Estimation of the impact of particulate organic matter drained from a freshwater reservoir on the sea using diatom tracking

Eisaku Shiratani, Hirohide Kiri, Hiroaki Shimokawa, Yoshihiro Yokoyama and Masataka Nakashima

ABSTRACT

We estimated the extent of suspended solids (SS) and particulate organic matter (POM) discharged from a freshwater reservoir, called the Isahaya Reservoir, into a sea area by tracking the diatom frustules produced in the reservoir. The estimation method is based on the fact that Skeletonema subsalsum and S. costatum, are the predominant diatoms in the reservoir and the sea, respectively, and the discharged SS and POM contain the freshwater diatom, S. subsalsum, and that the diatom frustules remain undecomposed in the environment even after the plankton decays. The results of the sediment trap experiment and bottom sediment survey showed that the distribution of diatom frustules in the bottom sediment had good agreement with that in the water column in the sea, and the greatest amounts of the drained SS and POM were estimated to have reached and settled down on the bottom sediment in the sea area within approximately 2 km from the drainage gates of the reservoir.

Key words | bottom sediment survey, freshwater reservoir, sea environment, sediment trap experiment

INTRODUCTION

The organic pollution of water and bottom sediment in a sea is an important issue to be solved to conserve the habitat for sea benthos. The pollutant loading from rivers could seriously effect the sea environment, especially in an enclosed coastal bay, and estimation of the extent and the concentration of the impact of the pollutants is essential in order to control the pollution.

To estimate the impact of particulate organic matter (POM) in river water inputs on a sea area, the ratios of carbon $^{13}$C/$^{12}$C and nitrogen $^{15}$N/$^{14}$N stable isotopes make it possible to differentiate river and marine organic matter sources (Riera & Richard 1997; Bănaru et al. 2007). The technique is based on the fact that the isotopic composition of organic materials differs among primary producers. However, in cases where the POM is almost entirely composed of algae grown in an enclosed freshwater body close to a sea area it could have similar ratios of carbon and nitrogen stable isotopes to those of the POM in the sea, thus quantitative differentiation of freshwater and seawater organic matter sources is impossible where the seawater melds with the water from an enclosed freshwater body.

The sea area in the present study, Isahaya Bay and its surroundings (Figure 1), is exactly a case of this kind. The freshwater reservoir, called the Isahaya Reservoir, is located at the end of Isahaya Bay and discharges freshwater into the bay through two drainage gates after rainfall to control the water level. We tried to estimate the extent of SS and POM discharged from a freshwater reservoir by considering a diatom characteristically growing in freshwater areas as a tracer that could be used to track the freshwater flow into the sea. The estimation method of tracking diatom frustules produced in the reservoir is based on the fact that as every

Diatom species grows to match the salinity conditions, whether it is freshwater, brackish water or seawater, the discharged SS and POM from the freshwater reservoir could contain freshwater diatoms, such as *Skeletonema subsalsum*, and that the diatom frustules remain undecomposed in the environment even after the plankton decays.

The bottom sediment in the reservoir and the sea area was surveyed, and the sediment trap experiment was conducted for three days after the reservoir discharged freshwater into the bay, to clarify the origin of SS and POM in the bay.

**MATERIALS AND METHODS**

**Study area and water quality monitoring**

The study area is the Isahaya Reservoir, the Isahaya Bay and its surroundings (Figures 1 and 2). The bay is located in the western part of the Ariake Sea, and a 15 km² area of agricultural land and a 20 km² area of freshwater reservoir, the Isahaya Reservoir, were developed by closing off approximately one-third of the bay with a 7 km long dyke in 1997.

The reservoir has two functions, one is to supply irrigation water to the newly reclaimed agricultural land, the other is to protect it against flooding caused by heavy rain and the approach of storm surges during a typhoon, so that the water level of the reservoir is controlled at 1 m lower than the mean sea level by preventing the inflow of seawater when the tide rises above the inner water level and by discharging fresh water through two drainage gates when the inner water level is higher than 1 m below the mean sea level.

