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ENVIRONMENTAL CONDITIONS AND THE DISTRIBUTION OF BENTHIC MACROINVERTEBRATES IN THE ESTUARY OF THE TOYO RIVER, JAPAN

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ABSTRACT

The Toyo River is one of the major rivers flowing into Atsumi Bay, a part of Ise Bay, central Japan. We measured water depth, temperature, salinity, turbidity, and dissolved oxygen levels and analyzed bottom sediments in the estuary of the Toyo River to determine the relationship between benthic macroinvertebrate distributions and these variables. We also performed stable isotope analysis for benthic invertebrates, sediments, and suspended solids to investigate the food sources of the benthic macroinvertebrates.

Bivalves such as Japanese littleneck (*Ruditapes philippinarum*), Japanese corbicula (*Corbicula japonica*), and mussel (*Musculista senhousia*) were commonly found, and their abundance was mainly controlled by salinity. Water depth also affected the distribution of macroinvertebrate taxa. The biomass of these three bivalves was large in relatively shallow areas characterized by sandy sediments. Bottom anoxia in the area offshore of the river mouth can negatively impact the suitability of habitat near the river mouth.

Stable isotope analysis showed that bivalves feed on organic compounds supplied from both the river and bay. Organic compounds can be food for bivalves and also the cause of oxygen consumption. This suggests that the topography of the estuary substantially affects the value of the habitat for bivalves. Since parts of this area have been excavated and deepened, the restoration of shallow estuary areas will improve the quality of the habitat and increase the biomass of bivalves, leading to the accelerated consumption of organic compounds without causing anoxia.

Keywords: benthic macroinvertebrate, estuary restoration

1. INTRODUCTION

The estuary of the Toyo River, Aichi, Japan has been substantially altered by anthropogenic impacts resulting from the construction of a flood diversion channel, excavation of the riverbed, reclamation of tidal flats, and an increase of water pollutant load. Anoxic bottom water in the bottom of Atsumi Bay, which occurs during summer, is often upwelled to the coastal area by wind-driven currents and has led to the destruction of benthic ecosystems. When large-scale upwelling occurs, the anoxic waters even intrude into the river channel and negatively impact the aquatic ecosystem in the estuary. The depth of the Toyo River channel has been increased by excavation. This alteration has made the downstream end of the Toyo River more saline and more vulnerable to the intrusion of anoxic water from the bottom of Atsumi Bay.

A restoration plan for this area is under preparation. This plan is a part of the Toyo River Environmental Restoration Project and the restoration of benthic ecosystems is a major concern. The construction of shallow areas that mimic tidal flats are planned for previously excavated deep areas in the river channel as a pilot project. This study aims at understanding the correlation between the physical environment and macroinvertebrate distributions within this area. The information obtained in this study can help in the design of the shallow areas to be constructed, ensure that they are suitable for native macroinvertebrates, and improve accuracy in assessing the outcome of the construction. We have conducted several surveys and performed numerous analyses to fulfill these purposes.

2. TOYO RIVER

2.1 General description

The Toyo River is one of the largest rivers flowing into Atsumi Bay, a part of Ise Bay (Figure 1). It has a watershed area of 724 km^2, and the length of the main stem is about 77 km. The highest elevation in the drainage basin is 1152 m at the summit of Mt. Danto-san. Total population in the watershed is about 210,000 residents. The Toyo River starts in a mountainous area, flows through upland areas, confined valleys and an alluvial plain, and empties into Atsumi Bay. The Toyo River passes through landscapes typical of Japanese rivers (i.e., forested mountain, steep valley, alluvial plain used for rice fields, and densely populated urban areas).

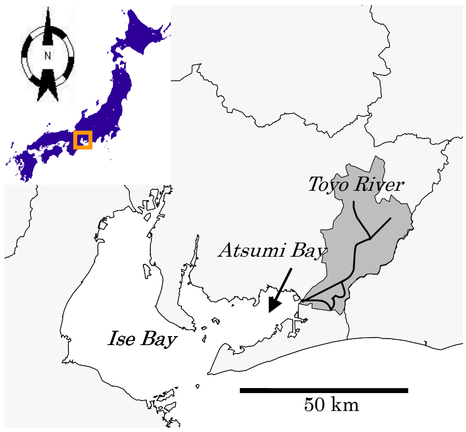

Figure 1 Plan view of Toyo River.

