

STUDY ON MECHANISMS OF ENVIRONMENTAL CHANGE IN AN ARTIFICIAL TIDAL FLAT

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ABSTRACT: The Ariake Sea, a typical closed bay on the west coast of Kyushu Island, has suffered from several external impacts. However, the relative contribution of the various factors and processes is still unclear. In this study, field observations were conducted inside the artificial tidal flat to model the physical, chemical and ecological attributes of the tidal flat system for the preservation and recovery of the coastal environment in the Ariake Sea. The communities and environment within the artificial tidal flat pond became established within one year of the artificial pond being completed. Meteorological and tidal conditions were found to strongly affect the topography of the pond, particularly the region between the sub-tidal zone to the supra littoral zone, the development of which itself resulted in stabilization of the tidal flat habitat within the pond.

KEYWORDS: Artificial Tidal Flat, Field Observation, Environmental Change, Ecosystem

1. Introduction

The Ariake Sea, a typical closed bay on the west coast of Kyushu Island, is characterized as having a tidal range of approximately 6.0 m at spring tide. The tidal flats are extensive (207 km²), occupying approximately 40% of the total area of Japan. This range in tidal and other environmental conditions has resulted in the establishment of considerable ecological heterogeneity and has also facilitated the establishment of a delicate environmental balance with the marine environment.

In recent years however, environmental deterioration in the Ariake Sea has occurred with increasing frequency. These events include the color-dulling damage for sea weed such as laver in the winter of 2000-2001 and massive red tide blooms. Consequently, the remediation the tidal environment system (ecosystem, the purification of the sea water and tidal bottom soil) has become necessary.

Factors contributing to environmental deterioration in the Ariake Sea have been widely

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discussed by Japanese engineers and scientists (Nakata et al., 2002; Takikawa e.g., et al., 2003), and several environmental recovery programs have been proposed. However, the process of how to facilitate the development of a natural tidal flat system is still unclear. A prerequisite for acquiring the knowledge necessary to understand this system is an integrated approach using field surveys, the findings of which can then be used to develop and implement sustainable environmental recovery programs.

The *Yacho-no-ike* pond was constructed in October 2002 at the northeastern end of Kumamoto Port (Fig. 1) to promote the establishment of a tidal flat ecosystem inside the bay that was independent of artificial influence. Field observations of water and sediment physicochemical parameters, and biological characteristics have been conducted since construction of the pond was completed. The purpose of this study was to investigate whether construction of the pond has benefited tidal flat ecosystem integrity and resulted in the establishment of tidal flat communities within the pond. To achieve this aim, variation in environmental variables and the mass budget were investigated.

2. Field Observations in the Artificial Tidal Flat

2.1. The establishment of a tidal flat ecosystem within an artificial pond (*Yacho-no-ike*)

The *Yacho-no-ike* pond was constructed in October 2002 at the northeastern end of Kumamoto Port (Fig. 1). The pond was constructed in order to facilitate the establishment of a tidal flat ecosystem inside the port to avoid the need for artificial control. Figure 2 is a plan of *Yacho-no-ike*. The artificial pond is separated from the open sea by a stone masonry-type seawall. The artificial pond is a so-called ‘semi-open system’ with a muddy bottom and four pass-pipes (1.0 m in diameter) that connect the pond to the sea and facilitate the exchange water, nutrients and biota according to tidal fluctuations (Fig. 2). The gradient within the pond is approximately 1:36, which is steeper than that of the surrounding tidal flat (1:600). The soil particles are composed primarily of mud 70% (w/w). The total area of the pond is 23,000 m² and the relative extent of the tidal flat zones inside the pond in 2002 was a sub-tidal zone of 1,028 m², an inter-tidal zone of 4,222 m², and a supra-littoral zone of 17,750 m². The sub-tidal zone remains underwater at low tide and is less than 1.0 m at its deepest (mean = 0.3 m).

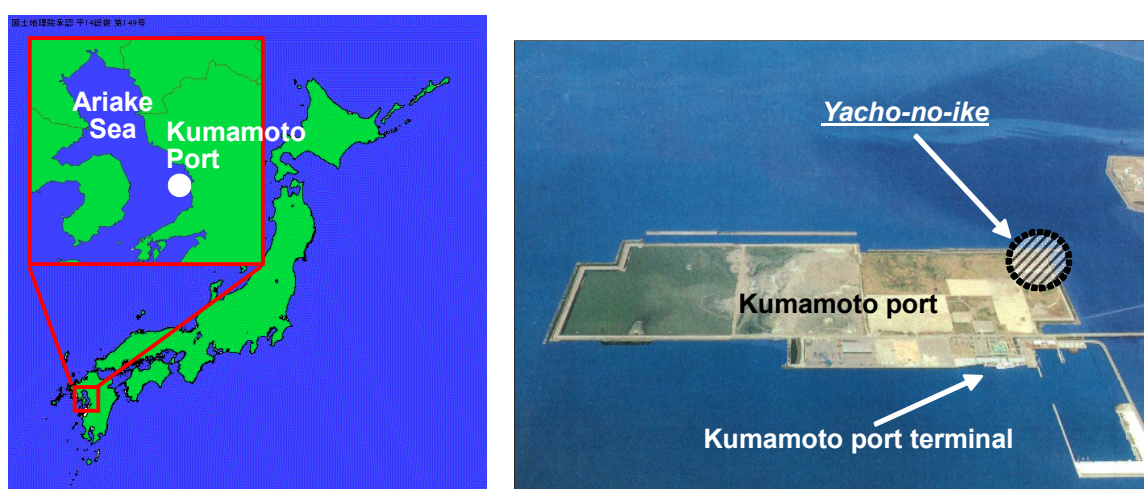


Fig. 1 Location of study site (the artificial pond *Yacho-no-ike* in the Ariake Sea)

2.2. Observation methods

Topographical survey of the artificial pond was performed by setting up a longitudinal transect with piling from DL (Datum Line) +2.5 m in the tidal zone to DL +4.5 m of H.W.L at 10 points along transects A and B at 0.5 m intervals (Fig. 2). In addition, a soil compaction meter (Cone Penetrometer) was inserted into the ground at eight points (A2-A5, B2-B5) in the tidal zone to assess cone bearing capacity.

