New Technology for Developing Biologically Productive Shallow Area in Ago Bay

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Abstract In Ago Bay, sediment eutrophication and frequent occurrence of hypoxia has caused the deterioration of benthic ecosystem and decrease of biological productivity in recent years. Furthermore, harmful algal blooms and infectious diseases make sustainable pearl culture difficult. It is considered that one of the major causes of these phenomena are stagnation of the material circulation by reduction of the shallow coastal areas. The natural shallow coastal areas were decreased everywhere in the inner parts of the bay by land reclamation and the dike construction. Then we made clear that approximately 70% of the tidal flat and shallow areas have already been decreased in Ago Bay. Therefore, for environmental restoration of Ago Bay as a major site of pearl culture, it is necessary to enhance the biological productivity which these shallow areas provide and to enhance the material circulation around the shallow areas. In this study, the suitable range of sediment quality of tidal flat for benthic species was found to be 3-10mg/g dry weight for chemical oxygen demand and 15-35% for mud content ratio. New technology for enhancing the biological productivity in the reclaimed shallow areas by controlling sediment quality was developed.

Key words: Tidal flat, biological productivity, Ago Bay, dredged sediment, macrobenthos

Introduction

Ago Bay is located in Ise-Shima National Park and is famous for the cradle of the pearl culture. However, harmful algal blooms and infectious diseases make sustainable pearl culture difficult. Furthermore, sediment eutrophication and frequent occurrence of oxygen-deficient water has caused the deterioration of the benthic ecosystem and decreased biological productivity in recent years. It is considered that one of the major causes of these phenomena is reduction of the material circulation by reduction of shallow coastal area including a tidal flat, sea grass and seaweed beds. The natural shallow coastal areas have decreased everywhere in inner parts of the bay due to land reclamation and the dike construction. Then we found out by the multi-spectrum aerial photo analysis that approximately 70% of tidal flat and shallow areas have already been lost in Ago Bay. Therefore, for environmental restoration of Ago Bay as the major site of pearl culture, it is necessary to enhance the biological productivity which tidal flats, seagrass and sea weed beds provide, and to recover good material circulation around the shallow areas. New technology for enhancing biological productivity by controlling sediment quality was developed.

Experimental Suitable Sediment Condition for the Benthic Species

To determine the suitable sediment condition for the benthic species, six experimental tidal flats in which the organic content has changed, were set up in Ago bay. The sediment qualities and benthic species of the experimental tidal flats were monitored for three years. The results indicated that the suitable range of sediment qualities of tidal flats for benthic species was 3-10mg/g dry weight for chemical oxygen demand (COD) and 15-35% for mud content ratio. By utilizing the above

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results, the two types of artificial tidal flats by controlling sediment condition were constructed in Ago Bay.

Enhancing the Biological Productivity in the Relatively Oligotrophic Tidal Flat in Front of a Dike by Using Dredged Sediment

In Ago Bay, natural tidal flats in front of the dike are relatively oligotrophic. Total area of the tidal flats is about 84 ha. The sediment of the tidal flats are gravel and contain low organic matter because the dike shut out the nutrient supply from the land. Thus, in these tidal flats, the abundance and diversity of benthos are very low. To enhance the biological productivity of such ecosystems, new artificial tidal flat using muddy dredged sediment from Ago Bay was constructed. A total area is about 7,200m^2. The artificial tidal flat was constructed by mixing muddy dredged sediment with existing oligotorophic sediment in front of the dike (Figure 1). The construction of the artificial tidal flat was completed in March, 2005.

The sediment samples from the artificial tidal flat and neighboring natural tidal flat were measured for COD, TOC, TN, IL, AVS, ORP, particle size, chlorophyll *a*, benthic abundance and species numbers every season for two years. (Figure 1). In April 2004, before construction, sediment samples were obtained and analyzed for same characteristics. To analyze for chlorophyll *a*, this sediment samples were sliced into the 1 cm sections from the surface. For analyzing other sediment characteristics, samples were sliced up to 12 cm from the surface.