2.2 Historical environmental changes around the Toyo River estuary

The areas around the downstream segment and estuary of the Toyo River have been substantially altered since the 1960s. A flood diversion channel was completed in 1965 and a large area of tidal flats in the estuary was reclaimed for the construction of a water quality control facility at the mouth of the river, which started operation in 1980 (Figure 2). In addition to these large projects, the river was excavated to supply concrete aggregate until 1970. A large-scale irrigation system that supplies water withdrawn from the Toyo River to the Atsumi peninsula started operation in 1968, which reduced the water flow in the Toyo River estuary. These anthropogenic impacts have resulted in the loss of tidal flats around the river mouth and changed the habitat distribution within the estuary area.

Following these alterations to the downstream end of the Toyo River, there may have been an increase in salinity within the river channel. Thus, the restoration project in the Toyo River estuary area includes plans to construct shallow areas to recreate a

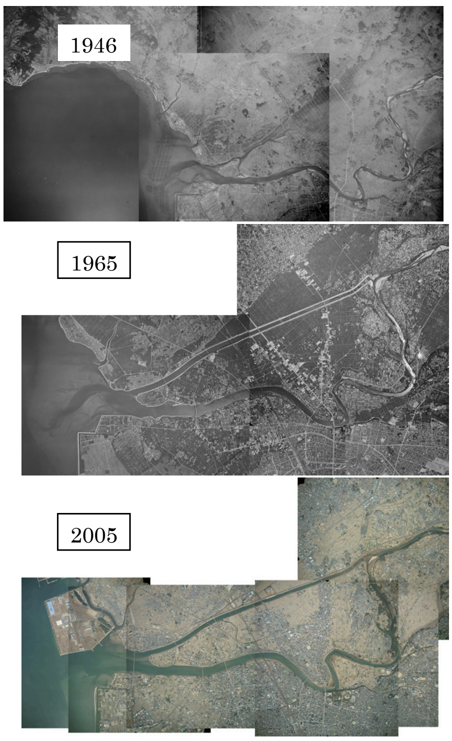

Figure 2 Historical changes in Toyo River estuary area.

topography similar to that before these impacts.

3. METHODS

3.1 Topographic surveys

We conducted detailed topographic surveys from 13 to 23 February 2007 over a 6.8-km length of the downstream end of the Toyo River and in the tidal flats around the river mouth using a depth sounder (Type PDR1300, Senbon Electric Inc., Numadzu, Japan) mounted on a boat. The location of the boat was tracked by a global positioning system (GPS; AgGPS 124, Trimble Navigation Ltd., Sunnyvale, CA, USA). The elevation of the riverbed or tidal flat was calculated using the record of the sounding and the tidal level at the time of measurement.

3.2 Water quality measurements

Temperature, salinity, turbidity, and dissolved oxygen (DO) data were recorded every 10 min at the surface and bottom at five stations from 12 May to 2 June 2007 (Figure 3) using multiparameter water-quality monitoring sondes (YSI6000, YSI Inc., Yellow Springs, OH, USA). Sondes for monitoring surface water quality were suspended from buoys 50 cm beneath the water surface such that they followed fluctuations of the water surface. Those for monitoring bottom water quality were set 50 cm above the bottom sediments.

