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In order to estimate the fluxes of total suspended matter (TSM), particulate organic carbon (POC), organic nitrogen (PON) and phosphorus (PP) transported through the boundary between the inner part and central part of Osaka Bay, temporal variations of current velocity and concentration of the TSM, POC, PON and PP were measured at three locations along the boundary between these two parts in September 1994. The TSM flowed from the central part of the bay through the entire boundary into the inner part at a rate of 43 ton day$^{-1}$. On the other hand, the POC, PON and PP flowed out from the inner part to the central part of the bay at rates of 89, 22.8 and 1.43 ton day$^{-1}$, respectively. These results indicate that suspended particles with low organic content are transported from the central part to the inner part of the bay, while suspended particles with higher organic content are transported from the inner part, where eutrophication of sea water is serious and primary production is high, to the central part of the bay.

1. Introduction

Osaka Bay is one of the most polluted regions of the Seto Inland Sea, Japan. Especially in the inner part of the bay, large amounts of nutrients, organic matter and heavy metals are supplied from rivers such as the Yodo and the Yamato. The pollutants-rich water has introduced serious water pollution problems, such as outbreaks of red tides and oxygen-deficient water mass (Joh, 1989; Montani et al., 1991; Yuasa et al., 1993). In order to protect the coastal water environment, the transport mechanism of the pollutants must be urgently clarified. Since suspended particles play an important role in cycling as a transport agent for various natural and man-made substances, an understanding of the behavior of suspended particulate matter is essential to the study of pollutants in Osaka Bay.

In this study we have investigated the temporal variations of current velocity and the concentrations of total suspended matter (TSM), particulate organic carbon (POC), particulate organic nitrogen (PON) and particulate phosphorus (PP) at three locations along the boundary between the inner and central parts of the bay. The fluxes of TSM, POC, PON and PP transported through the boundary were also estimated.

2. Observational Methods

We selected two study areas: the inner and central parts of Osaka Bay (Fig. 1). In the inner part of the bay salinity in the surface layer is less than 30 psu. The behavior of dissolved and particulate matter in this area is greatly influenced by the freshet of the Yodo and other rivers. The boundary between the inner and central parts of the bay is shown in Fig. 1. Measurements were conducted at three moored buoy stations, Stns. 12, A7 and A10, along the boundary during September 5–6, 7–8 and 9–10 in 1994, respectively. The temporal variations of current velocity and turbidity were continuously measured with an electromagnetic current meter (Alec ACM-16M) with a backscattering-type turbidity sensor at the surface layer (3 m depth), the middle layer (10 m depth) and the bottom layer (0.5 m above the bottom sediment) for 25 h. Data on current and turbidity were recorded at 2 second intervals and averaged every 1 minute. The vertical distributions of water temperature, salinity and turbidity were also measured with a CTD meter (Alec ASTU-1000M) equipped with a turbidity sensor. Water samples were collected with a 5-liter Van-Dorn sampler at 2 hour intervals at the same depth as the current meters. Subsamples were filtered through membrane (millipore HA type) and glassfiber (Whatman GF/F type) filters. Total suspended matter (TSM) concentrations were estimated using the weight of residuals on the membrane filters. Particulate organic carbon (POC) and particulate organic nitrogen (PON) on the glassfiber filters were analyzed using a CHN analyzer (Yanagimoto CHN Corder MT-5). Particulate phosphorus (PP) on the membrane filters was analyzed using an auto-analyzer (Bran & Luebbe Traacs 800) after extraction with 4% $K_2S_2O_8$ solution at 120°C for
The values measured with a turbidity sensor were converted into the TSM concentration (mg l$^{-1}$) by using a calibration curve between the TSM in the water samples and the measured values (Tur), expressed as $TSM = 0.65 \times Tur + 1.17 \ (r = 0.85)$.

In addition to measurements at mooring stations, water samples were collected at about thirty stations (Fig. 1) during September 5–7 in 1994 to obtain the horizontal distributions of the TSM, POC, PON and PP in Osaka Bay.

