the allochthonous and autochthonous deposited rate. By considering that

the composition of allochthonous matter is similar to those of resuspended matter as described later, we could separate DM into resuspended sediments and autochthonous matter.

From the mass balances of DM and tracer's substance, the ratio of autochthonous matter to total DM (r) is given by

$$r = (C_d - C_s) / (C_a - C_s) \quad (1)$$

in which C_d , C_a , C_s are the tracer's concentration of DM, autochthonous matter, and resuspended sediments.

To calculate the value of r by this equation, (1) the value of C_s , (2) the value of C_a , (3) the substance for the tracer should be determined. As to (1), the tracer's concentration in the surface sediments of 5mm was taken for the value of C_s . This depth nearly equals the depth to which it would be

resuspended in stormy conditions (Fukushima *et al.*, 1984). Table 1 shows the averages and standard deviations of POC, PON, PP, Chla, and Ti concentrations in the surface sediments at five stations.

With regard to (2) above, the concentration in seston has been employed for C_a (Gasith, 1975). In the Takahamairi Bay, however, it frequently happens that the concentration in seston varies to a great extent (Sta. 3, POC (%) = 27.8 ± 11.9 ($n=51$)). This fact implies that the seston in lake water contains the resuspended sediments and/or allochthonous matter. Figure 2 (1) and (2) show the relationship between Ti and POC concentrations in seston, and the relationship between Ti and Chla concentrations in seston, respectively. Including the value of sediments, linear relationships with negative slopes are found. Similar tendencies with respect to

Table 1. POC, PON, PP, Chla, and Ti concentration in the surface sediments (0–5 mm).

	Sta. 1	Sta. 2	Sta. 3	Sta. 4	Sta. 5
POC (%)	$3.16 \pm 1.62^{(18)}$	$4.97 \pm 0.45^{(23)}$	$5.26 \pm 0.85^{(23)}$	$5.85 \pm 0.84^{(23)}$	$6.45 \pm 0.70^{(24)}$
PON (%)	$0.27 \pm 0.18^{(18)}$	$0.47 \pm 0.15^{(23)}$	$0.65 \pm 0.13^{(23)}$	$0.70 \pm 0.15^{(23)}$	$0.73 \pm 0.19^{(24)}$
PP (%)	$0.15 \pm 0.07^{(17)}$	$0.23 \pm 0.01^{(24)}$	$0.25 \pm 0.02^{(24)}$	$0.23 \pm 0.01^{(24)}$	$0.17 \pm 0.03^{(24)}$
Chla ($10^{-6} \text{g} \cdot \text{g}^{-1}$)	$92 \pm 55^{(17)}$	$97 \pm 35^{(24)}$	$147 \pm 58^{(24)}$	$165 \pm 32^{(24)}$	$184 \pm 68^{(24)}$
Ti (%)	0.470 (2)	0.492 (2)	0.510 (2)	0.463 (2)	$0.370 \pm 0.016^{(8)}$

1) average, 2) standard deviation, 3) number of samplings

Fig. 2. (1) Relationship between Ti and POC concentrations in seston at Sta.3. ○: July 1981–October 1981, □: November 1981–May 1982, △: June 1982–September 1982, ●: August 1984–May 1985, ★: sediments.

Fig. 2. (2) Relationship between Ti and Chlorophyll a concentrations in seston at Sta.3. Symbols are explained in Fig. 2, (1).

PON and PP existed in place of POC or Chla. Because of the much smaller Ti concentration in phytoplankton than seston ($0-137 \mu\text{g}\cdot\text{g}^{-1}$, (Matsunaga, 1982)), the Ti concentration in seston would represent the rate of resuspended or allochthonous matter.