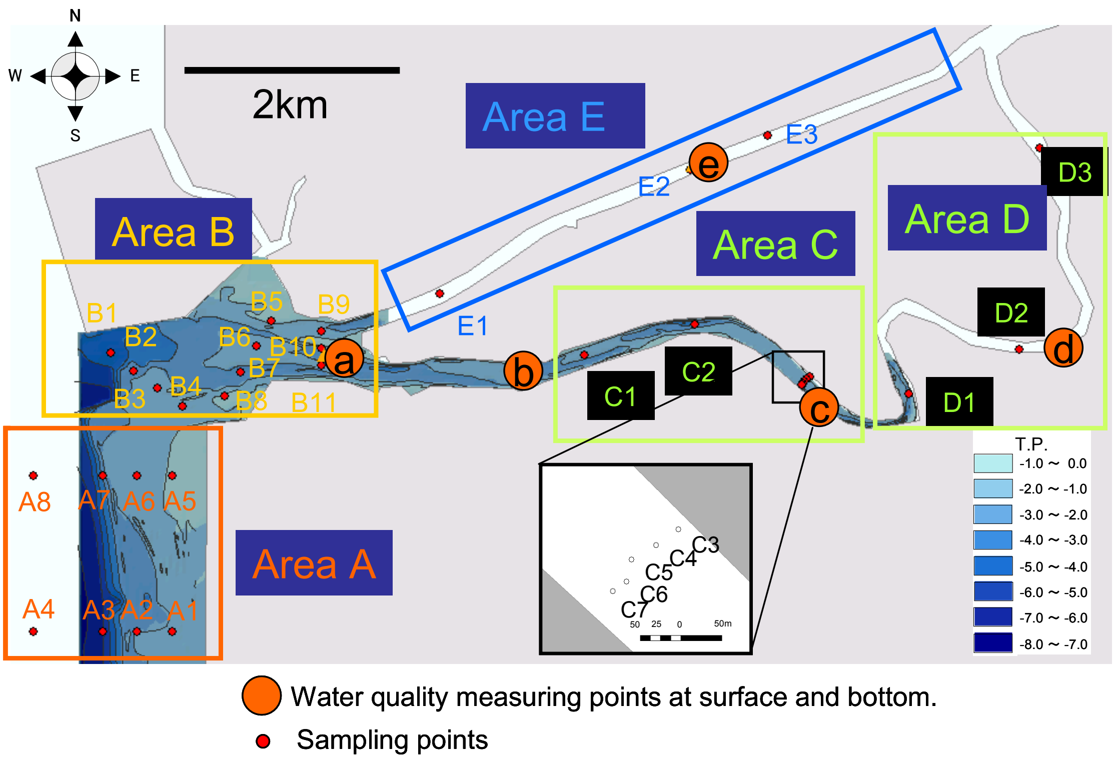

Figure 3 Monitoring and sampling locations and initial area classification.

3.3 Sampling and analysis of water and bottom sediments

Water and bottom sediments were collected from 32 sampling points. These sampling points were distributed in five areas, each of which was thought to represent a different habitat for benthic macroinvertebrates (Figure 3). Eight sampling points were allocated to Area A, which represents tidal flats along the coastline. Area B is located at the river mouth and has complex topography. Eleven sampling points were allocated to Area B. Area C, with seven sampling points, is located in the river channel, which is strongly influenced by saline water. Area D, with three sampling points, also includes the river channel. However, this upstream area is not affected by saline water as much as Area C. Area E is the flood diversion channel and has three sampling points. Water and bottom sediments were sampled from 28 February to 2 March 2007.

Water was collected using a 5-L Van Dorn sampler from a depth half the bottom depth at each point. Bottom sediments were obtained by using a Smith-McIntire sediment sampler (0.05 m^2). Water and sediment samples were stored in a cooler for transport to the laboratory and then kept frozen (-20°C) until analysis.

Particulate organic matter (POM) was defined as the organic particulates in the total suspended solids in water samples, which were collected on precombusted (400 °C for about 2 h) GF/C glass-fiber filters (mean pore size, 1.2 µm; Whatman International Ltd., Kent, UK). The concentration of total suspended solids was determined from the difference in the dry weight of the filters before and after filtration. The total suspended solids samples used for isotope analysis of POM were dried at 60 °C and put into a desiccator and exposed to HCl fumes overnight to eliminate inorganic carbon, such as calcium carbonate ($CaCO_3$).

All samples that were dried for carbon and nitrogen isotope analysis were crushed well and homogenized by using a ceramic mortar and pestle. The stable isotope ratios were determined using a mass spectrometer (Delta Plus XL, Thermo Electron, Bremen, Germany) equipped with an elemental analyzer (Flash EA 1112, Thermo Electron, Milan, Italy); the molar C/N ratio was also simultaneously determined. Isotope ratios are expressed as the deviations in parts per thousand (‰) from a Pee Dee Belemnite standard for carbon and from atmospheric nitrogen gas for nitrogen, according to the accepted isotope terminology (Fry, 2006):

$$\delta^{13}C \quad \text{or} \quad \delta^{15}N = \left(R_{sample}/R_{s\tan dard} - 1\right) \times 1000, \qquad (1)$$

where R is the corresponding ratio of $^{13}C/^{12}C$ or $^{15}N/^{14}N$ of the sample or standard. Analytical precision was better than ±0.2‰ for carbon and ±0.3‰ for nitrogen.

The particle size distribution of bottom sediment samples was determined by following Japanese Industrial Standards (JIS) procedure A1204. The total nitrogen (TN) and total organic carbon (TOC) contents in bottom sediments were measured by an organic elemental analyzer (Micro Corder JM10, J-Science LAB, Kyoto, Japan). The total phosphorus (TP) concentration in bottom sediments was determined by the molybdenum blue method using a spectrophotometer (V-530, JASCO, Hachi-ohji, Japan).

3.4 Sampling and analysis of benthic macroinvertebrates

Benthic macroinvertebrates were sampled in duplicate by using a Smith-McIntire sediment sampler (0.05 m^2) at 32 points, the same as the water and sediment sampling points on the same day of water and sediment sampling. Sampled sediments were sieved with a 1-mm mesh sieve on the survey boat to collect macroinvertebrates in sediment samples. Macroinvertebrate samples were stored in 10% formalin and individuals identified later in the laboratory. A few individuals of each bivalve species were picked out at the same time and stored in a cooler for isotope analysis.