After the closing off the sea, the salinity of the water in the reservoir gradually decreased to level off at approximately 600 mg/L of chlorinity in recent years. As the result, the water becomes eutrophicated and SS and POM are produced due to algal growth and erosion of the bottom sediment mud in the reservoir, so that fishermen in the Ariake Sea are concerned that discharged water from the reservoir into the sea may have some negative impact on the sea environment.

The Ministry of Agriculture, Forestry and Fisheries of Japan has been monitoring the state of the water environment, such as the tidal currents, water quality including plankton and bottom sediment quality since 1990 in the reservoir and the bay.

**Bottom sediment survey**

The bottom sediment survey was conducted on 5, 6 and 22 of November 2004, and 8 January 2005 at 15 stations as listed in Table 1 and Figure 2.

Undisturbed sediment samples using a columnar corer (0.5 m length, and 0.1 m diameter) in the sea area, and disturbed sediment samples using a Smith-Macintyre grab (0.1 m²) were collected from the bottom in the sea area and the reservoir. The surface fluid-like mud of each sample was 5% formalin-fixed to make up the analysis sample. The sample was ultrasonically dispersed for one minute and the particle size distribution was analysed by laser scattering (Horiba LA-910). The number of diatoms (*S. subsalsum* and *S. costatum*) was counted under a light microscope (Nikon Optiphot-2).
Sediment trap

Sediment traps were deployed at five sites (S1, S1', S7, S12 and B4) for three days from 7 to 10 of March 2005. Fresh water was discharged at 1,230 \( \times 10^3 \) m\(^3\)/d from the reservoir through the North Gate on 8 March. The cylinder used for the sedimentation trap was 0.05 m diameter and 0.35 m length, which is considered to be sufficient to prevent resuspension of the deposited matter in the cylinder (Hargrave & Burns 1979), and was installed at 0.5 m above sea bottom (S1 and S1') or 1.0 m depth (S7, S12 and B4) as shown in Figure 3.

Water quality (SS = suspended solids, VSS = volcanic SS, COD\(_{\text{Mn}}\) = chemical oxygen demand, DCOD = dissolved chemical oxygen demand, TOC = total organic carbon) and the particle size of the SS were analysed for samples trapped in the cylinder. A fraction of the precipitate in the cylinder was formalin-fixed, and the number of \( S. \ subsalsum \) and \( S. \ costatum \) were counted.

In addition, the drained water from the reservoir was collected on 8 March 2005, to analyse the water quality and count the number of \( S. \ subsalsum \) and \( S. \ costatum \).

RESULTS

Water quality in the reservoir and bay

The annual mean concentration of total nitrogen (T-N), total phosphorus (T-P) and COD\(_{\text{Mn}}\) are approximately 1.2 mg/L, 0.25 mg/L and 9.0 mg/L, respectively, which are much higher than those of seawater.

The key phytoplankton species has been \( S. \ subsalsum \) in the reservoir since 2000 (Figure 4), while the species might be found only in the sea area close to the reservoir during a couple of weeks after a freshwater discharge. On the other hand, \( S. \ costatum \) has predominated in the sea area as shown in Figure 5. While \( S. \ subsalsum \) is

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Dates of bottom sediment survey</th>
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<tbody>
<tr>
<td>Station</td>
<td>Location</td>
</tr>
<tr>
<td>S1</td>
<td>32°53'46&quot;N, 130°9'40&quot;E</td>
</tr>
<tr>
<td>S6</td>
<td>32°51'29&quot;N, 130°11'30&quot;E</td>
</tr>
<tr>
<td>B3</td>
<td>32°53'48&quot;N, 130°12'59&quot;E</td>
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<tr>
<td>B4</td>
<td>32°56'14&quot;N, 130°13'45&quot;E</td>
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<tr>
<td>S10</td>
<td>32°54'44&quot;N, 130°15'39&quot;E</td>
</tr>
<tr>
<td>B5</td>
<td>32°53'53&quot;N, 130°16'44&quot;E</td>
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<td>A</td>
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<td>32°53'9&quot;N, 130°9'11&quot;E</td>
</tr>
<tr>
<td>B2</td>
<td>32°51'38&quot;N, 130°10'21&quot;E</td>
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<td>32°53'46&quot;N, 130°10'12&quot;E</td>
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<tr>
<td>S7</td>
<td>32°53'46&quot;N, 130°10'43&quot;E</td>
</tr>
<tr>
<td>S12</td>
<td>32°55'7&quot;N, 130°11'55&quot;E</td>
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Figure 3 | Sediment trapping method at (a) stn. S1 and S1', and (b) stn. S7, S12 and B4.
distinguished from *S. costatum* morphologically by its structure of connecting processes (*Hasle & Evensen 1975*), other species that are similar to *S. subsalsum* or *S. costatum* are suggested to occur (*Hasle & Evensen 1976; Sarno et al. 2005*). However, *Skeletonema* species found in the reservoir and the sea area could easily be morphologically distinguished from each other even under the light microscope. The most notable differences were the cell size and the girdle view in which the *Skeletonema* cells connect. The cells of *S. subsalsum* found in the reservoir and *S. costatum* in the sea area were 3–5 μm and 8–10 μm in diameter, respectively, and the girdle of *S. costatum* cells was clearly visible compared to that of *S. subsalsum*.