3. Results

3.1 Horizontal distribution of total suspended matter (TSM) and particulate organic carbon (POC)

Figures 2(a) and (b) show the horizontal distributions of the TSM concentration in the surface layer and the bottom layer of Osaka Bay. In the surface layer, the TSM tended to be high in the central part of the bay and off the eastern coast of Awaji Island, and low in the inner part of the bay (Fig. 2(a)). In the case of bottom layer, the distribution of TSM was similar to that of the surface layer, although the TSM in the bottom layer was higher than that in the surface layer by a factor of 3 to 10. Hoshika et al. (1994) reported that the sedimentation rate in the off shore of Sennan City was high. In this study we found that the TSM was higher than 50 mg l$^{-1}$. The layer near the bottom sediment with a high TSM concentration, the so-called bottom turbid layer, was also observed by Kawana and Tanimoto (1984), and Sakamoto and Kawana (1989) in the Seto Inland Sea. The horizontal distributions of POC content per unit weight of suspended particles in the surface and the bottom layers are shown in Fig. 3. In contrast to the TSM distribution pattern, POC content was high in the inner part and low in the central part of the bay. The horizontal distributions of PON and PP content in the surface and bottom layers were similar to that of the POC (not shown). This implies that the organic-poor suspended particles are distributed in the central part of the bay.
3.2 Vertical distributions of water temperature, salinity, sigma-t, TSM, POC, PON and PP

Figure 4 shows the vertical distributions of water temperature, salinity, sigma-t, TSM, POC, PON and PP at Stn. A7, which is located near the boundary between the inner part and the central part of the bay. The temperature, salinity and TSM were uniform from the surface to 5 m depth. From a depth of 5 m to 7 m below the sea surface, pycnocline was developed, generated by the temperature and salinity stratifications. From 15 m depth to the bottom, the TSM increased rapidly with depth. On the other hand, the POC, PON and PP were high in the surface layer and low in the bottom layer. A similar distribution pattern was also observed at Stns. 12 and A10 along the boundary and did not change during the observation period. These results indicate that the structure of water quality in this area consists of three layers: from the sea surface to 5 m depth, from 5 m to 15 m depth, and from 15 m depth to the bottom.

3.3 Temporal variations of current velocity and TSM

The temporal variations of current velocity and TSM in the bottom layer at Stn. 12 is shown in Fig. 5. The bottom flow shows a periodic change with the period of about 12 h. A similar flow pattern was also observed in the three layers at Stn. A7, as well as in the surface and middle layers at Stn. 12. On the other hand, at Stn. A10 near the coast, the average flows were dominant: west-southwestward in the surface layer, south-southwestward in the middle layer and southward in the bottom layer (Fig. 6(a)). The temporal variations between the current velocity and TSM in the bottom layer
Fig. 4. Vertical distributions of water temperature (T), salinity (S), sigma-t (σt), total suspended matter (TSM), particulate organic carbon (POC), particulate organic nitrogen (PON) and particulate phosphorus (PP) at Stn. A7.

Fig. 5. Temporal variations of total suspended matter (TSM) concentration and current velocity in the bottom layer (0.5 m above the bottom sediment) at Stn. 12.

did not show any significant correlations at all stations. These results indicate that suspended particles in the bottom layer were not merely resuspended bottom sediments by water flow, but mainly were transported from the adjacent areas.

3.4 Averages flow and flux of TSM in the inner part of Osaka Bay

Figure 6(a) shows the average flow (residual flow) vectors calculated by harmonic analysis of the current velocity. The average flows at all stations tended to decrease from surface to bottom. A minimum velocity of 1 cm s$^{-1}$ was measured in the bottom layer at Stn. 12. At this station, the average flow in the surface layer was to northeast and that in the middle layer to east-northeast, both flowing toward the inner part of Osaka Bay. At Stn. A7, the direction of the average flow in the surface layer was opposite to those in the middle and bottom layers. The average flows in the three layers at Stn. A10 were larger than those at Stns. 12 and A7. In particular, the average flow in the surface layer at Stn. A10 was faster than 20 cm s$^{-1}$. These average flows appeared to circulate in a clockwise direction in the inner part of the bay. Its current pattern corresponds well to the Nishinomiya coastal circulating flow and the southward residual flow along the east coast of Osaka Bay from the mouth of the Yodo River (Yanagi and Takahashi, 1988; Fujiwara et al., 1989).