Identification of macroinvertebrates was done in the laboratory and the number collected and the wet weight were recorded for each taxa. The stable isotope ratios for carbon and nitrogen were determined by the same procedure used for POM.

3.5 Benthic macroinvertebrate assemblage analysis with environmental variables

We performed canonical correspondence analysis (CCA) to explore the relationships between environmental variables and benthic macroinvertebrate assemblages by using PC-ORD (version 5, MjM Software Design, Gleneden Beach, OR, USA). We analyzed the relationships between the invertebrates taxa collected and the environmental variables of salinity, mean depth, and particle size and organic matter content of bottom sediments. The salinity values used for this analysis in the river section (Areas C and D; Figure 3) were estimated by interpolating mean salinity values obtained from 20 days of continuous measurement. Based on this analysis, we also determined how sampling point locations were related to these environmental variables. A Monte Carlo permutation test with 999 permutations was performed to test if benthic macroinvertebrates were related to environmental variables on the first axis eigenvalue.

4. RESULTS

4.1 Topography and bottom sediments

Although the riverbed of the downstream end of the Toyo River had been excavated, the area around the mouth of the river is shallow overall. The mean water depth in most parts of the survey area is shallower than 5 m, using the mean sea level of Tokyo Bay (Tokyo Peil, T.P.) as a reference. Figure 3 includes a contour map showing the bottom topography. The following is a summary of the topography and bottom sediment characteristics (Figures 4 and 5) for the five survey areas.

Area A: A shallow area (about 1 to 2 m deep) and covered by sand near shore, extending about 1 km from the coastline, and including an area with a steep slope that connects to a deeper area (depth, about 8 m). The deeper area, represented by points A4 and A8, has bottom sediments consisting of silt and clay (Figure 4). The organic matter concentration is high in this deep area (Figure 5).

Area B: The main channel (original river channel) and flood diversion channel merge in this area. The topography in this area is complicated. Bottom sediments in this area seem to move and large floods can change the bottom structure. A deep area is located close to the reclaimed land in the northwest corner of this area. This was created by excavation for the reclamation project, and bottom sediments here include clay and silt (Figure 4, B1) and have high concentrations of organic matter and nutrients (Figure 5, B1).

Area C: Bottom sediments in this area are coarser than those in Areas A and B, due to the flushing effect of the river current. Meandering of the river channel results in an asymmetric cross section. Sampling points C3 to C7 were located across the river channel from the right to left bank of the river (Figure 3). Points C6 and C7 are deeper than C3 by about 1 m. However; unlike in Areas A and B, the deeper points have coarser bottom sediments because the current in the river channel tends to be faster in the deeper portion along the river bank.

Area D: This area is located upstream of Area C and is least affected by saline water. Although the sediment features at D1 and D2 are not very different from those at many points in Area C, D3 has finer bottom sediments. D3 is located in an area with a pool-like morphology and this may allow the accumulation of fine sediments at the bottom even in the river channel.

Area E: Because this area encompasses the flood diversion channel, freshwater flow is very low except during floods. The bed slope is steeper than that of the main river channel in the section located upstream of E2, and bottom sediments consist of coarser material in this section (Figure 4). However, very fine sediments such as clay and silt were found in proportions similar to those in Area B. This is different from what is found in Areas C and D in the main river channel. The low volume of freshwater flowing downstream allows fine material from the bay to be transported and deposited during high tide. This clay and silt may be flushed out of the channel during flood diversion.