The distribution of the particle size of the fluid-like mud on the bottom surface in the reservoir is shown in Figure 6. There was a frequency peak around 10 μm, which was approximately the same as that of the cell size of *Skeletonema*.

**Bottom sediment survey and sediment trap**

The number of frustules of *Skeletonema* in the surface fluid-like mud on the bottom sediment collected was shown in Figure 7. The frustules of *S. subsalsum* and *S. costatum* were $7.7 \times 10^5 - 1.3 \times 10^6$ cells/g and $7.9 \times 10^5 - 9.6 \times 10^4$ cells/g, respectively, in the reservoir. As the seawater had been introduced into the reservoir as a trial for 27 days, from 24 April through 20 May 2002, *S. costatum* was considered to have flowed into the reservoir and settled on the bottom surface at the same time.

The frustules of *S. costatum* were predominantly found in the sea area. On the other hand, the frustules of *S. subsalsum* were observed at only $4.5 \times 10^4$ cells/g and $1.3 \times 10^5$ cells/g at Stn. S1 and S6, respectively, and both of these stations are close to the drainage gate of the reservoir, and $0-1.6 \times 10^4$ cells/g were found in the other sea areas.

The settling rates of particulate matter observed in the sediment trap are shown in Figure 8. All the precipitates were observed in relatively large quantities at Stns. S1 and S1’, and likely decreased with distance from the drainage gate. While the cylinders at Stns. S1 and S1’ were deployed deeper than at the other Stns. S7, S12 and B4 because the bay is shallow to a considerable distance from the shore, the particulate matter was considered to be easier to resuspend and be collected in the cylinders at Stns. S1 and S1’. The percentage of POM, which was indicated by VSS, PCOD or TOC, in the SS seemed to be lower in areas closer to the drainage gate, and was highest at Stns. S7 or B4 (Figure 9).
The distribution of the frustules of *S. subsalsum* collected had a similar tendency to other precipitates as shown in Figure 10. However, the frustules of *S. costatum* collected declined over the distance from the gate to Stn. S7 and increased offshore.

In addition, the water discharged from the reservoir collected on 8 March 2005 contained *S. subsalsum* and *S. costatum* at $34.8 \times 10^4$ cells/g and $6.4 \times 10^4$ cells/g, respectively.

**DISCUSSION**

As the key species of phytoplankton was *S. subsalsum* and the particle size of the SS and that of *S. subsalsum* in the reservoir were approximately the same, to estimate the extent of SS and POM discharged from the reservoir in the sea was considered to be possible by tracking the frustules of *S. subsalsum*.

From the results observed in the bottom sediment survey, POM including *S. subsalsum* discharged from the reservoir was considered to have largely settled down within the sea area close to the drainage gate, and to be rarely transported beyond the middle of Isahaya Bay. On the other hand, the frustules of *S. costatum* in the fluid-like mud on the bottom surface were roughly evenly distributed in the bay, and the number of frustules of *S. costatum* was higher than that of *S. subsalsum*. Consequently, the greater part of POM deposited on the bottom in the bay likely originated from marine POM. Specifically in the middle and/or the mouth area of the bay, as the frustules of *S. costatum* accounted for more than 98% of *Skeletonema* frustules, the POM discharged from the reservoir has had little effect on the bottom sediment there.