Sediment sampling was performed by obtaining mud cores of approximately 30 cm at 10 sites along the longitudinal profile of the pond and at 2 points in the outside pond (Fig. 2). Core samples were divided into four layers - surface layer (0 to -0.5 cm), upper layer (-9 to -11 cm), middle layer (-19 to -21 cm) and a lower layer (-29 to -31 cm) - each of which was analyzed for the following parameters: grain size distribution, water content, chemical oxygen demand (COD), ignition loss (IL), moisture content, total sulfide (T-S), oxidation-reduction potential (ORP) and hydrogen ion concentration index (pH).

The water quality investigation was done by two methods: one was by continuous *in situ* observations using multi parameter water quality meter (W-23XD, HORIBA, located St.1 and St.2) and the other was a detailed analysis of water samples in a laboratory off site. The following water physicochemical parameters were analyzed: chemical oxygen demand (COD), dissolved chemical oxygen demand (D-COD), total nitrogen (T-N), dissolved total nitrogen (D-T-N), $\text{NH}_4\text{-N}$, $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$, $\text{PO}_4\text{-P}$, chlorophyll-a (Chl-a), suspended solids (SS), pH, and dissolved

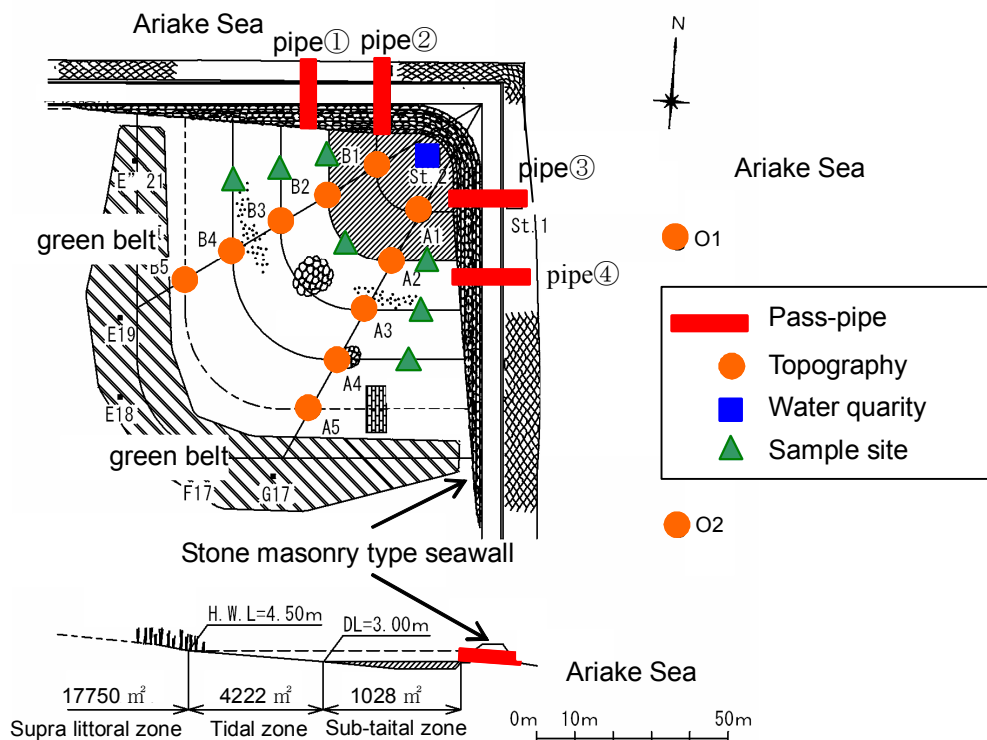


Fig. 2 Sample sites and transects at “Yacho-no-ike”



Fig. 3 Density of burrow entrances per m²

oxygen (DO). The continuous measurements were taken at St.01 and St.02 shown in Fig.02. Measurements at St.02 were taken at a depth of 10 cm below the surface and at a point 30 cm from the bottom.

Biota was assessed quantitatively and qualitatively. The number of benthic and fish species was investigated using a nets and visual observations. Benthos was also sampled using a cuboid soil sampler (25 cm in width and 20 cm in depth) and the density of burrow entrances was investigated by counting the number of holes per m² (Fig. 3).

3. Results and Considerations

3.1. Topography survey and bottom quality investigation

The rate of deposition in the sub-tidal zone of the artificial pond was 10 cm in the six months following construction, reaching 25 to 30 cm after approximately two years (Fig. 4). It is thought that this sediment was derived from SS from the open ocean and through erosion of the green belt to the south of the tidal flat by rainfall and wave action.

Cone bearing capacity showed that sediments became softer at almost all sample locations and layers during summer in response to activation of living thing and a change in the temperature of mud. Figure 5 shows an example of cone bearing capacity at site B2. At site B2, it can be thought that the increase in the number of entrance holes (described later) was found to contribute to the increased softness of the mud.

Figure 6 shows the distribution in grain size for samples taken on 19 Nov. 2002 and 9 Dec. 2004 at sites B1 (left panel) and B3 (right panel), respectively. The mass of mud and silt increased in all layers and the water content also increased at the sub-tidal zone at site B1 in the two years of sampling at the site. It was suggested that the present lower layer lay to the surface on 19 Nov. 2002, a lot of mud clay with small particle deposited because of erosion by rainfall and wave action at sub-tidal zone. At site B3, it increased slightly. That is, there was a continuous supply of silt to site B3 from supra littoral zone and tidal zone in spite of the soil on the surface a lost amount for sub-tidal zone.