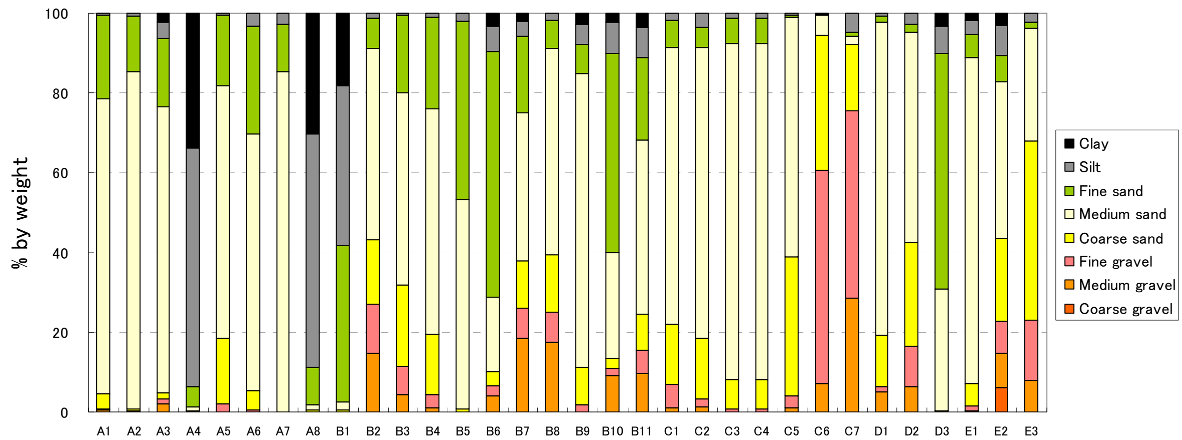

Figure 4 Particle size distribution for bottom sediments at sampling points.
Particle sizes are categorized as follows (all sizes are in mm): clay < 0.005 < silt < 0.075 < fine sand < 0.25 < medium sand < 0.85 < coarse sand < 2.0 < fine gravel < 4.75 < medium gravel < 19 < coarse gravel < 75.

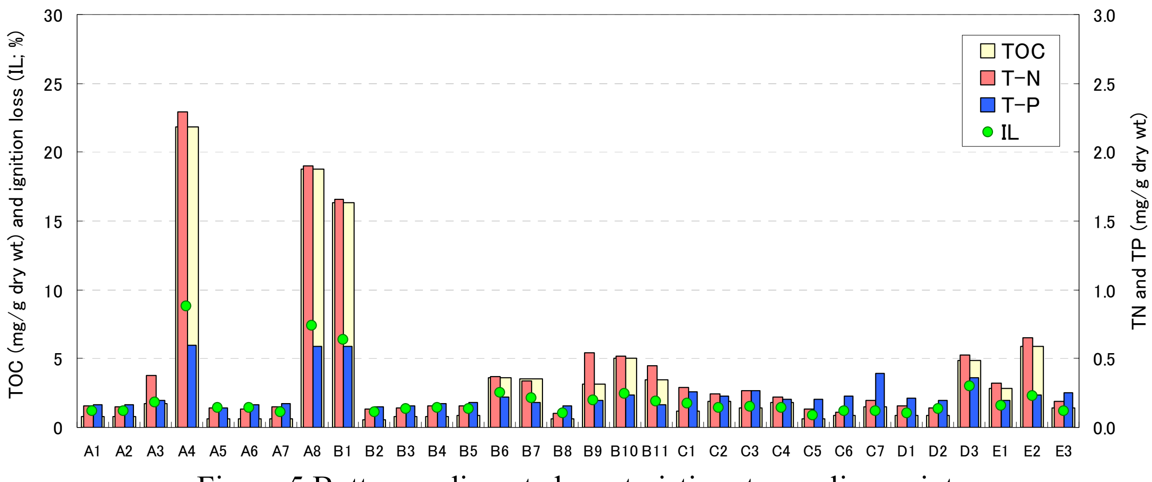

Figure 5 Bottom sediment characteristics at sampling points.

4.2 Salinity and dissolved oxygen

The salinity of the bottom layer at stations a and b is as high as that of sea water during high tide, whereas it drops substantially during low tide. The diel fluctuation of salinity frequently exceeds 20 psu at these sites. Although the magnitude of fluctuation is similar, the salinity is lower at station c. Saline water intrusion reaches to station d when the freshwater flow is low and the diel tidal level fluctuation is low. Because the freshwater flow is very low in the flood diversion channel, the salinity at station e does not drop as much as that at

