Recent Attempt towards Environmental Restoration of Enclosed Coastal Seas: Ago Bay Restoration Project Based on the New Concept of *Sato-Umi*

Osamu MATSUDA*

Abstract Since the present status of the enclosed seas along the coast of Japan is more or less "damaged" or "deteriorated" mainly due to prolonged impact of human activities, environmental restoration followed by rehabilitation of the natural ecosystem is one of the most important subjects to be tackled from the view point of both environmental conservation and living resource management. Ago Bay is one of the deteriorated areas especially from the viewpoint of aquaculture grounds in Japan. Although the bay is known to be a world-famous cradle of pearl culture, conditions of the bay in terms of sediment quality, dissolved oxygen and harmful algal blooms have deteriorated during the long history of pearl culture. The ongoing "Environmental Restoration Project on Enclosed Coastal Seas" in Ago Bay mainly deals with restoration of deteriorated tidal flats and seagrass beds and also development of environmental forecasting technology based on environmental monitoring and modeling. Since the project conducted under the collaboration program of the Japan Science and Technology Agency with industries, academies and public services includes not only scientific and technological studies but also components of environmental education, environmental management and wider cooperation with varieties of stakeholders, it can be a model of environmental restoration and management of enclosed coastal seas. The outline of the project as well as its present status and future perspective is introduced with particular emphasis on the new concept of *Sato-Umi*, which in Japanese means coastal sea under the harmonization of sustainable wise use with conservation of appropriate natural environment and habitat conditions. An automatic monitoring system to monitor water quality has been established and real time observation data are open to the public through the Internet. Varieties of restoration methods for damaged shallow environments and habitats with the use of environment friendly technology based on the concept of *Sato-Umi* is being developed and applied in this project.

Key words: environmental restoration, environmental monitoring, enclosed coastal sea, Ago Bay, pearl culture, Sato-Umi

Introduction

Since the present status of the enclosed seas along the coast of Japan is more or less "damaged" or "deteriorated" mainly due to prolonged impact of human activities, environmental restoration followed by rehabilitation of the natural ecosystem is one of the most important subjects to be tackled from the viewpoint of both environmental conservation and living resource management. Among 88 officially designated enclosed coastal seas in Japan, Ago Bay is one of the deteriorated areas especially from the viewpoint of environmental quality and aquaculture grounds. Although the bay is known to be a world-famous cradle of pearl culture, environmental conditions in the bay in terms of sediment quality, dissolved oxygen in bottom water and occurrence of harmful algal blooms have deteriorated during the long

2009年8月10日受理（Received. August 10. 2009）

* Professor Emeritus, Hiroshima University; Core Research Laboratory, Ago Bay Restoration Project 3098-9 Kawamukai, Ugata, Shima, Mie 517-0501 Japan
Email: matsuda036@go3.enjoy.ne.jp

history of pearl culture spanning more than 100 years. Ago Bay is located in Ise-Shima National Park, Mie prefecture, the central part of Japan and the enclosed topography of the bay surrounded by deeply indented rias-type coastline protects the intrusion of ocean waves from the sea and provides an adequate place for pearl culture.

The "Environmental Restoration Project on Enclosed Coastal Seas" conducted in Ago Bay during 2003-2007 under the collaboration program of the Japan Science and Technology Agency (JST) with industries, academies and public services mainly deals with restoration of deteriorated tidal flats and seagrass beds and also the development of environmental forecasting technology based on the real time environmental monitoring and modeling. The central organization for implementation of this project is the Mie Industry and Enterprise Support Center (MIESC) and the Mie Prefecture Science and Technology Promotion Center (MPSTPC) has full administration responsibilities. Since the project includes not only scientific and technological studies but also includes components of environmental education, environmental management and wider cooperation with varieties of stakeholders, it can be a model of environmental restoration and management of small scale enclosed coastal seas.

This paper outlines the project as well as the present status and future perspective with particular emphasis on the new concept of *Sato-Umi*, which in Japanese means coastal sea under the harmonization of sustainable wise use with conservation of appropriate natural environment and habitat condition. In this project, varieties of restoration methods for damaged shallow environments and habitats with the use of environment friendly technology based on the concept of Sato-Umi are developed and applied. Compared with deteriorated coastal environments, Sato-Umi is able to provide higher biological diversity for habitat and higher biological productivity for living resources. These characteristics of *Sato-Umi* are also suitable sites for demonstrating multi-functional roles of fisheries.