Since the amount of seston in lake water is several times as high as that in river water except during the direct runoff period, it is presumed that resuspended matter occupies a larger portion of seston than allochthonous matter (Fukushima *et al.*, 1987). The intercept of the regression line at $\text{Ti} = 0\%$, consequently, gave the value of autochthonous matter composition. The POC, PON, PP, and Chla concentrations obtained in this way are summarized in T1-T4 (four different periods) of Table 2. There were some differences in these concentrations due to the different sampling periods. Stational variations were smaller than these differences. The compositions of Aoko (mainly blue-green algae collected in Lake Kasumigaura (Takamura *et al.*, 1981)) and oceanic phytoplankton (Richards *et al.*, 1965) are also shown in Table 2 and agree closely with the above-mentioned values.

As to (3) mentioned above, Table 3 shows the POC, PON, PP, Chla, and particulate titanium (P-Ti) concentrations in lake and river water. The concentrations in lake water are higher than those

in river water except for P-Ti, but more than ten times the differences are found particularly in Chla. By using Chla for the tracer, it would be implied that the probability of the risk to mistake allochthonous deposited matter for autochthonous deposited matter is minimized. An excellent agreement between the value of r with the aid of Ti and that with the aid of Chla may further reveal the appropriateness of the selection of Chla (Fukushima *et al.*, 1984).

Applying the above method, the deposited rate of autochthonous matter $Q_{\text{auto}}^{\text{ss}}$ is given by

$$Q_{\text{auto}}^{\text{ss}} = r Q_{\text{t}}^{\text{ss}} \quad (2)$$

in with Q_{t}^{ss} is the total deposited flux of seston.

A comparison of $Q_{\text{auto}}^{\text{ss}}$ at different depths (the lowest was the standard depth) is shown in Figure 3. The value of a_h indicates the ratio of the trap depth to the water depth. The sums of $Q_{\text{auto}}^{\text{ss}}$ for 106 days (11 sampling periods, Sta. 4) are 251, 294, and $335\text{g}\cdot\text{m}^{-2}$ for upper, middle, and lower traps, respectively. The depth of the production layer (1-3m), the mineralization in the settling process, and the turbulence in lake water may affect the difference of deposition rates at different depths, and an estimate of those rates can be given by the rate observed at the standard depth (0.5-1m off the bottom).

Next, we examined the calculation of resuspension

Table 2. POC, PON, PP, and Chla concentrations of autochthonous matter (%).

	T 1	T 2	T 3	T 4	Aoko ¹⁾	Oceanic phytoplankton ²⁾
POC	37.1	39.1	36.8	32.8	37.7	35.9
PON	5.89	6.04	5.82	5.79	9.42	6.30
PP	0.60	0.62	0.65	0.60	0.70	0.87
Chla	0.55	0.85	0.92	0.67	0.56	—

T1: July 1981 — October 1981, T2: June 1982 — September 1982, T3: November 1981 — May 1982, T4: April 1985 — May 1986, 1) Takamura *et al.* (1981), 2) $(\text{CH}_2\text{O})_{106}(\text{NH}_4)_{16}\text{H}_3\text{PO}_4$, Richards *et al.* (1965)

Table 3. POC, PON, PP, Chla, and Ti concentrations in lake and river water.

	Sta. 2	Sta. 4	R. Koise	R. Amano	R. Sanno
POC ($\text{mg}\cdot\text{l}^{-1}$)	6.11 ± 7.12	6.72 ± 7.74	1.15 ± 0.72	0.97 ± 0.62	3.75 ± 3.21
PON ($\text{mg}\cdot\text{l}^{-1}$)	1.04 ± 1.14	1.12 ± 1.21	0.15 ± 0.08	0.14 ± 0.07	0.54 ± 0.43
PP ($\text{mg}\cdot\text{l}^{-1}$)	$.125\pm .091$	$.119\pm .088$	$.059\pm .039$	$.053\pm .034$	$.127\pm .068$
Chla ($\mu\text{g}\cdot\text{l}^{-1}$)	116 ± 125	128 ± 134	6.2 ± 3.2	8.3 ± 8.9	12.6 ± 10.3
P-Ti ($\text{mg}\cdot\text{l}^{-1}$)	$.083\pm .083$	$.053\pm .038$	$.095\pm .077$	$.069\pm .072$	$.133\pm .318$

rate Q_{re}^{ss} at the bottom of the lake. The first approximation of Q_{re}^{ss} , which assumes a uniform concentration of resuspended matter in whole depths, and the settling of the matter in still water, lead to the following equation.