Investigation of the Oxygen Consumption and the Primary Production Rate on the Artificial and Natural Tidal Flats

Two transparent chambers (made from chloroethylene diameter 25cm, height 20cm), one each on the artificial and natural tidal flats in front of the dyke, were set on their sediment surface (Figure 2). The oxygen consumption rate was measured continuously for two hours with dissolved oxygen probes in both chambers. Solar radiation was measured continuously with a light quantum sensor. The sediment samples under their chambers were measured for AVS, TOC, TN, chlorophyll *a*, DIN, and DIP (interstitial water). These measurements were carried every month in 2005. The primary production rate was calculated by subtracting the oxygen consumption rate in the dark chamber from that in light chamber.

Investigating Changes in Water Quality During Ebb and Flow on the Artificial Tidal Flat

The artificial tidal flat was enclosed in two areas with polyethylene sheets. First was all the artificial tidal flat area (DL = +1.5 m to about -1.5 m) which contained a rich macrobenthos area (DL = 0 m to about -1.5 m). Second was a relatively shallow artificial tidal flat area (DL = +1.5 m to about 0 m) that did not contain an area of rich macrobenthos (Figure 3). Water quality was investigated every hour for one day during ebb and flow conditions in the two areas. Those studies were carried on during the summer (21-22 July and 4-5 August 2005), autumn (13-14 October and 2-3 November 2005), and winter (26-27 January and

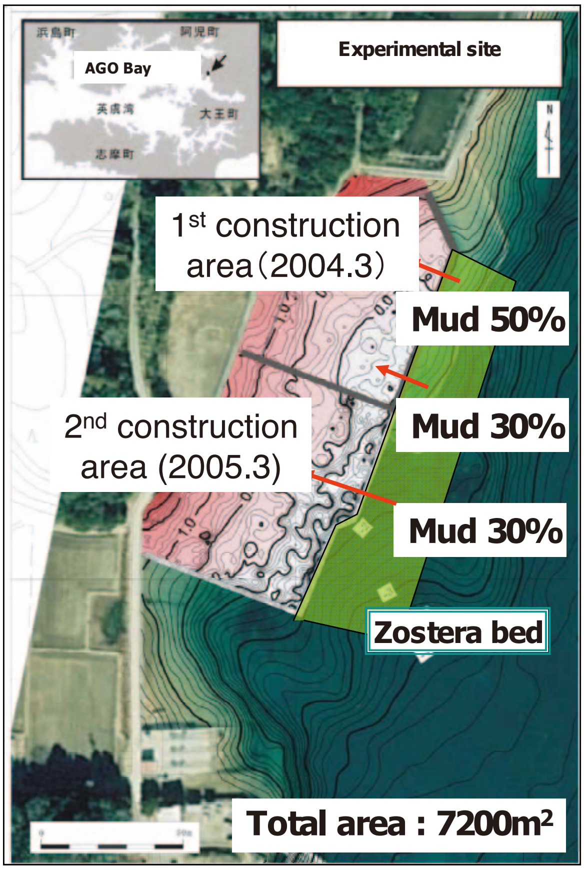

Fig. 1. Outline of the artificial tidal flat.

16-17 February 2006), during flood tides. The study areas are shown in Figure 3. DO, salinity, turbidity and pH were measured by multi-sensor every hour. At the same time, sea water samples were collected. Water temperature, depth, and light were measured on the artificial tidal flat every 10 minutes with recording instruments. The water samples were filtered in the field and analyzed for SS, chlorophyll *a*, TOC, DOC, TN, DTN, TP, DTP, DIN, and DIP.

Enhancing the Biological Productivity on the Hypertrophic Wetland Behind the Dike by Promoting Water Exchange

Behind the dike there were hypertrophic wetlands which in the past were a part of the natural tidal flats prevalent in Ago bay. Such areas add up to some 153 ha. The sediments of the wetland are muddy and contain high levels of organic matter because the dikes accumulate nutrients and organic matter due to runoff from the land. In these wetlands, the abundance and diversity of benthos are very low. Attempts were made to enhance the biological productivity by