Figure 7 shows the vertical profiles for specific water content, ignition loss, Chemical Oxygen

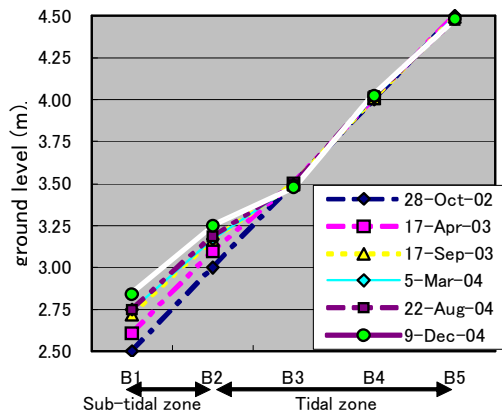


Fig. 4 Change of topography at the pond (transects B)

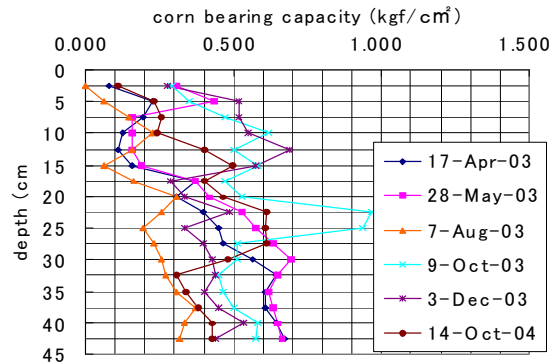


Fig. 5 Profile of cone bearing capacity at point B2 (tidal zone)

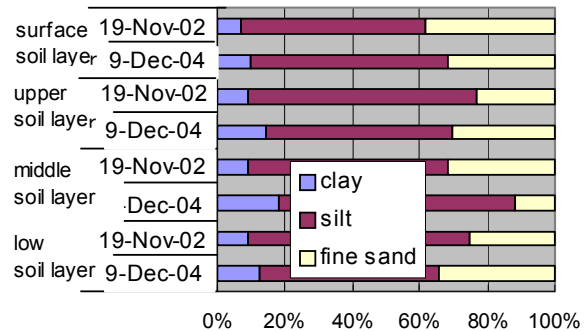
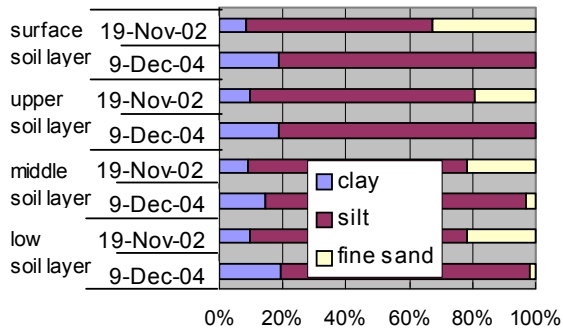


Fig. 6 Variation of grain size distribution (B1, left; B3, right)

Demand (COD) and total sulfate content. Each of these parameters sampled at site O2 (outside pond) and along transect B (inside pond) is shown in the left and right panels of the figure, respectively. A marked increase in water content was observed in the sub-tidal zone of the pond in 2004 compared to 2003 (Fig. 7B). Interestingly, this increase was not observed at site O2 outside the pond (Fig. 7A). Ignition loss decreased in summer both inside and outside of the tidal flat pond. In both areas, IL tended to increase in winter. The amount of organisms is increased during summer when biomass production was high. This trend was observed at all sites in the pond.

Chemical Oxygen Demand (COD) levels exhibited a pattern similar to that of ignition loss (Fig. 7E and 7F). Given the preference among tidal flat biota for clay environments, the deposition of clay in the surface layer of the substrate is likely to have been responsible for the increase observed in COD. Moreover, compared with the outside pond, the sub-tidal zone inside the pond was characterized as having high values in COD in 2004, while in 2003 the outside pond was characterized as having higher values (Fig. 7E). It is thought that colonization of the environment by organisms could occur easily at this stage because the particle size of sediments was less than 0.05 mm.

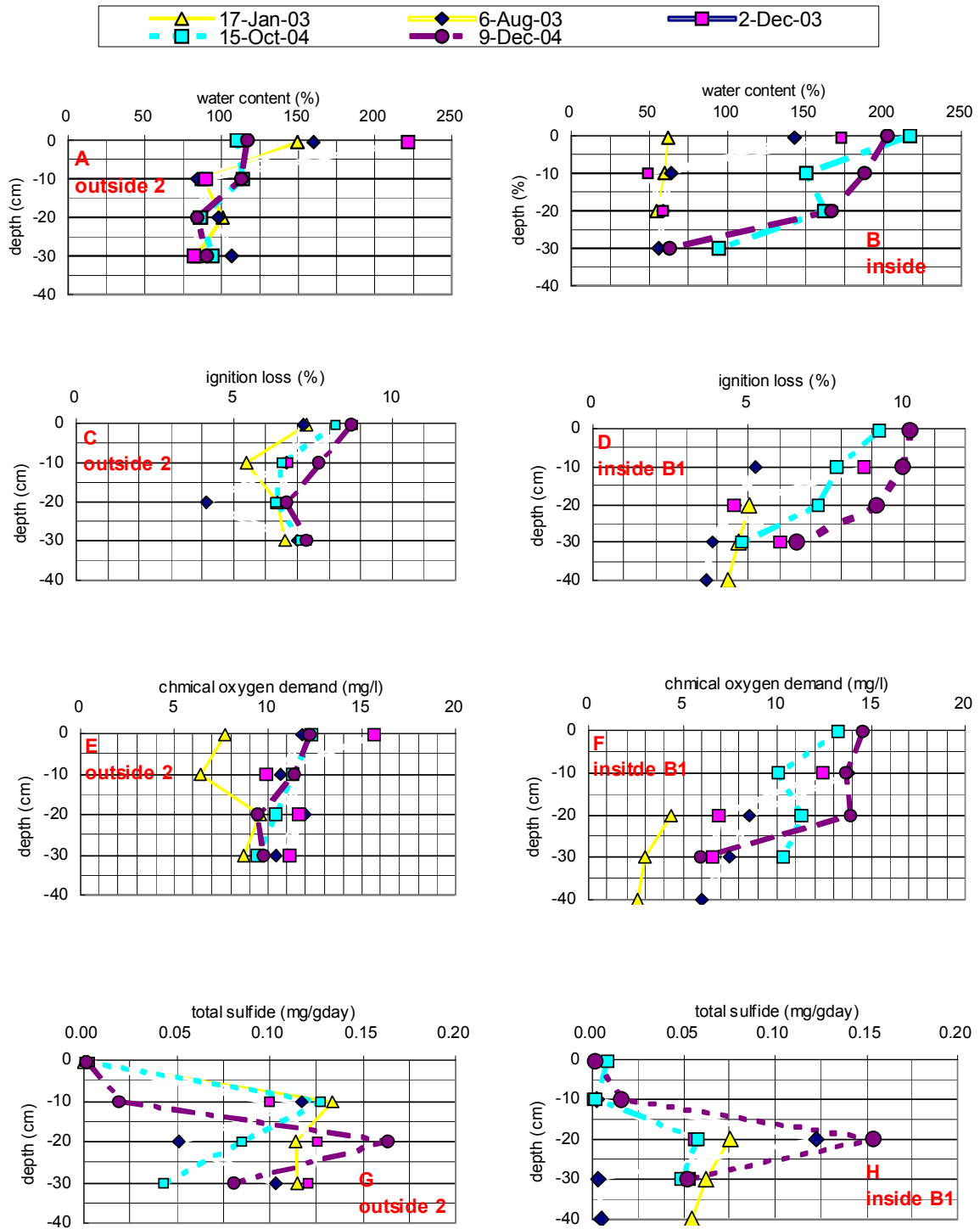


Fig. 7 Vertical profile of sediment characteristics (site O2, left; site B1, right)