$$Q_{re}^{ss} = (Q_{ss_t} - Q_{ss_{auto}}) / a_h \quad (3)$$

Figure 4 shows a comparison of Q_{re}^{ss} obtained by eq.(3) at different depths. The fairly good agreement indicates the appropriateness of this equation. Consequently, the autochthonous deposited rates of nutrients Q_{auto}^a (a is the target substance) can be given by

$$Q_{auto}^a = Q_{ss}^a C_d^a - (Q_{ss_t} - Q_{ss_{auto}}) C_s^a \quad (4)$$

in which C_d^a , C_s^a are the concentrations of a in the

deposited matter and sediments, respectively.

3-2. Factors influencing autochthonous deposition and resuspension rate

The seasonal, yearly, and stational variations in autochthonous deposited flux and resuspension rate are described here to elucidate the factors influencing these processes. Figure 5 shows the seasonal variations in autochthonous deposited flux of seston $Q_{ss_{auto}}^{ss}$, resuspension rate Q_{re}^{ss} , SS and Chla concentrations in lake water, amount of rainfall, and water

Fig. 3. Comparison of autochthonous deposited fluxes at different depths at Sta.4. Upper: $a_h=0.25$, Middle: $a_h=0.6$, Lower: $a_h=0.75$.

Fig. 4. Comparison of resuspension rates of sediments at bottom Q_{re}^{ss} obtained by eq. (3) at different depths. $\circ$: Sta.1 (Upper: $a_h=0.3$, Lower: $a_h=0.7$), $\triangle$: Sta.4 (Upper: $a_h=0.6$, Lower: $a_h=0.75$), $\blacksquare$: Sta.5 (Upper: $a_h=0.5$, Lower: $a_h=0.8$).

Fig. 5. Seasonal variations in autochthonous deposited fluxes of seston, resuspension rates, SS and Chla in lake water, amount of rainfall, and water temperature at Sta.3.

temperature at Sta. 3. Nearly the same seasonal variations were also observed at other stations. Whereas Chla in lake water had two peaks in March – April and July – September, the peaks of Q^{ss}_{auto} were found in April – May and August – September. No distinct seasonal variation was observed in Q^{ss}_{re} .

Annual deposited fluxes of seston, Chla, carbon, nitrogen, and phosphorus, as well as the means of SS and Chla in lake water and water depth at five stations for July 1981–June 1982, are summarized in Table 4. The fluxes of Q^{ss}_{auto} and Q^{Chla}_{auto} are of nearly the same order of magnitude; the fluxes of Q^C_{auto} , Q^N_{auto} , and Q^P_{auto} at Sta. 1 and 2 are much larger than those at Sta. 3, 4 and 5. The resuspension rate decreases with increasing mean water depth. Yearly comparisons of autochthonous fluxes of carbon and nitrogen at Sta. 3 for August–September are shown in Table 5. The mean Chla concentration in lake water, amount of rainfall, and air temperature are also tabulated. The values of Q^C_{auto} and Q^N_{auto} in 1981 were about twice those in other years. In this year, the mean Chla concentration was much lower.

With respect to the seasonal change in autochthonous deposited flux, Figure 6 shows the seasonal variations in primary production rate (Takamura *et al.*, 1984) and autochthonous deposited flux of

Fig. 6. Seasonal changes in primary production rate (○) and autochthonous deposited flux (▲) at Sta.5.

carbon at Sta. 5. Though the primary production rate had a clear peak in mid–summer, Q^C_{auto} had that in September. This time lag of one or two months explained the surprising increase in lake Chla concentration in mid–summer (Fig. 5). A similar seasonal variation in autochthonous flux had been observed in Lake Wignra with a mean depth of 2.4m (Gasith, 1975). Deeper lakes possessing a stable thermocline in summer had considerably different patterns according to which the deposited flux of autochthonous matter had two peaks in spring and fall (Lastein, 1976; Fukushima *et al.*, 1988).