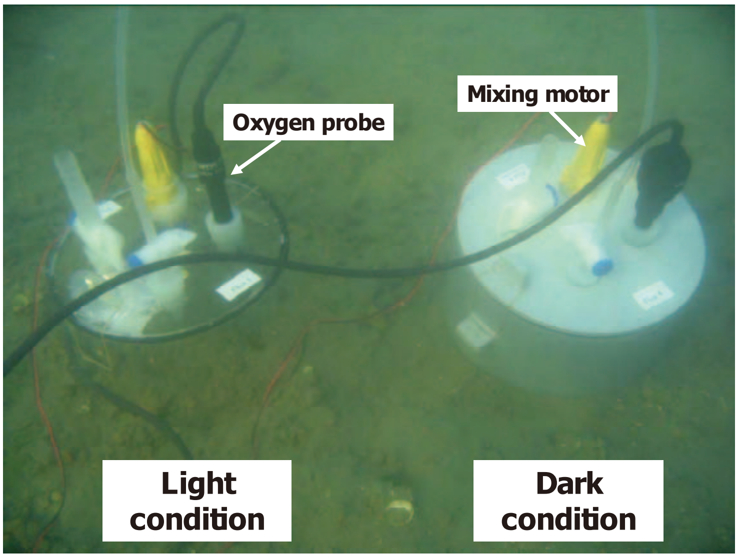

Fig. 2. Light and dark chambers on the tidal flat.

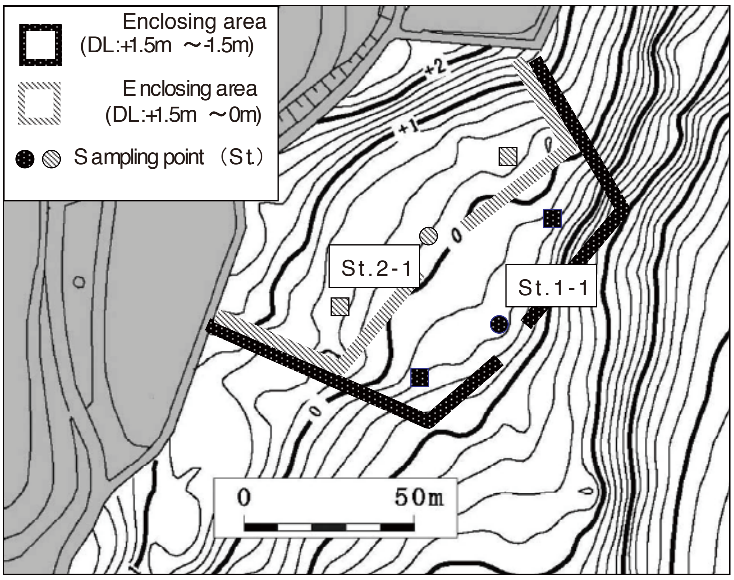

Fig. 3. Outline of the flux investigation area.

promoting water exchange between the wetland and bay using pumps in conjunction with a pipeline system. Improvements were evaluated by monitoring sediment quality, benthic abundance and species diversity seasonally.

Results and Discussion

The Function of Habitat on the Artificial Tidal Flat:

Seasonal Changes in the Abundance and Diversity of Macrobenthos

The seasonal changes in chlorophyll *a* in the sediments (DL = +0.5m) on the natural and artificial tidal flats containing 50% and 30% mud are shown in Figure 4. After two months, chlorophyll *a* on the experimental tidal flat increased significantly compared to that of the natural tidal flat. One year after construction the chlorophyll *a* on the artificial tidal flat was about four times higher than before construction. On the other hand, after one year the abundance of macrobenthos on the artificial tidal flat had increased markedly and subsequently, the chlorophyll a was the same as before construction due to greater grazing pressure. These results indicated that benthic algae increased soon after construction because dredged sediments contained rich in organic matter.

The seasonal changes in abundance of macrobenthos on the artificial tidal flat sediment (DL = +0.5m) comprised of 50% and 30% mud are shown in Figure 5.

The macrobenthos were classified as polychaeta, bivalvia, gastropoda, crastacea, and ichthyoid. Immediately after the construction, the gastropoda and the crastacea were dominant. After six months, the polychaetes and the bivalves had increased, and after 10 months, species numbers also increased remarkably compared to the present before construction, indicating increased diversity. After four months, the abundance of macrobenthos had increased significantly, and after one year they had increased four-fold compared to before construction and had reached steady state.