3.2. Water quality

3.2.1. Diurnal variation

Figure 8 shows precipitation and salinity values at 10-minute intervals between 2nd and 12th Sep. 2004. Tidal action at the surface mixes the fresh water from outside the pond and decreases the salinity of the surface water. Furthermore, given that the mouth of the Shira river is located approximately 1.5 km northeast from the pond, water with a low salinity sometimes enters the pond after precipitation events such as when Typhoon 0418 hit Kyushu on 7th Sep. 2004. According to an automated weather station nearby, the minimum barometric pressure recorded during the year was 962.5 hPa, approximately 50 hPa lower than the fine weather in summer. Maximum wind speeds of 46.9 m s⁻¹ were recorded on 7th Sep. 2004. These conditions of low pressure and high wind speeds could account for the anomalous higher elevation. After the typhoon passed, the salinity inside the pond remained below 30psu.

Figures 9 and 10 show the diurnal variation of pH, DO and incoming solar radiation flux density. The pH and DO both increased in the daytime in response to phytoplankton photosynthesis, while at night the production of O₂ by phytoplankton stopped and the dissolved

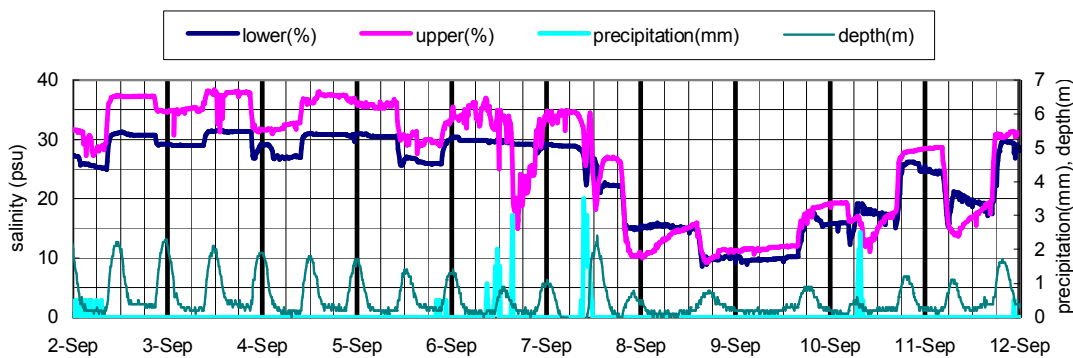


Fig. 8 Change in precipitation, depth and salinity between 2 to 12 Sep., 2004

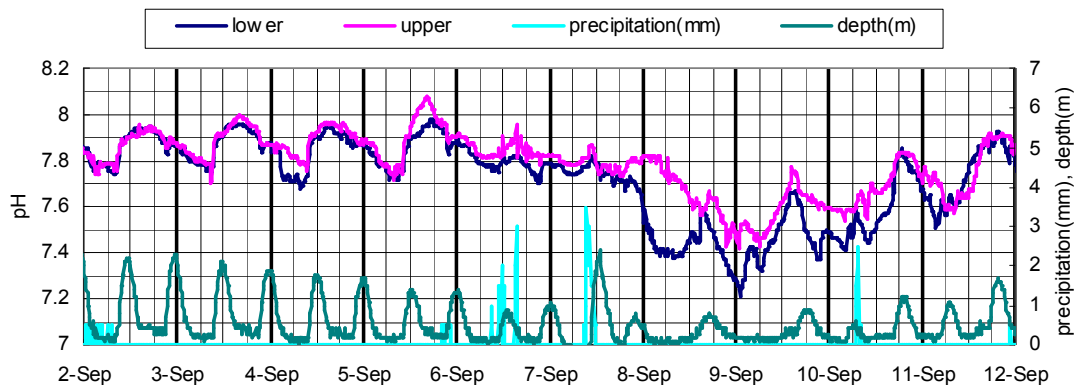


Fig. 9 Change in precipitation, depth, and pH between 2 to 12 Sep., 2004

oxygen was consumed. On Sep. 8, the reason for the decrease of DO in the bottom layer is thought to be correlated with high rainfall causing resuspension of the substrate.

This resuspension is apparent Fig. 11 where a marked increase in SS levels of the bottom layer was observed on the same day. However, recovery of average density after several days indicates the stability of the pond environment as a site biological activity.

3.2.2. Seasonal variability

Figures 12 and 13 show the changes in water quality during summer and winter, respectively. As for inorganic nitrogen, nitrate levels increased while organic nitrogen decreased at high tide (Figs. 12A and 13D). So it is inferred nitrification because the aerobic environment in the tidal zone is maintained. On the other hand, organic nitrogen increased and nitrate nitrogen decreased at low tide. This can be inferred since the environment of the sub-tidal zone was anaerobic and inorganic nitrogen was removed outside the pond. As for the increase in organic nitrogen associated with drying up at night, the microorganism was able to resolve the organism and because of COD being decreased. Since it is unlikely that the pond dried up during the day was