The TSM flux was calculated by multiplying TSM concentration by current velocity. The average TSM fluxes per unit area are shown in Fig. 6(b). Since the temporal
variation of TSM was small, being in the range of 2 to 8 mg l\(^{-1}\) during the observation period, the direction of the TSM flux corresponded to that of the average flow. However, the TSM flux in the bottom layer was large, even with the low average flow, because TSM in the bottom layer was a few times larger than that in the surface and middle layers. The TSM flux was the largest in the surface layer at Stn. A10 with a maximum value of 600 mg m\(^{-2}\) s\(^{-1}\).

3.5 TSM, POC, PON and PP transport through the boundary between the inner and central parts of Osaka Bay

The fluxes of suspended particles being transported through the boundary between the inner and central parts of Osaka Bay were estimated as follows. First, the components of the average flow which are normal to the boundary were calculated using the average flow distribution shown in Fig. 6(a). The boundary was then divided into a matrix of 9 boxes corresponding to three measuring stations horizontally and the three layers vertically (from sea surface to 5 m depth, from 5 m to 15 m depth, and from 15 m depth to the bottom as shown in Fig. 4). Since the average depth of the boundary was 18.4 m according to the chart, D1, D2 and D3 in Fig. 7(a) were set to 5, 10 and 3.4 m, respectively. The daily variation of mean water level was considered small enough to be neglected. The L3 was set to 6500 m based on the horizontal distribution of salinity in the surface layer. On the other hand, in order to determine the horizontal distances of L1
and L2, a mathematical calculation was made based on the assumption that net volume transport through the entire boundary must be zero. According to the measurements of horizontal distribution of current velocity with an ADCP (Acoustic Doppler Current Profiler) by the Hydrographic Department of the Maritime Safety Agency (unpublished data), the current velocities near the northern and southern shores of the boundary in September 1994 were extremely low. Therefore, average flows just at the both shore lines were consequently assumed to be zero. The distributions of average flows from the northern shore to Stn. 12 and from the southern shore to Stn. A10 were then respectively estimated by linear interpolation. By these assumptions, together with the whole data extrapolations, the distances of L1 and L2 were thus determined to be 14800 m and 4300 m, respectively. Water flow volume per box was calculated by multiplying average flow (Fig. 7(a)) by the area of the box.

Figure 7(b) shows TSM transport per day calculated by multiplying water flow volume by TSM concentration. The maximum TSM transport from the central part to the inner part of the bay was in the surface layer at Stn. 12, and the maximum TSM transport from the inner part to the central part was in the surface layer at Stn. A10. The TSM transport through the entire boundary from the inner part to the central part of the bay was 1423 ton day$^{-1}$ while that from the central part to the inner part of the bay was 1466 ton day$^{-1}$, making the balance of 43 ton day$^{-1}$ from the central part to the inner part of the bay. The direction of TSM transport balance obtained here agrees with the one calculated using a box model analysis by Yanagi et al. (1993). Hoshika et al. (1994) made it clear that a large amount of suspended particles is supplied to the Akashi Channel by the Yodo and other rivers during floods, the suspended particles then being retransported to adjacent areas. Their results also supports the results of our calculations.

Figures 7(c), (d) and (e) show the transport of POC, PON and PP per day calculated by the same method as for the TSM. The POC, PON and PP transport of each box were directed in the same direction as that of the TSM. Since the concentrations of POC, PON and PP were high in the surface layer and low in the bottom layer, it is thought that most of the transport took place through the surface layer. The POC, PON and PP transport from the inner part to the central part of the bay were 428 ton day$^{-1}$, 82.1 ton day$^{-1}$ and 11.2 ton day$^{-1}$, respectively, and those from the central part to the inner part of the bay were 339 ton day$^{-1}$, 59.3 ton day$^{-1}$ and 9.77 ton day$^{-1}$, respectively, for the entire boundary. This means that the POC, PON and PP as a whole were transported from the inner part to the central part at the rates of 89 ton day$^{-1}$, 22.8 ton day$^{-1}$ and 1.43 ton day$^{-1}$, respectively. The following interesting results became clear after the investigation of the balance across the entire boundary. Total suspended matter was transported from the central part to the inner part of Osaka Bay, while POC, PON and PP were transported in the reverse direction. The POC:PON:PP atomic ratios of fluxes of suspended particles transported from the inner part to the central part of the bay and transported in the reverse direction are 99:16:1 and 89:13:1, respectively, the former ratio being very close to the Red Field Ratio of planktonic organic matter. These results indicate that suspended particles with low organic content are transported from the central part to the inner part of the bay, while suspended particles with higher organic content are transported from the inner part to the central part of the bay. On the other hand, total phosphorus (TP) transport through the surface layer from the inner part to the central part of the bay was estimated as 26.5 ton day$^{-1}$ in September 1985 (Yuasa et al., 1993). Our results suggest that the net flux of PP transported through the surface layer was 3.24 ton day$^{-1}$ in the same direction (Fig. 7(e)). The transport of TP can then be estimated as 10 ton day$^{-1}$ on the base of the TP/PP ratio of 3 of the standing stocks in the bay (Montani et al., 1991). This value is of the same order as that found by Yuasa et al. (1993).