Outlined framework of the environmental restoration project

The bay is a typical enclosed coastal sea, connected to the Pacific Ocean with a very narrow and shallow entrance (Figure 1). The environmental quality of the bay, in particular of the sediments quality, has deteriorated in conjunction with the continuation of pearl culture and development of the coastal area. Therefore, in the project, attempts are being made to improve the natural self-purification capability in the shallow areas of the bay by constructing functional tidal flat and seagrass beds that contribute to the enhancement of both the biological diversity and biological productivity of *Sato-Umi*. At the same time, sustainable aquaculture system is also developed to build a new ecosystem based management of pearl culture. The project consists of following two themes.

Theme 1. Integrated restoration of coastal environment and ecosystem to establish a regional model of *Sato-Umi*. In Ago Bay, deteriorated sediments with COD values higher than 30 mg/g dry sediment have been dredged up as an administrative measure for environmental improvement. In order to make use of the dredged sediments rich in organic matter accumulated at the bottom of the bay, technology for dewatering dredged sediment was developed and the treated sediments were applied as raw material to construct functionally improved artificial tidal flat and seagrass beds. The function of tidal flats and seagrass beds were quantitatively evaluated from the viewpoint of material cycling, self-purification, biological diversity and biological productivity in order to establish a reliable method for constructing functional tidal flats and seagrass beds. In addition to the development of technology to make the best use of dredged sediments, practical methods for environment friendly pearl culture were also developed.

Theme II. Development of an automatic environmental monitoring system and environmental forecasting technology. An automatic monitoring system to monitor water quality has been established in Ago Bay and the

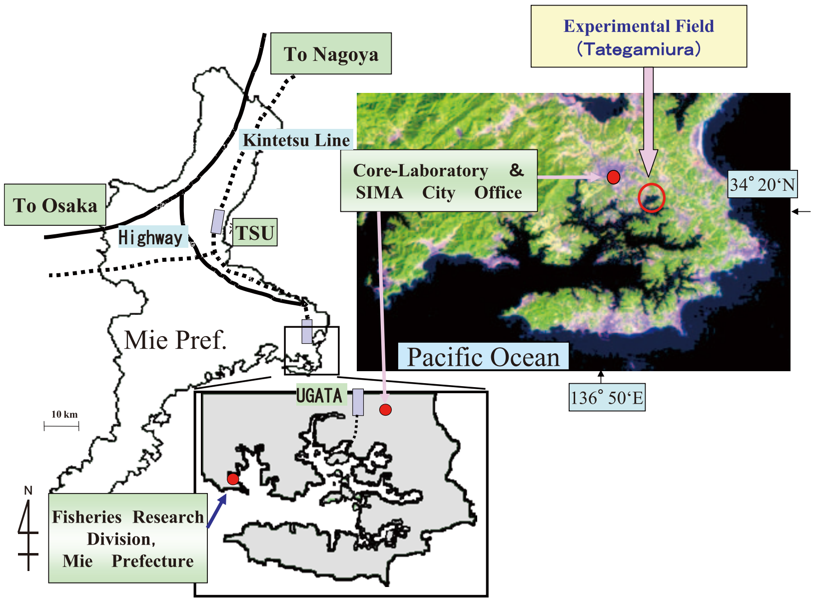

Fig. 1. Location of Ago Bay and its outline showing the enclosed topography and rias-type coastline.

real time observation data are open to the public through the Internet. An ecosystem model is also being developed. By combining these two tools, construction of a system that can forecast environmental changes in water quality is being developed.

New technology for developing biologically active tidal flats

Sediment eutrophication and the frequent occurrence of oxygen-deficient water at the bottom layer has caused the destruction of the benthic ecosystem and hence a decrease in biological activity in recent years. As a result of multi-spectrum aerial picture analyses, it was found that approximately 70% of the tidal flat and shallow areas had been decreased by land reclamation and other artificial environmental transformation along the coast of Ago Bay (Figure 2). Therefore, one of the major causes of environmental deterioration is considered to be reduction of shallow coastal areas, including tidal flats and seagrass beds that originally provided shallow areas with natural purification capability. In this context, the present Ago Bay Restoration Project aims to enhance the natural purification capability and to recover better material circulation around the shallow areas. New technology has been developed for constructing functional artificial tidal flats using muddy dredged sediment which contains rich organic matter but has always been treated as useless material in Ago Bay.