The recovery time for the macrobenthos in 30% mud on the experimental tidal flat was faster than that of the community in 50% mud. Furthermore, according to the results of the carbon and nitrogen stable isotope analyses, the carnivores were not present on this tidal flat. Thus, the community was in a transition phase toward stability. Therefore, these results indicated that it takes more than one year to develop a stable habitat on an artificial tidal flat.

It is clear from the study that after the construction of tidal flats, benthic algae increase first, followed by the macrobenthos. On the other hand, after the dredged sediment was mixed, deposit and suspension feeders became more abundant. Thus, the constructed tidal flat ecosystem had changed to an ecosystem with high diversity. For about one year the abundance and diversity of benthos had increased more than four-fold compared with the pre-construction situation.

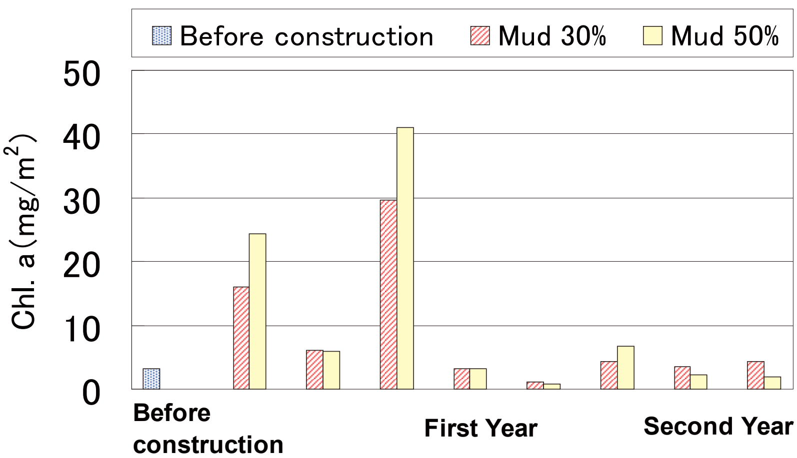

Fig. 4. Seasonal changes of chl. a in artificial tidal flat.

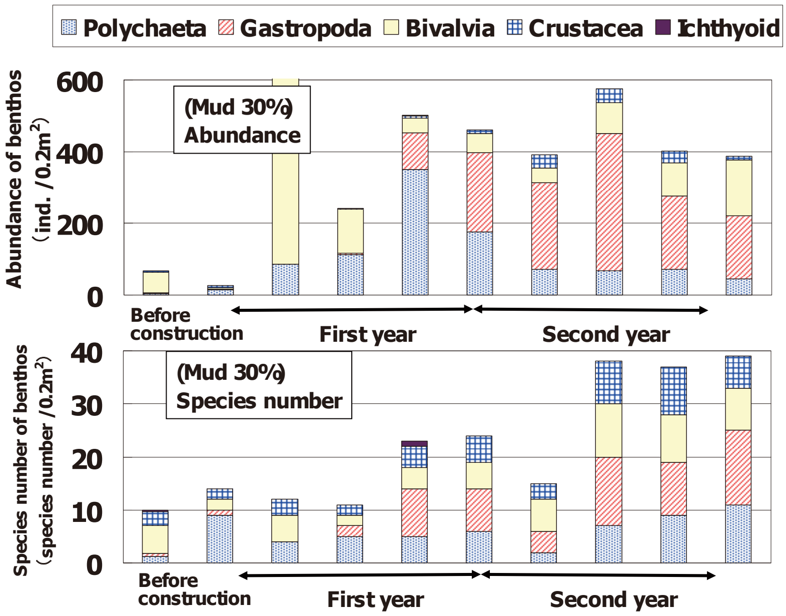

Fig. 5. Seasonal changes in abundance and diversity of the macrobenthos.

Tsopographic Change on the Artificial Tidal Flat

The changes in elevation a year beginning immediately after construction of the artificial tidal flat are shown in Figure 6. The ground elevation increased from 30-40 cm below DL= 0 m, and above DL = 0 m elevation had decreased 10-20 cm. It is thought that tidal flat sediments moved offshore. The inner part of Ago Bay in which artificial tidal flat was constructed is characterized by calm water, but it is possible that large amounts of the tidal flat sediments can be moved by turbulence caused by typhoons. Therefore, to estimate the topographic change in the artificial tidal flat, it is necessary to understand the pattern of change in wave patterns. To protect the loss of silt and clay, it is necessary to provide stability for the tidal flat sediments.