Furthermore, we discuss the circulation of suspended particles in the inner part of Osaka Bay based on the results of our observation. The balance equation of TSM in the inner part of the bay in the steady state is expressed as follows:

$$Q_{\text{river}} - Q_{\text{sediment}} + Q_{\text{flow}} + \alpha = 0$$

where $Q_{\text{river}}$ is the inflow flux from Yodo and Yamato Rivers, $Q_{\text{sediment}}$ is the sedimentation flux, $Q_{\text{flow}}$ is the net flux transported through the entire boundary (the plus sign denotes the flux from the central part to the inner part of the bay) and $\alpha$ is the generation-decomposition flux of TSM. The $Q_{\text{river}}$ can be obtained from the product of the average inflow per day of fresh water in September 1994 (13.7 × 10$^6$ m$^3$day$^{-1}$) and the TSM concentration of the fresh water (38 mg l$^{-1}$) (River Bureau, Ministry of Construction, 1995). The $Q_{\text{sediment}}$ can be calculated by multiplying the sedimentation rate of 8.3 g m$^{-2}$day$^{-1}$ (Hoshika et al., 1994) by the horizontal area of the inner part of the bay (311.2 × 10$^6$ m$^2$). Therefore, the $Q_{\text{river}}, Q_{\text{sediment}}$ and $Q_{\text{flow}}$ are 521 ton day$^{-1}$, 2583 ton day$^{-1}$ and 43 ton day$^{-1}$, respectively. Consequently, the generation-decomposition flux of TSM ($\alpha$) is estimated to be 209 ton day$^{-1}$ from Eq. (1). The inflow flux from the rivers and net flux transported through the entire boundary are 20% and 2% of the sedimentation flux of TSM, respectively. These results indicate that most of TSM in the sea water is produced by primary production and the TSM is circulated in the inner part of the bay.

On the other hand, Montani et al. (1991) showed that the flux of total nitrogen (TN) flowing out from the inner part of the bay to the outer area due to water exchange was...
larger than the amount of organic nitrogen removed by sedimentation by a factor of about 10. The sedimentation flux of organic nitrogen in the inner part of the bay is estimated to be 9.4 ton day$^{-1}$, a value obtained by multiplying the sedimentation flux of TSM by the contents of organic nitrogen (3.7 mg g$^{-1}$) in the surface sediment (0 to 1 cm) (Hoshika et al., 1994). In this present study, the net flux of PON transported from the inner part to the central part of the bay was found to be 22.8 ton day$^{-1}$. The transport of TN can then be estimated as 103 ton day$^{-1}$ on the base of the TN/PON ratio of 4.5 of the standing stocks in the bay (Montani et al., 1991). The results of our calculations also coincide with those given by Montani et al. (1991).

The main conclusions obtained from this study are as follows:

1. A large amount of suspended particles with low organic content were transported from the central part to the inner part of Osaka Bay, because they were more densely distributed in the central part than in the inner part of the bay.

2. In the inner part of the bay, large amounts of nutrients and pollutants are supplied from rivers such as the Yodo and the Yamato, and primary production is high. Therefore, the suspended particles with a higher organic content were transported from the inner part to the central part of the bay, mainly through the surface layer along the east coast of the bay.

References