Table 4. Annual deposited fluxes of seston, Chla, carbon, nitrogen, and phosphorus at five stations for July 1981 – June 1982.

	Q^{ss}_{auto} $m \cdot g^{-2} \cdot d^{-1}$	Q^{ss}_{re} $m \cdot g^{-2} \cdot d^{-1}$	Q^{Chla}_{auto} $mg \cdot m^{-2} \cdot d^{-1}$	Q^C_{auto} $g \cdot m^{-2} \cdot d^{-1}$	Q^N_{auto} $mg \cdot m^{-2} \cdot d^{-1}$	Q^P_{auto} $mg \cdot m^{-2} \cdot d^{-1}$	mean of SS $mg \cdot l^{-1}$	mean of Chla $\mu g \cdot l^{-1}$	depth m
Sta. 1	2.05	1160	13.5	24.6	3054	1243	11.7	17	1.5
Sta. 2	1.99	349	12.7	1.68	323	71.5	28.7	103	2.1
Sta. 3	3.81	144	24.6	0.81	105	18.3	31.7	134	2.8
Sta. 4	4.39	66.5	27.3	0.79	153	14.5	29.9	123	3.5
Sta. 5	4.02	45.7	25.2	0.85	176	14.8	24.7	107	4.1

Table 5. Yearly comparison of autochthonous fluxes of carbon and nitrogen at Sta. 3 for August – September.

	1981	1982	1983	1985
Q^C_{auto} ($mg^{-2} \cdot m^{-2} \cdot d^{-1}$)	4040	1294	1293	2140
Q^N_{auto} ($mg^{-2} \cdot m^{-2} \cdot d^{-1}$)	601	385	339	270
mean of Chla ($\mu g \cdot l^{-1}$)	132	238	169	234
Rainfall (mm)	251.5	511.0	370.0	201.5
Air temperature (°C)	21.9	22.6	22.9	23.7

It could be inferred that the depth of the lake and the condition of water movement affect the seasonal change in autochthonous deposited flux. In addition, the rates of autochthonous deposited flux divided by Chl *a* concentration in lake water were higher in spring peaks than in summer peaks except in the summer of 1981 (Fig. 1). The difference in the dominant species of phytoplankton (spring: diatoms such as *Synedra* and *Cyclotella*; summer: blue-green algae as *Microcystis* and *Anabaena*, Takamura *et al.*, (1984)) would change the degree of the contribution of deposition and that of mineralization to the decline of autochthonous matter.

For the stational variations in autochthonous fluxes, two factors should be considered: primary production rate and influence of allochthonous matter. The primary production rates measured at Sta. 3, 4 and 5 for October 1981–September 1982 amounted to 698, 606, and 643 gC·m⁻²·yr⁻¹, respectively (Takamura *et al.*, 1984). Insignificant stational differences in Q^{ss}_{auto} and Q^{Chl}_{auto} would result from these nearly same conditions in primary production. On the other hand, the higher values of Q^C_{auto} , Q^N_{auto} , and Q^P_{auto} at Sta. 1 and 2 than Sta. 3, 4 and 5 could be attributed to the contamination of autochthonous deposited matter by allochthonous deposited matter. Since carbon, nitrogen, and phosphorus contents in allochthonous matter are higher than those in sediments (Table 1, 3), the sample contaminated by allochthonous matter shows apparently higher of autochthonous carbon, nitrogen, and phosphorus deposited fluxes than their original values (if the ratio *r* is calculated by eq. (1)). In the backwater region or near the mouth of the inflow river, it should be noted that the allochthonous deposited fluxes cannot be neglected.