We set up the six experimental tidal flats in which the mixing ratio of dredged sediment with original sandy sediment in the area was changed stepwise (Figure 3). Sediment quality and benthic species on experimental tidal flats have been monitored for three years. The following results were obtained from the field study: 1) The number of benthic species in the experimental tidal flats constructed by muddy dredged sediment increased after six months (Figure 4), and 2) The suitable range of sediment quality on tidal flats for macrobenthic species was found to be 3-10 mg/g dry sediment for COD and 15-35% for mud content ratio (i.e. silt and clay content ratio). These results indicate that macrobenthic species decreased not only when organic matter and mud content was too high but also when organic matter and mud content was too low in the sediments. Accordingly, artificial tidal flat material mixed with muddy dredged sediment rich in organic matter and natural tidal flat sediments provides better conditions for the habitat of the benthic species than a conventional construction method of a tidal flat that uses clean sand.

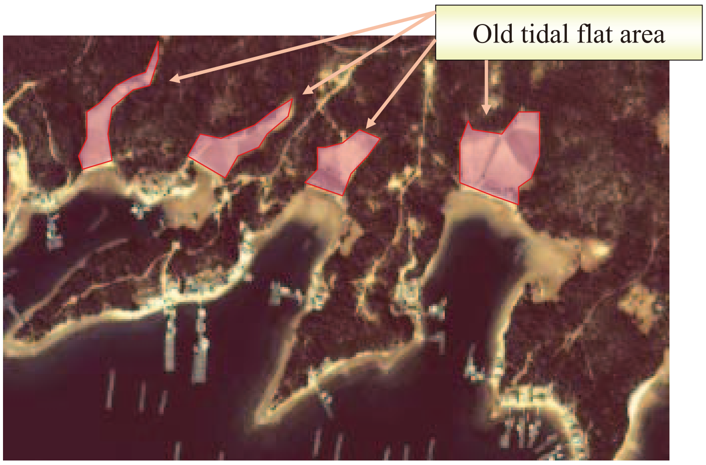

Fig. 2. An aerial photograph in which transformation of shallow coastal areas to reclaimed land (shaded area) are shown.

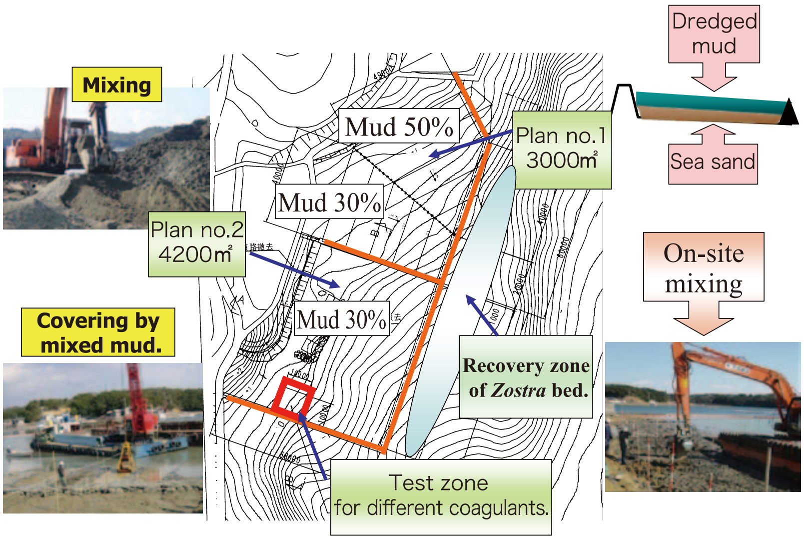

Fig. 3. Sketch of the experimental site and scenes of construction at Tategamiura where new technology for tidal flats and *Zostera* beds were developed.