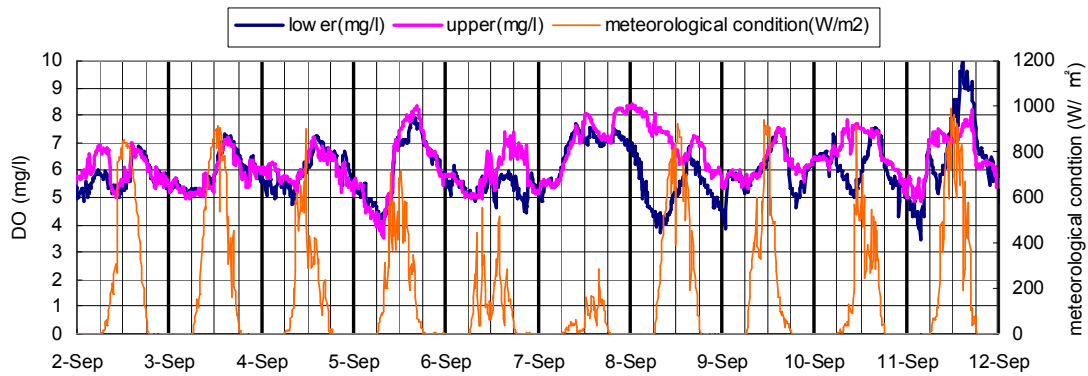


Fig. 10 Change in dissolved oxygen and meteorological condition between 2 to 12 Sep., 2004

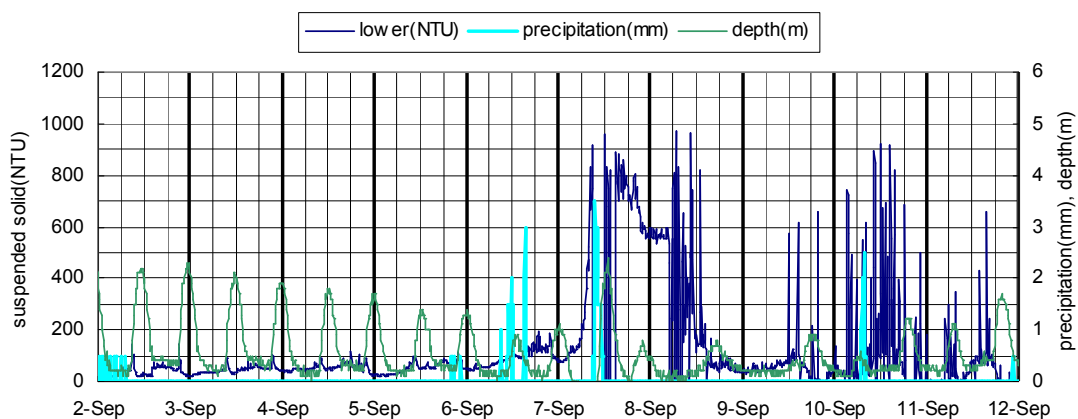


Fig. 11 Change in precipitation, depth, and suspended solid levels between 2 to 12 Sep., 2004

dissolved the organism from an increase COD, an increase in organic nitrogen was caused by the resuspension of sediments. This relationship between SS and DO is shown in Fig. 12 (B) and Fig. 13 (C). A similar tendency could be observed in winter, although the mass balance was less than it was in summer. It is thought that the climate in summer favors denitrification compared to nitrification. Moreover, SS exhibited the tendency to decrease at low tide. These findings suggest that the SS that entered the pond from the open sea was deposited in the tidal and the sub-tidal zones of the pond.

As for COD, there was no decrease or nor any change associated with drying at low tide. As a result, it appears that the organisms that entered the pond from the open sea was dissolved by the benthos in the pond or deposited in the tidal and the sub-tidal zones. A decrease in COD and increase in DO was observed and can be attributed to the resolution of a particle organism and becoming a dissolubility organism.

Chl-a decreased during the day and at low tide at night. This reason is thought to be because the phytoplankton from open sea settled and stayed in the sub-tidal zone and tidal zones of the pond. Additionally, another reason for the decrease in phytoplankton was due to consumption by zooplankton; withering for becoming the organism, but the difference between low and high tide was not marked. In addition, average Chl-a concentrations were high during summer (4.5 to 15.0

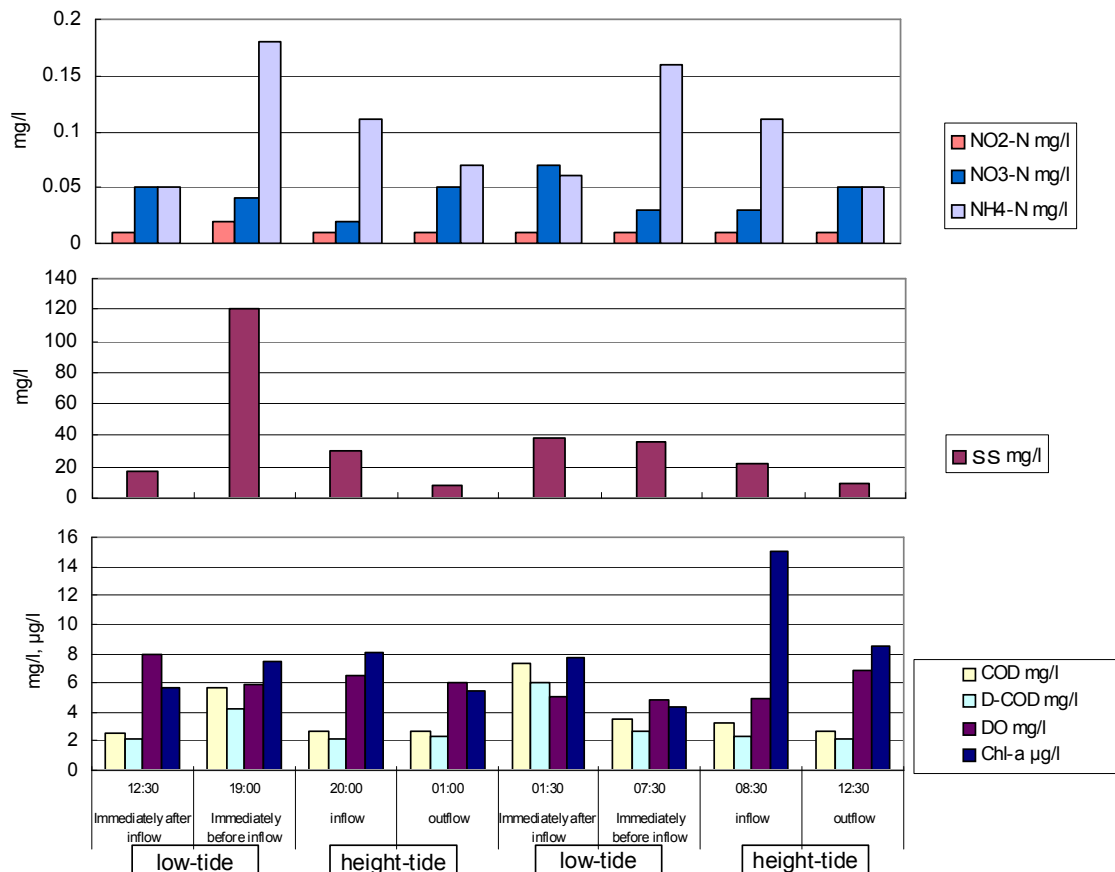


Fig. 12 Changes in NO₂-N, NO₃-N, NH₄-N, SS, COD, D-COD, DO, Chl-a between 16 to 17 Sep., 2004