However, we should note that the discharged water from the reservoir contains *S. costatum* in it as described above, so that the *S. costatum* frustules in the sea area might originate from the reservoir. For the moment let us look closely at results of the sediment trap.

It is assumed that the number of *S. costatum* frustules that originated from the reservoir can be calculated using following equation:

$$TSCR = \frac{TSS \times DSC}{DSS}$$

where $TSCR$ = reservoir-originated *S. costatum* frustules trapped (cells/g), $TSS = S. \ subsalsum$ frustules trapped (cells/g), $DSC = S. \ costatum$ frustules in the drainage from the reservoir (cells/g), and $DSS = S. \ subsalsum$ frustules in the drainage from the reservoir (cells/g).
The number of *S. costatum* frustules that originated from the sea is also calculated as

$$TSC_S = TSC - TSCR$$

(2)

where $TSC_S$ = sea-originated *S. costatum* frustules trapped (cells/g), and $TSC = *S. costatum* frustules trapped (cells/g).

As *S. costatum* and *S. subsalsum* were predominant in the sea area and the reservoir, respectively, the number of phytoplankton that originated from the reservoir and the sea are approximated in Equations (3) and (4),

$$TPHR = TSCR + TSS$$

(3)

$$TPHS = TSCS$$

(4)

where $TPHR$ and $TPHS$ = reservoir-originated and sea-originated phytoplankton trapped (cells/g), respectively.

Assuming that the settling rate of the POM is in direct proportion to that of the phytoplankton, the settling rates of the POM that originated from the reservoir and the sea are estimated using the following equations, respectively.

$$SR_R = TSR \times \frac{TPHR}{TPHR + TPH_S}$$

(5)

$$SR_S = TSR \times \frac{TPHS}{TPHR + TPH_S}$$

(6)

where $TSR$ = settling rate of POM (g m$^{-2}$ d$^{-1}$), $SR_R$ and $SR_S$ = settling rate of reservoir-originated POM and sea-originated POM (g m$^{-2}$ d$^{-1}$).

The estimated settling rate of the reservoir-originated POM decreased by approximately 20–40% between Stns. S1 and S1’, and by 80–90% between Stns. S1’ and S7 as shown in Figure 11. In addition, based on these findings, the percentages of POM that originated from the reservoir and the sea are shown in Figure 12. More than 70% of the POM observed was estimated to have originated in the marine environment. The POM originating from the reservoir was at approximately 30% in the sea area nearer the drainage gate than that in the mid-bay area, at Stns. S1, S1’ and S7, and less than 3% at Stns. S12 and B4.

The results obtained in both the bottom sediment survey and the sediment trap indicated the same impact of SS and POM discharged from the reservoir on the bottom sediment in the sea area, that is, most of the discharged SS and POM settle down on the bottom within 2 km from the drainage gate and little discharged POM was transported out of the bay.

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**Figure 11** Settling rates of (a) volcanic suspended solid (VSS), (b) particulate chemical oxygen demand (PCOD), and (c) total organic carbon (TOC) at sediment trap stations with distance from the drainage gate. The dark zone and the gray zone mean the Isahaya Reservoir-originated and the sea-originated, respectively.

**Figure 12** Proportions of the Isahaya Reservoir-originated and the sea-originated particulate organic matter (POM).
CONCLUSION

The extent of SS and POM discharged from the Isahaya Reservoir in the sea area was estimated by tracking the frustules of *S. subsalsum* that had grown predominantly in the reservoir. The findings of the study are the following.

- As *S. sabsalsum* was predominant in the reservoir and size of the particles of *S. sabsalsum* and the fluid-like mud on bottom surface in the reservoir was approximately the same, we could estimate the extent of SS and POM discharged from the reservoir by tracking the frustules of *S. sabsalsum*.
- Most of the discharged amounts of SS and POM were estimated to have settled down on the bottom within 2 km from the drainage gate and little discharged POM was transported out of Isahaya Bay.

Further research based on extensive observations and the employment of numerical simulations is required to achieve more accurate estimations since the speed of the tidal current is high, with a rate of more than 1 m/s at spring tides, and is non-uniform in the bay and its surrounding area (Shiratani et al. 2007).

REFERENCES