Monthly Changes in the Oxygen Consumption and Primary Production Rates on the Artificial and Natural Tidal Flats

Monthly changes in the oxygen consumption rate on the artificial and natural tidal flats are shown in Figure 7. During winter the oxygen consumption rate on the flats were not very different. However, from May to October when the water was warmer, the oxygen consumption rate on artificial tidal flat increased significantly. In August and September, oxygen consumption was greater on the artificial flat than on the natural one. These results indicated that under aerobic conditions, decomposition of organic matter was enhanced on the artificial tidal flat from spring to autumn.

The monthly changes in the primary production rate and chlorophyll *a* on the artificial and natural tidal flats are shown in Figure 8. The primary production rates were low during summer, then increased and reached its highest level in autumn (from September to November). The chlorophyll *a* level in the tidal flat sediments was also low during summer and highest during autumn. It is concluded that grazing of benthic algae by macrobenthic organisms and the inhibition of primary production by strong solar radiation caused the lower primary productivity in summer. During August and November the primary productivity on the artificial tidal flat was higher than on the natural tidal flat. It is concluded that under aerobic conditions the rich organic matter in artificial tidal flat sediments decomposed and the benthic algae increased by taking up the nutrients that were released. Subsequently, the diversity and abundance of the benthos on the artificial tidal flat were enhanced over those on the oligotrophic natural tidal flat.

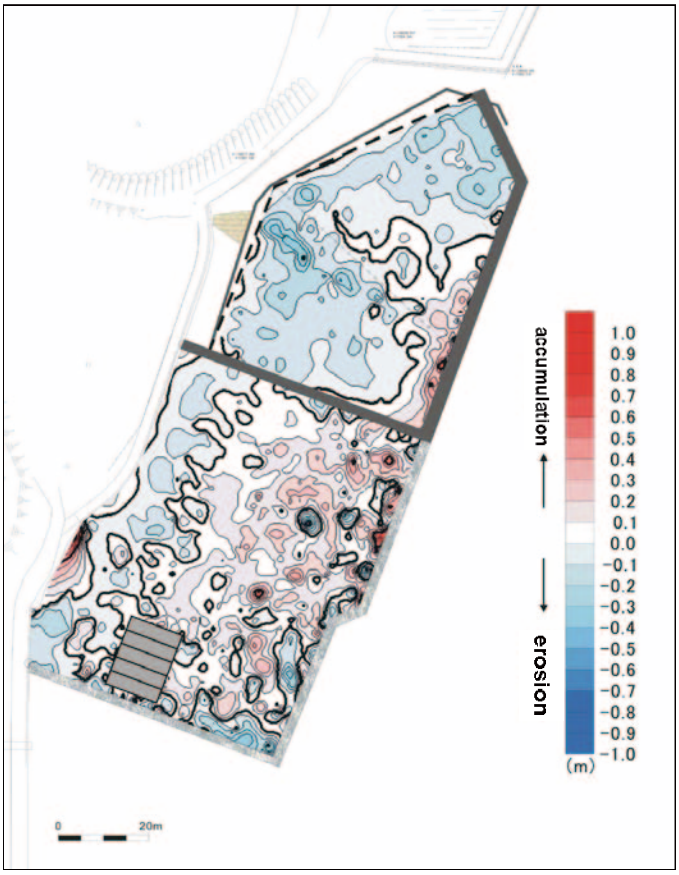

Fig. 6. The topographic change in the artificial tidal flat.

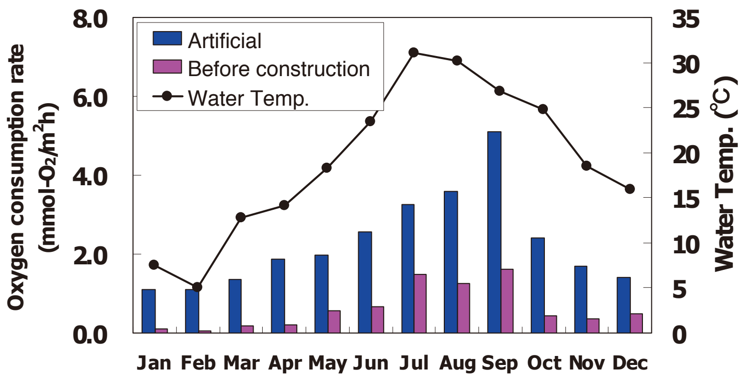

Fig. 7. Oxygen consumption rate on the artificial and natural tidal flats.