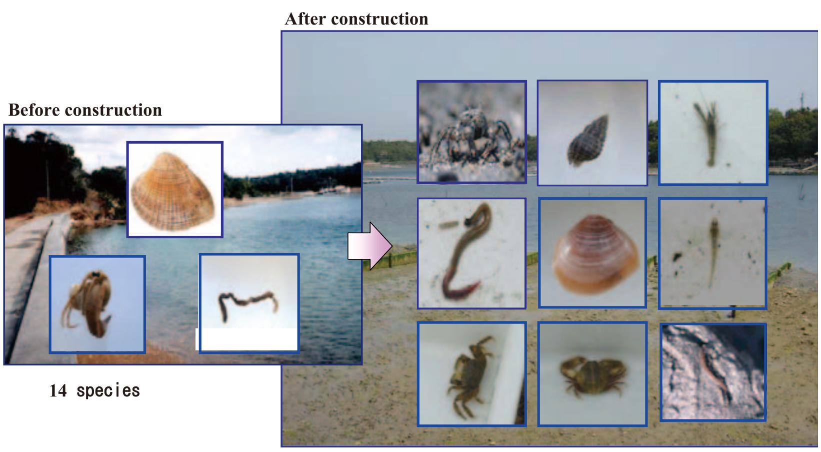

Fig. 4. Schematic display on the effects of tidal flat enrichment by dredged sediment in which species numbers and the biomass of macrobenthos increased.

Technology development for dewatering dredged sediments and its application

In Ago Bay area, dredged sediments have so far been placed in confined disposal sites but recently, acquisition of disposal sites is becoming difficult and the cost of land development is rising. Therefore, emphasis is shifting toward utilizing these materials for beneficial application in the marine environment. One of the main obstacles to treat dredged sediment is its extremely high water content. In order to overcome this problem, treatment by appropriate coagulants followed by dewatering are necessary to harden the dredged sediments for easy handling. A new technology to which the name Hi-Biah-System (HBS) was given, was developed in the project to perform this operation. Main components of HBS are: main stock tank, coagulant chamber, reactor, and dewatering system. Continuous flow operation can be achieved through a fully automatic system. Different coagulants were tested to check their abilities to form larger and more stable flocks. After coagulation and following the dewatering process, water content of the original sediments was remarkably reduced. Treated sediment cakes were applied in many ways for constructing different types of artificial tidal flats (Figure 5).

Another application of HBS is to provide suitable bases for seagrass beds that were prepared mainly from dredged sediments treated with a coagulant (Aquarefine: ARP), then mixed with different hardeners to be used as a bed for eelgrass (*Zostera marina* Linnè) germination. Hardeners used in this study were Gypsander, polyvinyl alcohol (PVA). Eelgrass germination and propagation were closely observed for almost six months. Data show high germination rates in the samples treated with hardeners compared with the ones without treatment. For original sandy sediments that were used as control samples, low germination rate was observed presumably due to the particle size and lack of organic matter. Leaf area index (LAI) for eelgrass germinated both in the control and dredged sediments without treatment were less than that for samples treated with ARP and other hardeners.

Bivalves are widely used as bio-indicators of heavy metals and other pollutants in coastal areas, since bivalves are well known to concentrate these contaminants, providing a time integrated indication of environmental contamination. Therefore, safety of treated sediments with different coagulants was checked through the growth of short necked clams in the prepared artificial tidal flats.

Five different experimental tidal flats were prepared with use of; ARP, Pellets, Gypsander,