There were considerable station differences in resuspension rates, which were attributable to the difference in stress exerted on sediments. In a shallow lake, wind driven current, wind wave, and river induced current are thought to be major sources of stress. Table 6 shows the correlation coefficients between Q^{ss}_{re} and some meteorological value averaged for each sampling period. The rainfall roughly represents the river induced current; the square and the cube of daily maximum wind velocity imply the stress and the energy exerted by wind on a water surface, respectively. As shown in Table 6, significant correlations with Q^{ss}_{re} are found in the amount of rainfall at Sta. 1 and in the cube of wind velocity at all stations except for Sta. 2. The logarithmic decrease in Q^{ss}_{re} against water depth (Table 4) possibly originates from the effect of wave action (Otsubo and Muraoka, 1985), but quantitative discussion cannot be conducted because of no information on the frequency distribution of wave height, the relation between the stress and the resuspension rate, etc. In a shallow lake, the resuspension of sediments must be taken into account anyhow, considering the larger proportion in deposited flux even in the offshore region.

As shown in Table 5, the yearly differences in Q^C_{auto} and Q^N_{auto} are not small. There were no great differences in the net photosynthesis rates of those years (Takamura, 1987). The influence of allochthonous matter would be rejected, because lower values of Q^C_{auto} and Q^N_{auto} were observed in the years having a larger amount of rainfall. In regard to the differences between 1981 and 1982, the difference in the compositions of the main species of phytoplankton is thought to be one of the causes. *Microcystis aeruginosa* was the dominant species in both summer, but the biomass of

Table 6. Correlation coefficients between resuspension rate of sediments and some meteorological conditions.

	Amount of rainfall	Average of daily maximum wind velocity	Square of daily maximum wind velocity	Cube of daily maximum wind velocity
Sta. 1	0.503 *	0.256	0.341	0.341 *
Sta. 2	0.012	0.139	0.156	0.196
Sta. 3	0.069	0.298	0.387 *	0.433 *
Sta. 4	0.412 *	0.270	0.414 *	0.527 *
Sta. 5	0.394 *	0.097	0.222	0.337 *

* means the value of correlation coefficient (r_c) which rejects the null hypothesis $r_c=0$ at the level of significance 0.01.

Anabaena flos-aquae and *Aphanizomenon flos-aquae* was not negligible in the summer of 1982 (Takamura *et al.*, 1984). Fallon and Block (1980) pointed out that decomposition appeared to be primarily important for *Anabaena* and *Aphanizomenon*, whereas sedimentation accounted for more of the decline of *Microcystis*. In 1981, experiments to measure the decomposition rate of seston were conducted under the conditions of 20 °C, in a darkened condition, and by stirring with a magnetic stirrer. The decomposition rates of Chla in the rapid step during the first two weeks were calculated as a first-order reaction coefficient and found to be $0.096 \pm 0.057 \text{ d}^{-1}$ ($n=7$) for June–July, $0.0047 \pm 0.0062 \text{ d}^{-1}$ ($n=4$) for August–September, and $0.098 \pm 0.040 \text{ d}^{-1}$ ($n=7$) for October–December. The lower rates for August–September correspond to the higher autochthonous deposited fluxes for this period. It can therefore be presumed that varieties of phytoplankton species affect the autochthonous deposited fluxes. In addition, it was noted that the mean Chla

concentration of lake water was lower in 1981 when $Q^{\text{C}}_{\text{auto}}$ and $Q^{\text{N}}_{\text{auto}}$ were larger. We cannot conclude now which is the cause or which is the result, but it should be noted that the autochthonous deposited fluxes are related to the Chla concentration of the lake water.

Finally, we compared the ratio of the autochthonous deposited flux to the primary production rate with those observed in other lakes. In the Takahamairi Bay, these ratios were calculated to be 0.32, 0.54, and 0.44 for Sta. 3, 4 and 5, respectively. For the lakes where the resuspension of sediments is negligible and/or the lakes where the separation method was applied, Figure 7 shows the relationship between the primary production rate and the autochthonous deposited flux of carbon. Except for Lake Suwa, the ratio ranges from 1/6 to 1/2. In Lake Suwa, sediment traps of funnel, which were known to underestimate the deposited flux in stormy conditions (Bloesch and Burns, 1978), were deployed (Hayashi, 1973). The values ranging from 1/6 to 1/2 are therefore considered as appropriate for the ratio.