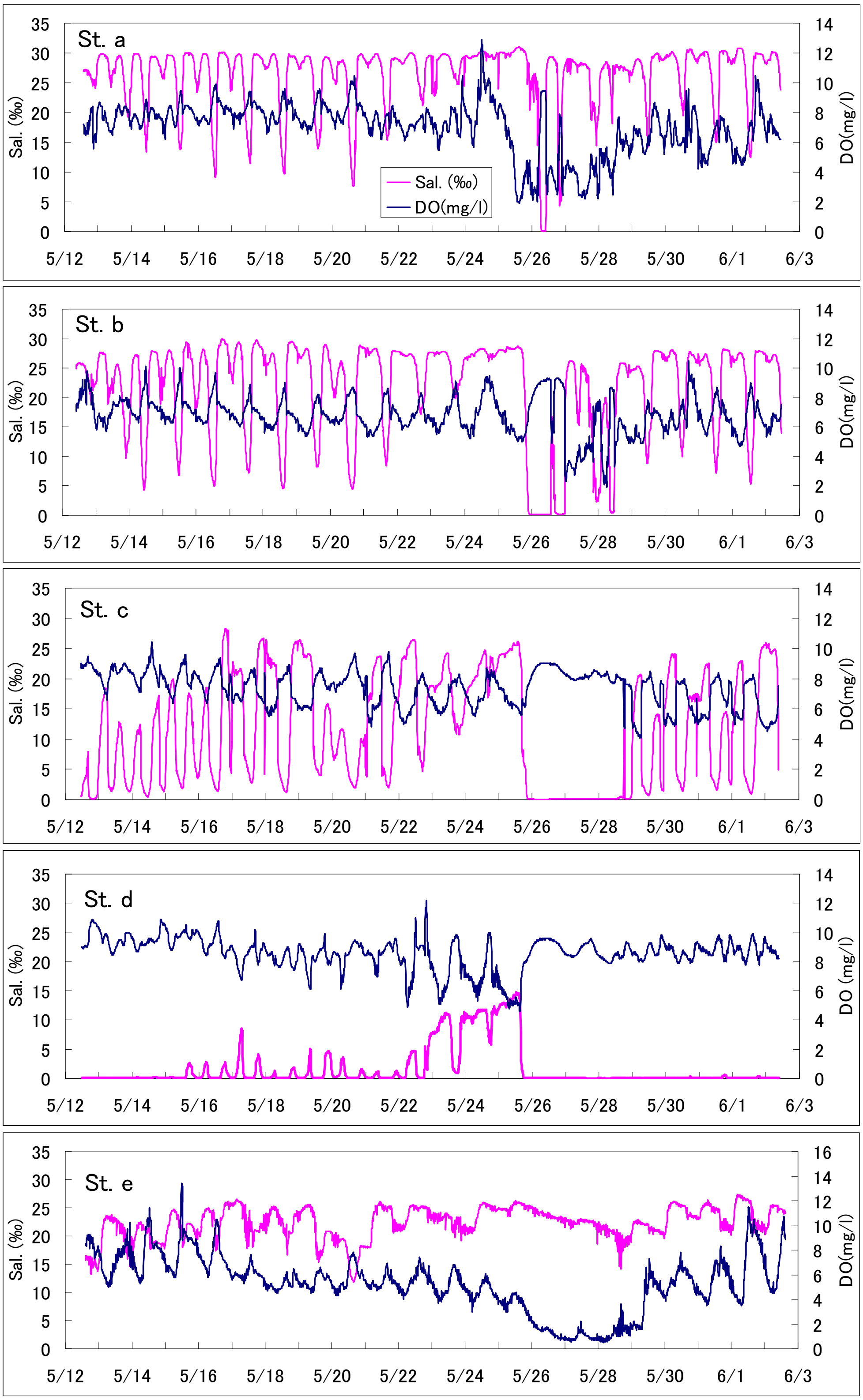

Figure 6 Salinity and DO at the bottom layer.

stations a, b, and c during low tide. The flood diversion channel, initially classified as Area E, seems to have a more brackish environment than the main river channel (Figure 6).

Fluctuations of DO concentrations are negatively correlated with those of salinity. DO decreased during high tide and increased during low tide. During the survey period, there was an increase of river flow up to an hourly maximum flow rate of 480 m^3/s on 25 May. This flood occurred during the period of neap tide and vertical mixing in the estuary was minimal, leading to the further intrusion of saline water upstream and to the decrease in DO at the bottom in the survey area. Because flood diversion was not performed during this flood, there was low freshwater flow through Area E, which was occupied by hypoxic saline water (Figure 6). The development of anoxic bottom water in Atsumi Bay is frequently observed during the summer (Aichi Prefectural Fishery Laboratory, 2008). When this anoxic bottom water develops, the area around the mouth of the Toyo River seems to be notably affected during neap tide by the depletion of DO.

4.3 Macroinvertebrates

The Japanese littleneck (*Ruditapes philippinarum*) was dominant within Areas A and B. *Ruditapes philippinarum* was also found at E1 in Area E. *Batillaria multiformis* and *Batillaria cumingii* were found in shallow areas (i.e., B5 and B8) that are exposed during low tide. Japanese corbicula (*Corbicula japonica*) was abundant in Area C; however, it was not found at C1, which is the sampling point closest to the river mouth within Area C. Instead of *C. japonica*, at C1 we found large numbers of *Musculista senhousia*, which prefers a more saline environment than that preferred by *C. japonica*. *Corbicula japonica* was also found at D1, D2, and E3, although their number was low at D2 and E3.

4.4 Benthic macroinvertebrate assemblage and environmental variables

The benthic macroinvertebrate assemblage was analyzed, focusing on shellfish. Benthic macroinvertebrates in the survey area can be classified into six groups in terms of preferences in the physical environment (Figure 7). Salinity was the primary environmental variable affecting the emergence of macroinvertebrates. The number of shellfish taxa found in saline environments (Areas A and B) was higher than in brackish or freshwater environments (Areas C and D).