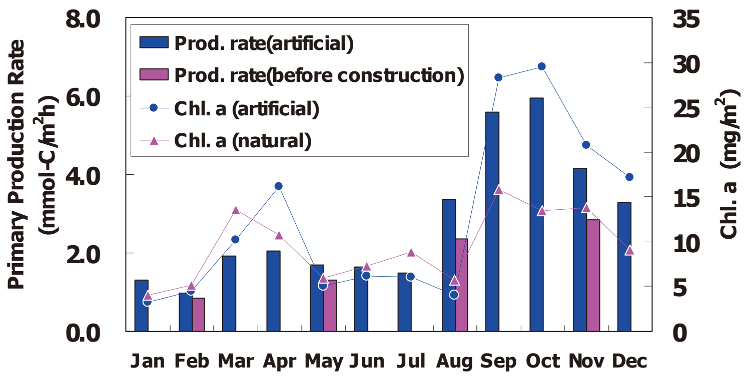

Fig. 8. Primary production rate on the natural and artificial tidal flats.

Nutrient Flux on the Artificial Tidal Flat

To investigate the changes in diurnal water quality around the artificial tidal flat, the clock, light, DIN, DIP, chlorophyll *a*, DO, depth, temperature, and turbidity were measured on 21-22 July 2005 (Figure 9) and 26-27 January 2006 (Figure 10).

Then the flux of water quality (TN, DIN, PON, TP, DIP, POP, and chlorophyll *a*) under ebb and flow conditions were calculated by integrating the data (Table 1). Negative values were indicated that materials were absorbed into the tidal flat, while positive values were indicated that the materials were flowed out of the tidal flat. During every season, particulate organic matter indicators (PON, POP, and chlorophyll *a*) showed absorption into the tidal flat, while dissolved inorganic nutrients (DIN and DIP) always flowed out of the tidal flat. These results indicated that the offshore water which contains rich particulate organic matter (POM), such as phytoplankton, flowed into the tidal flat with the high tide, and they were removed by filter feeders on the artificial tidal flat. This results indicated that the dissolved inorganic nutrients flowed out from the tidal flat by decomposition of the organic matter in tidal flat sediments and by being discharged from the macrobenthos. These phenomena were supported by increasing nutrient levels in the interstitial water and elution rate from tidal flat sediments (Kokubu *et al.* 2006). These