$\mu\text{g l}^{-1}$ in summer and 0.5 to $2.0 \mu\text{g l}^{-1}$ in winter), implying that phytoplankton production was high during summer because the daily amount of solar radiation is higher than it is in winter. Consequently, seasonal variations in solar radiation and tidal motion play a significant role in seasonal DO and Chl-a concentrations by affecting photosynthesis.

3.3. Biological investigation

Figure 14 shows the number of specimens and species sampled inside and outside the pond shortly after construction. Eleven species were found outside the pond after construction, mainly polychaetes, crustaceans and mudskippers. Only biota well adapted to the muddy environment of tidal flats were found outside the pond as the concentration of mud exceeded 80% (v/v). Conversely, the number of biota inside the pond increased slowly since hermit crab such as *Camptandrium sexdentatum* Stimpson was first observed in Nov. 2000. Species increased in the following order: mussel worms, crabs, and mudskippers. By Oct. 2003, 12 species had been observed, exceeding that observed outside the pond. In addition, rare species such as *Uca arcuata* and *Uca lacteal* were observed inside the pond, increasing the total number of species to 17 by Sep. 2004.

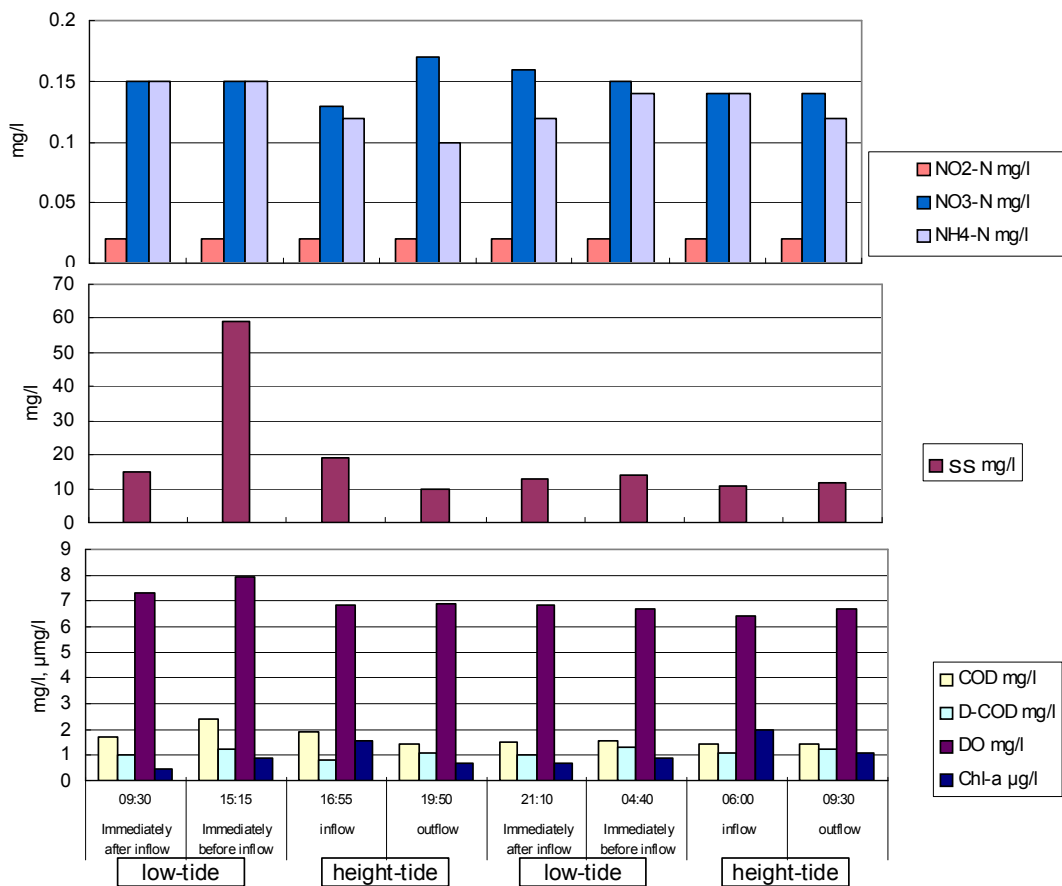


Fig. 13 Changes in NO₂-N, NO₃-N, NH₄-N, SS, COD, D-COD, DO, Chl-a between 9 to 10 Dec., 2004

It is thought that the Do you mean that habitat variability and gradient inside the pond accounted for the increase in the number of species inside the pond. Moreover, the number of taxa is expected to increase in the future because mollusks have not observed inside the pond.