Water depth was the second most important environmental variable influencing the habitat of shellfish. Bottom sediment features such as particle size and organic matter content have a strong correlation with water depth (Figure 7). The concentrations of organic matter and nutrients have a positive correlation with fine particles such as clay and silt (Figures 4 and 5). Finer sediments do not stay deposited in shallow areas because of resuspension by waves and currents; thus, water depth strongly affects the bottom sediment characteristics.

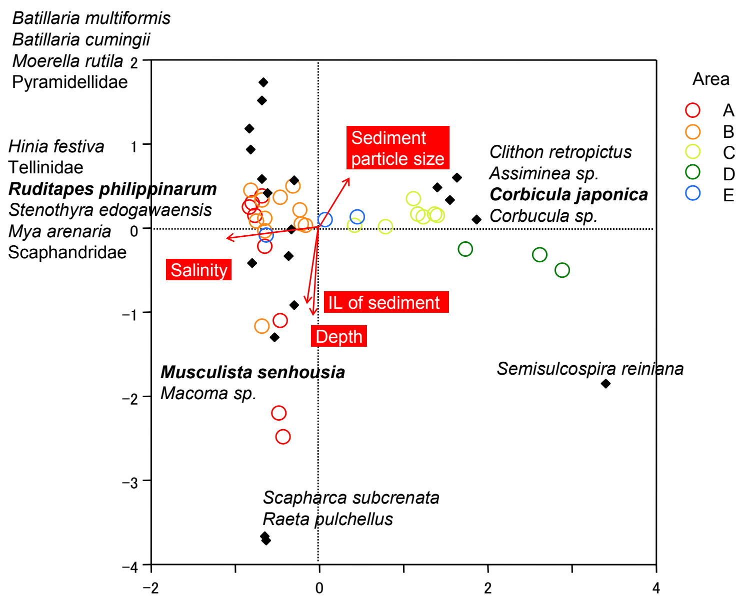

Figure 7 Results of CCA analysis plotted on two axes. Black dots represent the positions of the taxa. The length of an arrow and its closeness to CCA axes means its strength.

Three of the most abundant bivalve species had different habitat preferences. *Ruditapes philippinarum* preferred saline and shallow areas (depth about 1 to 3 m).

Musculista senhousia was also abundant in saline areas; however, it also seems to prefer deeper areas. *Corbicula japonica* was commonly found in brackish environments (around 5 to 20 psu). These salinity preferences are consistent with those previously reported (Ishida and Ishii, 1971; Tanaka, 1984; Ito, 2002).

Batillaria multiformis and *B. cumingii* are snails that graze on organic materials and marine macroalgae . Because this feeding behavior requires an undisturbed habitat, they were found in a shallow and stable area half enclosed by land (B5 and B8).

4.5. Food sources of bivalves

The phenomenon known as trophic enrichment results in higher $\delta^{15}N$ and $\delta^{13}C$ values for consumers compared to their food. The values for $\delta^{15}N$ increase by 2.2‰ to 3.4‰ and values for $\delta^{13}C$ increase by 0‰ to 1‰ (DeNiro and Epstein, 1981; Minagawa and Wada, 1984; Post 2002; McCutchan et al. 2003). Because the bivalves analyzed here are filter-feeders, their $\delta^{13}C$ and $\delta^{15}N$ values should increase by these amounts compared to the values in the POM in suspended solids or bottom sediments, which are assumed to be their food. The $\delta^{13}C$ and $\delta^{15}N$ values for *R. philippinarum* and *M. senhousia* were in almost the same range (about -16‰ to -20‰ for $\delta^{13}C$ and about +9‰ to +12‰ for $\delta^{15}N$), and suspended solids from coastal areas seems to be their diet, based on the differences in $\delta^{13}C$ and $\delta^{15}N$. The $\delta^{13}C$ values for *C. japonica* had a wide range, from –20‰ to –26‰. *Corbicula japonica* samples obtained from downstream sites had larger $\delta^{13}C$ values, implying that they feed on more suspended solids from coastal areas (Figure 8).

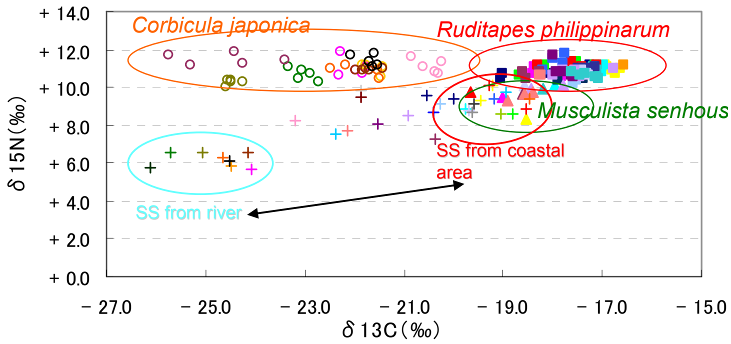

Figure 8 Stable isotope ratios for the three predominant bivalves and for suspended solids (SS)
(Circles, *C. japonica*; squares, *R. philippinarum*; triangles, *M. senhousia*; crosses, suspended solids.)