3-3. Comparison of autochthonous deposited fluxes with net sedimentation rates

There are two methods estimate the net sedimentation rates: (1) the mass balance method (Golterman, 1975) and (2) the sediment dating method (Krishnaswami and Lai, 1978). The mass balance method for total nitrogen and total phosphorus was applied to Box-1 (Fig. 1) every month for January 1978–December 1980 (Goda *et al.*, 1984). Inflow from river, rain, culture of carp and outflow by advection, dispersion, fishing, some water supplies and emergence of *Chironomid* were taken into account in the mass balance. The denitrification rate in sediments (Aizaki *et al.*, 1981) was evaluated for total nitrogen. As described in the previous section, the sediment accumulation rate was estimated to be $600\text{--}800 \text{ g} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$ as dry weight. Multiplying this ratio by the composition of sediments, we obtained the carbon, nitrogen, and phosphorus accumulation rates into sediments. Table 7 shows the autochthonous deposited fluxes (Sta. 5, July 1981–June 1982), the allochthonous deposited fluxes, residuals in mass balance (averaged for January 1978–December 1980), and sediment accumulation rates (sediments compositions at Sta. 5). The allochthonous deposited fluxes were estimated by the presumption that all of the particulate components in inflow matter settle in this box. The

Fig. 7. Relationship between primary production rate and autochthonous deposited flux in the nine lakes. 1: This study, 2: Lake Suwa (mean depth 4.1m, Hayashi (1973)), 3: Lake Rotsee (9.0m, Bloesch *et al.* (1976)), 4: Lake Esrom (12.3m, Lastein (1976)), 5: Lake Mendota (12.4m, Fallon and Brock (1980)), 6: Lake Kizaki (17.9m, Koyama *et al.* (1975)), 7: Lake Lugano (33m, Premazzi and Marengo (1982)), 8: Lake Lucerne (43m, Bloesch *et al.* (1977)), 9: Lake Chuzenji (94m, Fukushima *et al.* (1988)).

Table 7. Autochthonous deposited fluxes (Sta. 5, July 1981–June 1982), allochthonous deposited fluxes, residuals in mass balance (January 1978–December 1980), and sediment accumulation rates ($\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$).

	Autochthonous deposited fluxes	Allochthonous deposited fluxes	Residuals in mass balance including denitrification in sediments	Accumulation rates in sediments
Carbon	310			38.7–51.6 ²⁾
Nitrogen	64.2	11.8	7.2–9.8 ¹⁾	4.4–5.8 ²⁾
Phosphorus	5.4	3.8	3.8	1.0–1.4 ²⁾

1) Residual in mass balance = $17.1\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$, denitrification in sediments = $7.3\text{--}9.9\text{ g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$, 2) sediment accumulation rate in dry weight = $600\text{--}800\text{ g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$

proportions of the particulate component in total inflow load were 31% for nitrogen and 66% for phosphorus (Matsuoka, 1984).

The sums of autochthonous and allochthonous deposited fluxes exceed the residuals in mass balance and accumulation rates in sediments by a factor of 8–17 for nitrogen and by a factor of 2–10 phosphorus. The mass balance method has some errors due to inaccuracies in determining the inflow loads during direct runoff period etc., and the sediment dating method does not take into consideration the horizontal variations in sediment accumulation rates and sediment compositions. In addition, the allochthonous deposited fluxes were slightly overestimated owing this presumption. The differences between them are, however, so great that we cannot assume only one-way transport from water to sediments. Nutrient release rates from sediments under aerobic conditions, which is one of the counter transport processes, were $11.3\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ for nitrogen and $0.92\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ for phosphorus (Hosomi and Sudo, 1984). It is well known that the release of nutrients increases dramatically under anaerobic conditions, and the turnover through the activity of benthos has high rates in some seasons (Goda *et al.*, 1984). In a shallow lake, it could be inferred that the return flow from sediments to water is nearly as great as the freshly deposited flow. In addition, the reason for the higher return rate of nitrogen than phosphorus is the higher decomposition rate in particulate organic matter, the lower proportion of particulate components in allochthonous matter, and the higher proportion of dissolved components in fish excretion (Goda *et al.*, 1984).