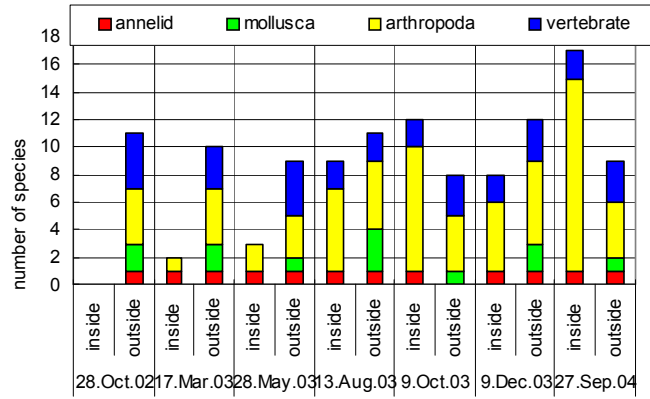


Fig. 14 Changes in numbers and species of biota inside and outside the pond

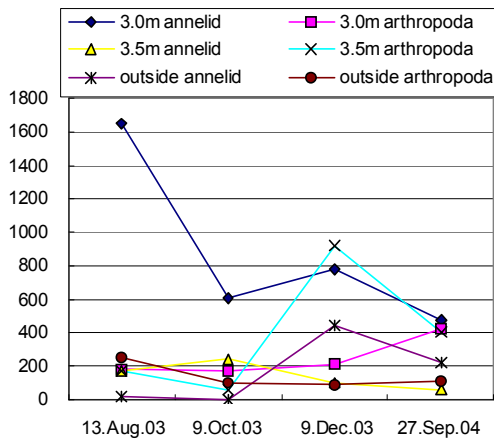


Fig. 15 Changes in number of biotic specimens at different sites

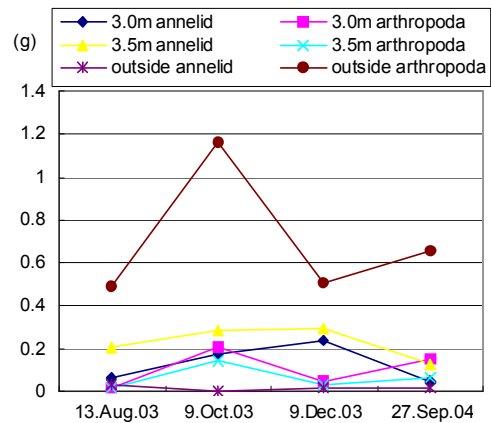


Fig. 16 Changes in biomass from different sites

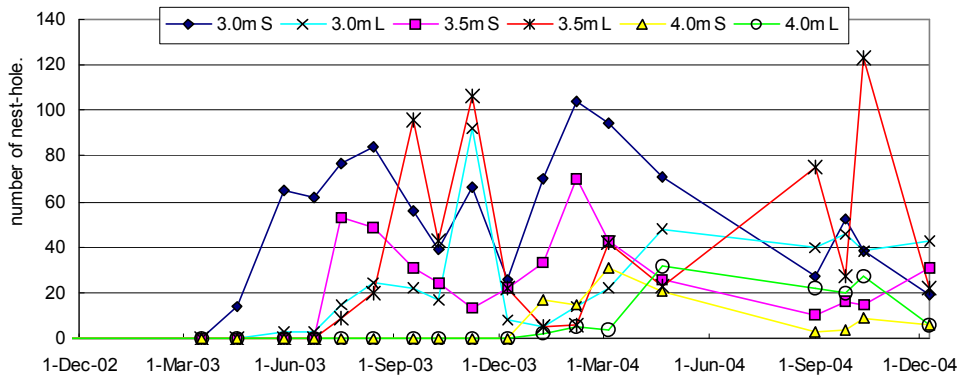


Fig. 17 Changes in the number entrance holes at D.L. 3.0, 3.5, and 4.0 m on the tidal zone (S: small biota, L: large biota)

Figure 15 shows the change in the number biota and figure 16 shows the change in biomass relative to height of 3.0 and 3.5 m. The number of annelids decreased in the pond. The mussel worms became established relatively quickly, while arthropod and vertebrate species increased gradually as the ecosystem became established. Therefore, it is thought that the number of mussel worms decreased due to predation or overcrowded.

Arthropod biomass was observed to differ inside and outside the pond and was associated with the appearance of priority species. The small crab *Ilyoplax pussilla* (0.1 to 0.2 g) and tiny *Amphioda* (0.008 to 0.01 g) were considered priority species inside the pond. The small crab, *Camptandrium sexdentatum* (0.1 to 0.4 g), and the middle-sized crab, *Macrophthalmus japonicus* (1.5 to 2.9 g), were priority species on the outside of the pond.

Figure 17 shows the changes in the number of burrow entrances inside the tidal zone. In the figure, "small" indicates the number of nest holes less than 5 mm, while "large" indicates holes greater than 5 mm in diameter. The assumption was made that the entrance holes of mussel worms is less than 5 mm in diameter. Consequently, entrance holes that were larger were considered to have been made by middle-size crabs, mudskippers and other predators that enter the holes to prey upon mussel worms. This meant that the number of entrance holes gradually increased from spring to autumn, peaking in October and November, before decreasing again in December. This decrease is thought to be associated with the death or hibernation of arthropods and vertebrates in the cold water during winter. Conversely, as for the number of nest-hole "Small", the number of "Large" change was more important than the seasonal variation.

4. Discussion

Figure 18 shows a flow diagram indicating the causal relationships that exist within the various components of the tidal flat system. Firstly, the erosion by rainfall, tidal variation inside the tidal zone, and the inflow of SS caused the deposition of the mud in the sub-tidal zone. This soil was less than 0.05 mm in diameter and led to an increase in the number of organisms and water content. In addition, decreased particle size and increased water content caused an increase in the number of entrance holes. However, the anaerobic environment had been maintained because deposition of the bottom layer caused an increase in sulfide compounds.

It is thought that the deposition of substrates consisting of small soil particles meant that the bottom substrate could easily enter into suspension. It was also observed that nitrogen, phosphorus and organisms dissolve when the mud is disturbed at high tide during the day. In addition, oxygen consumption increased in response to the increased microbial action associated with these nutrients entered into solution, decreasing DO. However, the decrease of DO was temporary as it was replenished by photosynthesis and the influx of seawater, reaching average levels several days after a typhoon. It is thought that the pond is thus a stable habitat that facilitates biological activity because of the marked changes in the pattern of production and consumption that occur every day and night.

It is thought that the appearance of new species occurred in response to the establishment of heterogeneous environmental conditions and habitat. This increase is due to the establishment of a continuity typical of a tidal flats - from the sub-tidal zone to the supra littoral zone - the bottom soil has become soft in the lower reaches of the pond, and because stable environments area conducive to biological activity.