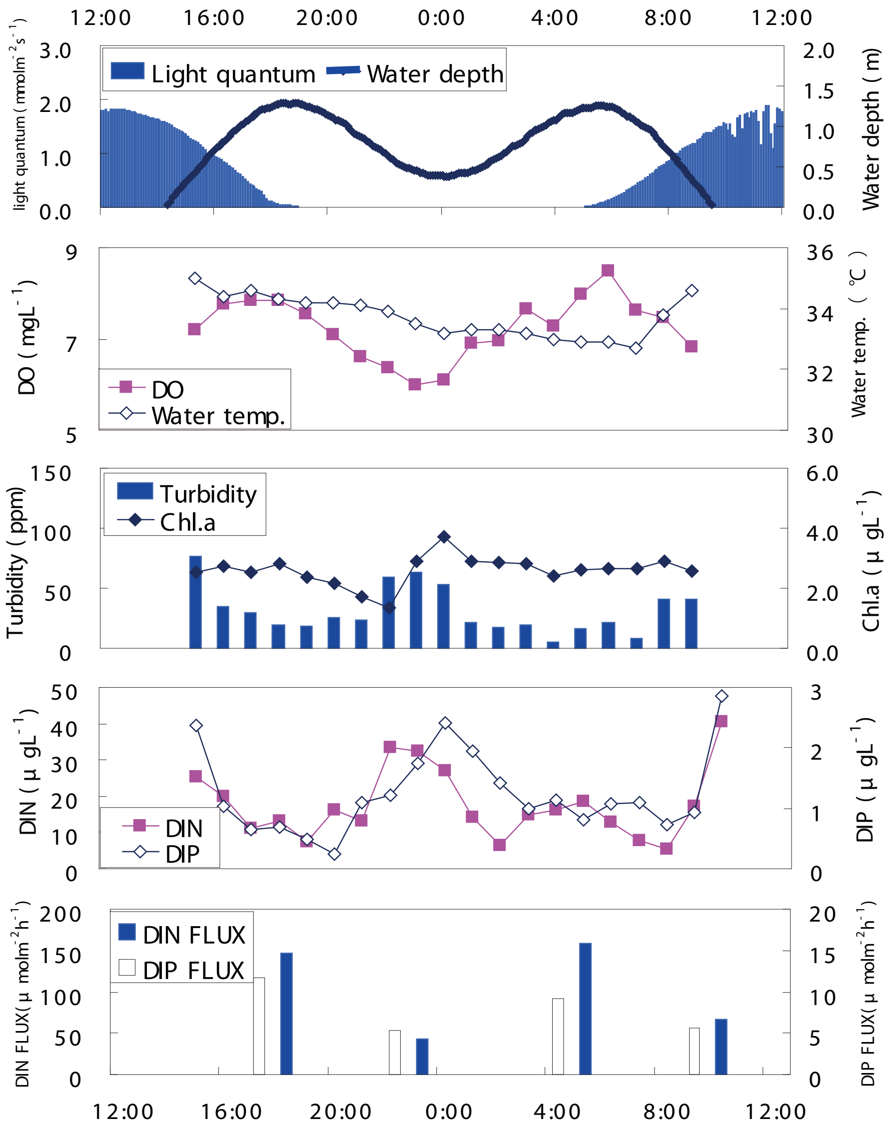

Fig. 9. Time course of the water quality during ebb and flow on the artificial tidal flat (4-5 Aug. 2005).