In Lake Mendota, of the original organic matter, 89% (57% then occurred in the water column and another 32% at the mud surface) was decomposed

before the material was buried in the sediments (Fallon and Brock, 1980). The ratio of the decomposed matter in sediments to the matter reaching the sediments was 76%. These ratios were reported to be 46%, 47% and 25% for carbon, nitrogen, and phosphorus in Lake Lugano (Premazzi, 1982) and 33% and 65% for carbon and nitrogen, respectively, in Lake Kizaki (Koyama *et al.*, 1975). These ratios are slightly lower than those in the Takahamairi Bay (over 80% for nitrogen and phosphorus).

Using the natural phytoplankton communities of Lake Kasumigaura, Aizaki and Takamura (1986) pointed out the decomposition rates of particulate nitrogen under static conditions were about 0.7 times as great as those under aerating conditions. Further, the annual mean biomass and annual production of *T. akamusi* in Takahamairi Bay (1977–1983) were $5.7\text{g}\cdot\text{C}\cdot\text{m}^{-2}$ and $8.8\text{g}\cdot\text{C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$, respectively, and those for *C. plumosus* were $1.2\text{g}\cdot\text{C}\cdot\text{m}^{-2}$ and $6.5\text{g}\cdot\text{C}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$, respectively (Iwakuma *et al.*, 1984). In winter, the standing crop of *Neomysis intermedia* was $56.76\text{g}\cdot\text{m}^{-2}$ in wet weight (Kasuga, 1981). These high densities of benthic animals would correspond to the high eutrophication level of this lake and could provide the major pathway of nutrients from sediments to water. The shallowness of this lake results in a lowering of the proportion of buried material in sediments because of the large resuspension rate followed by rapid decomposition in lake water and high activity of benthos.

摘 要

霞ヶ浦高浜入りにおける自生性沈殿と底泥の巻き上げ現象の特徴

霞ヶ浦高浜入りの5地点において、1981–1986年のある期間、セジメントトラップを用いて沈殿物を採集し、分析した。

1) クロロフィル a を指標物質として沈殿物の起源を自生性懸濁物と巻き上げられた底泥に分離する方式を検討した。湖水中懸濁物組成の時間的変化、水深の異なる位置での沈殿量の違い、チタン等をトレーサーにした場合の分離結果等から考えてこの方式が適切かつ有効であることを示した。

2) 高浜入中央部においても、年平均値として自生性沈殿量 $4 \text{ gm}^{-2} \cdot \text{d}^{-1}$ に対して底泥巻き上げ量は $46 \text{ gm}^{-2} \cdot \text{d}^{-1}$ ときわめて大きいことが明らかになった。自生性の沈殿量は植物プランクトンの一次生産量の変化に約 1, 2 カ月の時間遅れを有しつつ追従して変化すること、流入河川の背水域、河口近傍では有機態の炭素、窒素、およびリンの沈殿量が多く外来性懸濁物の沈殿が影響していると考えられること、底泥の巻き上げ量はその対数が水深にはほぼ逆比例するとともに風速、降水量と有意な関係を有することがわかった。

3) 高浜入を 1 ボックスとした物質収支算定から得られる収支残量、および年代測定結果を考慮した底泥への蓄積速度と比例して、自生性、外来性沈殿量の和は、窒素で 8—17 倍、リンで 2—10 倍も多く、再巻き上げ時の湖水中での分解速度の早さ、底生動物の盛んな活動を通して、底泥から湖水への栄養塩の回帰量がきわめて大きいことを示唆した。

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