Finally, it is very important to determine the relationship between species diversity and water conservation, particularly insofar as how these are affected by factors such as topography, sediment quality, water quality, biota, meteorological environment and seawater quality. It can

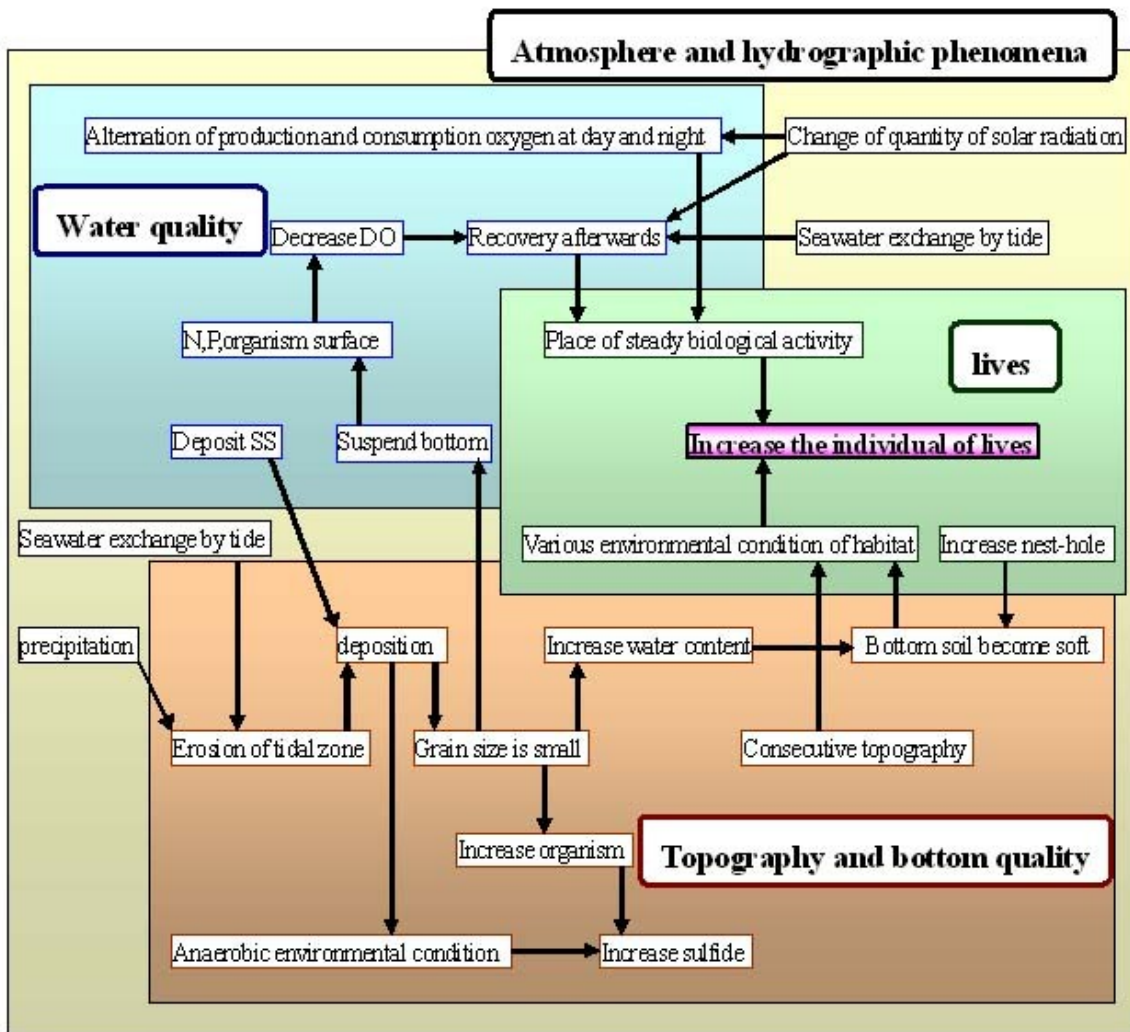


Fig.18 Four sphere interaction chart from this investigation

also be used to demonstrate how such measures can be used to reproduce and help remediate the tidal flat environment.

5. Conclusions

This research sought to determine the mechanisms associated with environmental change in the tidal flat environment by comparing environmental attributes, such as following topography, sediment quality, water quality, with an open bay environment. The conclusions of the study can be summarized as follows:

- (1) Approximately 25-30 cm of sediments have been deposited in the sub-tidal zone over the last two years. Sediments consisted of the SS load from the open sea and mud from erosion of the area to the south of the pond. The mass content was mainly mud and silt.

- (2) Inside the pond, the number organisms and sulfide increased because of mud and silt deposition.
- (3) The decrease in DO inside the pond was caused by resuspension of substrates in response to heavy rainfall.
- (4) Inside the pond at low tide, resuspension of substrates in the sub-tidal zone suspended bottom soil, dissolved nitrogen and phosphorus, and a corresponding decrease in DO.
- (5) DO exhibited diurnal variation caused by an alternation in production and consumption between day and night. In addition, recovery of DO levels to normal levels, even shortly after a typhoon, indicated the stabilizing effect the pond environment has on environmental variables.
- (6) The number of species inside the pond was higher than outside. The reason for this disparity is thought to be because of the marked difference in the gradient of the pond (approximately 1/36) compared the bay (approximately 1/600). Furthermore, the ground became soft in the lower reaches of the pond and these areas were also characterized as being environmentally heterogenous.
- (7) The large benthic species, such as the mud skippers and *Helice japonica*, are dominant from summer to autumn, while the smaller taxa, such as the mussel worms, are dominant from winter to spring when the number of larger predators has decreased. The effect of seasonality on the trophic structure of the pond environment was thus clearly observed.

Acknowledgments

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References

- Nakata, H., Sakai, Y. and Miyawaki, T. (2002). Growth-dependent and species specific accumulation of polychlorinated biphenols (PCBs) in tidal flat organisms collected from the Ariake Sea, Japan, *Archives of Environmental Contamination and Toxicology*, 42, pp.222-228.
- Takikawa, K., Tanaka, K., C, Aoyama, Nishioka, R. and Hokamura, T., (2003). Long-term variation of water quality variables in the Ariake Sea over 25 years, *Asian WATERQUAL2003 (IWA-Asia Pacific Regional Conf.)*, Bangkok, Thailand, pp.1-8.
- Takikawa, K. Iyatomi Y., Tanaka, K., Hokamura, T., and Nagamine, Y., (2003). Environmental remediation and countermeasure works on the tidal flat in the Ariake Sea, *Asian WATERQUAL2003 (IWA-Asia Pacific Regional Conf.)*, pp.1-8.