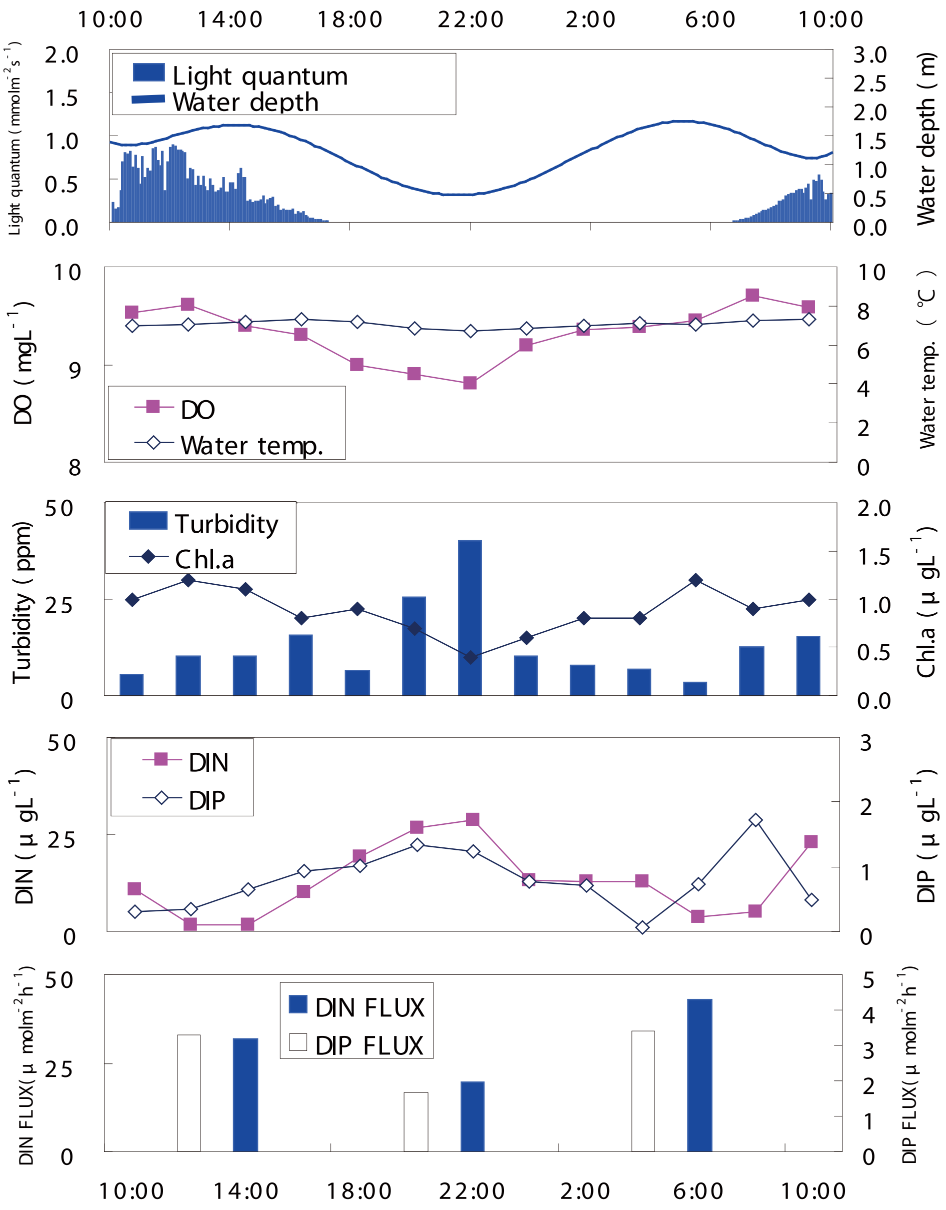

Fig. 10. Time course of the water quality during ebb and flow on the artificial tidal flat (26-27 Jan. 2006).

Table 1. The flux of water quality during ebb and flow on the artificial tidal flat.

	Cal. Time	TN	DIN	PON	TP	PO4-P	POP	Chl.a	
21.JUL	15:00-09:00	44.4	15.4	-52.2	-8.44	0.83	-1.67	-12.4	DL:+1.5m～+0m
04.AUG	13:00-10:00	-97.5	110	-109	4.95	7.62	-7.67	-23.1	DL:+1.5m～-1.5m
13.OCT	15:00-09:00	-55.0	13.8	-39.4	-2.00	1.44	-2.72	-10.3	DL:+1.5m～+0m
02.NOV	13:00-10:00	-60.9	30.9	-107	-4.71	6.14	-4.81	-14.2	DL:+1.5m～-1.5m
26.JAN	11:00-09:00	-38.2	3.41	-27.2	-0.18	0.55	-0.82	-2.36	DL:+1.5m～+0m
16.FEB	11:00-05:00	-69.3	5.83	-41.3	-1.50	1.39	-5.78	-5.67	DL:+1.5m～-1.5m

results corresponded with those from the Banzu tidal flat in Tokyo Bay as reported by Nomura *et al*. (2002). During all seasons the fluxes in water quality when all the artificial tidal flat areas were enclosed were larger than when only the relatively shallow artificial tidal flat area was enclosed.

Conclusion

In the present work, the new technology for enhancing biological productivity by controlling sediment quality was developed, and the function of habitat and material circulation were investigated. It was clear that the abundance and diversity of macrobenthos and biological productivity were enhanced by supplying nutrients to a relatively oligotrophic tidal flat in the form of dredged organic matter-rich sediments. Furthermore, the mechanism of enhancement of the biological productivity was clarified. First of all, the decomposition of the organic matter in added dredged sediment was rapid, resulting in greater regeneration and release of dissolve nutrients. The released nutrients were utilized by benthic algae. Subsequently, the macrobenthos increased more abundant by feeding on the algae. Thus these results were supposed that the benthos are strongly linked with material circulation on tidal flats, and artificial tidal flats work as sinks for particulate organic matter sources of dissolved nutrient. However, in the present artificial tidal flat ecosystem, after up to one year following construction, carnivores were still not existed, so the ecosystem was considered to still be in the transition phase. It was also evident that the organic matter in the artificial tidal flat was slightly decreased, so it is necessary to consider the stability and durability of tidal flat sediments. The present study is a part of the Ago Bay Environmental Restoration Project under the program of Japan Science and Technology Agency.

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