5. DISCUSSION

Before this study was carried out, the estuary area of the Toyo River was classified into five areas based on the expected habitats for benthic macroinvertebrates (Figure 3). Field surveys and CCA analysis show that shallow regions with an average depth of about 1 to 3 m can be categorized as dominated by *R. philippinarum* within Areas A and B and the downstream end of Areas C and E. The shallow margin of Area B, which is characterized by snails such as *B. multiformis* and *B. cumingii*, is separate from the *R. philippinarum*–dominated habitat. Places deeper than 3 m, which are found offshore in Area A, can be categorized as habitats different from *R. philippinarum*–dominated habitat.

The upstream half of Area C, the downstream end of Area D, and the upstream end of Area E can be categorized as *C. japonica*–dominated brackish habitat, with an average salinity from 5 to 20 psu. Areas upstream of D2 can be categorized as freshwater habitat.

The overall classification of benthic habitat in the Toyo River estuary can be summarized as follows: Areas A and B and the downstream part of Areas C and E should be classified as saline habitat, and these can be further separated into three habitats (i.e., *B. multiformis* and *B. cumingii*–dominated habitat, *R. philippinarum*–dominated habitat, and deeper habitat). The river channel and flood diversion channel, which are upstream of the saline habitat, can be divided into two habitats based on salinity: freshwater habitat with salinities below 5 psu and brackish habitat with salinities between 5 and 20 psu.

The bathymetry of the estuary area of the Toyo River has been altered and deepened in both the saline and brackish habitats. Restoration of an *R. philippinarum*–dominated habitat in Area B should have the first priority because historically that is a typical topography for this area. The deep area created by excavation (i.e., around B1) should be filled with sand and gravel, which should lead to the restoration of habitat for benthic macroinvertebrates and suppress the emergence of anoxic water. It is also recommended that the deep area where the flood diversion channel meets the bay be covered with sand and gravel to prevent the accumulation of fine sediments. The transport of bottom sediments during floods and high tides must be studied before undertaking these works, to ensure that any recovered habitat is sustained.

Organic matter produced by phytoplankton and benthic algae in coastal areas, and POM transported by the river, are presumed to be important sources of food for bivalves in the estuary of the Toyo River. The results of stable isotope analysis suggest that POM from the river is mainly used only by *C. japonica* located in upstream areas seldom reached by saline water (Figure 8). Bivalves in *R. philippinarum*–dominated habitats seem to feed on organic matter produced in coastal areas. Filling in of the excavated depression around B1 will increase the intrusion of surface seawater during high tide. Surface seawater has higher concentrations of both phytoplankton and DO and should further enhance habitat conditions in terms of food and oxygen.

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REFERENCES

Aichi Prefectural Fishery Laboratory (2008), Report of anoxia in Ise and Mikawa Bay, H20-3.

DeNiro, M.J. and Epstein, S. (1981), Influence of diet on the distribution of nitrogen isotopes in animals, Geochimica et Cosmochimica Acta, 45, pp.341-351.

Fry, B. (2006), *Stable isotope ecology*, Springer, USA.

Ishida, O. and Ishii, T. (1971), Tolerance of *Corbicula japonica* to high salinity, Aquaculture Science, 19, pp.167-182.

Ito, H. (2002), What kind of animal is the clam *Ruditapes philippinarum*? - Introduction to its ecology and fishery, Japanese Journal of Benthology, 57(1), pp.134-138.

McCutchan, J.H., Lewis, W.M., Kendall, C. and McGrath, C.C. (2003), Variation in trophic shift for stable isotope ratios of carbon, nitrogen, and sulphur, Oikos, 1-2, pp.378-390.

Minagawa, M. and Wada, E. (1984), Stepwise enrichment of N-15 along food-chains: Further evidence and the relation between $\delta^{15}N$ and animal age, Geochimica et Cosmochimica Acta, 48, pp.1135-1140.

Post, D.M. (2002), Using stable isotopes to estimate trophic position: models, methods, and assumptions, Ecology, 83, pp.703-718.

Tanaka, Y. (1984), Salinity tolerance of *Corbicula japonica*, Bulletin of National Research Institute of Aquaculture, Fisheries Research Agency, 6, pp.29-32.