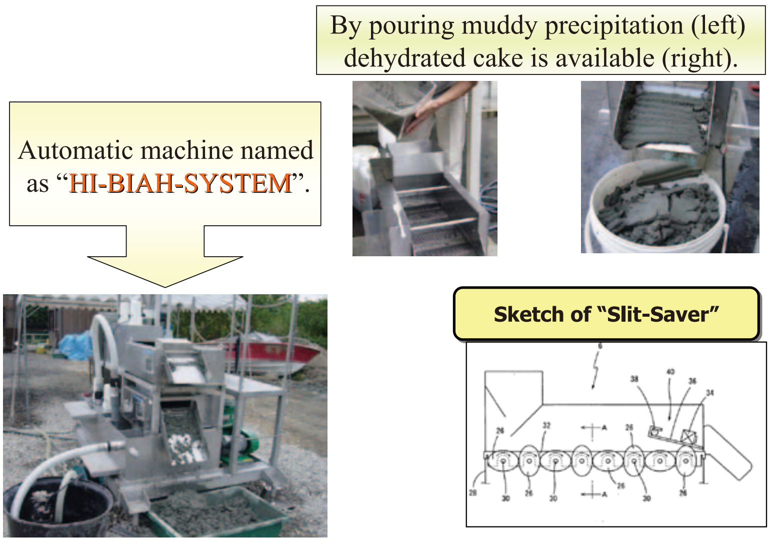

Fig. 5. Appearance of the automatic dewatering system of dredged sediment and scenes of dewatering processes.

Ecorton, and sand only (without treatment). On each flat, 200 short-necked clams were deployed inside stainless steel cages covered with nylon net. After three months of deployment, sampling was carried out to monitor mortality, length, height, growth, and heavy metals in the clam tissues. Maximum mortality was obtained with control flat (16%), whereas minimum mortality was obtained with Pellets (0%). Reasonable growth, which exceeed 50% from the original values, was observed for the clams in the different flats. Heavy metals were measured by ICP-MS. Although heavy metals in general showed a little increase after three months of deployment, the concentrations were below the level of international harmful standards.

Development of a new method for recovering *Zostera* bed

Zostera marina Linnaeus is widely distributed in the temperate zone of the northern hemisphere. It grows in calm and inner coastal areas and forms a dense populations called *Zostera* beds or *Zostera* zones on sandy or muddy bottoms. This seagrass bed performs a major role as a primary producer in the coastal ecosystem and serves coastal fish and other animals with an important nursery and spawning ground. In Japan, Z. *marina* had long been distributed in almost all coastal regions, but since the 1950s the beds have decreased drastically. So, not a few recovering programs of *Zostera* bed have started since the 1960s in various regions for conservation of the coastal environment and the propagation of fishery recourses. Several effective methods for recovering the beds have been developed, but the methods are generally complicated and sometimes very difficult for routine use by local people because of the need for special instruments or technologies and considerable SCUBA diving effort. In this project, a simple, convenient and effective method named the *Zostera* mat system that is applicable to local fisherman, was developed.

Reproductive shoots of *Zostera* with developing seeds were collected from late spring to summer and were put in mesh bags for promoting maturation of seeds in sea water for about a month. Fully matured seeds were preserved under low temperatures of 0-4℃, which promoted germination. In late autumn when water temperature decreases to less than 20℃, the seeds begin to germinate. The *Zostera* mat system to sow seeds for growing the plants was developed. The size of the mat is 50x50 cm and is 2 cm in thickness and about 1.2 kg in weight. The mat is constructed with four layers; those are iron net of 4 cm mesh, jute net of 2 mm mesh, jute fiber mat of 5 mm in thickness and iron net of 4 cm mesh. Seeds were sowed between jute mesh net and jute fiber mat. Then, many bases were connected with cotton ropes in a row at intervals of 50 cm. Thus, the bases were easily settled on the sea bottom continuously on the straight line from a small boat. Many seeds germinated after a month, and grew up after three months. We set 250 and 400 bases of *Zostera* mat in 2004 and 2005, respectively. Growth patterns and seasonal changes in density of *Zostera* on the bed were surveyed. Optimal and upper limit temperatures for germination and growth of this plant were also studied in the laboratory (Figure 6).

Several advantages of the *Zostera* mat proved are as follows. When seeds germinate, seedlings can make root in the jute mat which helps seedlings attach tightly to the bottom. By connecting *Zostera* mat with ropes in a row, it is easy to set many bases on the sea bottom without any kind of diving effort. Fisherman can do all the procedures, such as collecting mature plants, promoting maturation of seeds, preserving seeds, sowing seeds on the bases and deploying the bases on the sea bottom without special instruments and the use of difficult techniques. This base is made only of natural materials such as jute fiber and cotton ropes, i.e. environment-friendly resources.

Automatic environmental monitoring system

The automatic monitoring system in Ago Bay consists of five sets of the automatic water quality observation stations (WQOS) and two sets of the automatic flow observation stations (FOS). One of the WQOS placed at the bay mouth collects information closely related to open sea, while the rest of the WQOS are established in the center

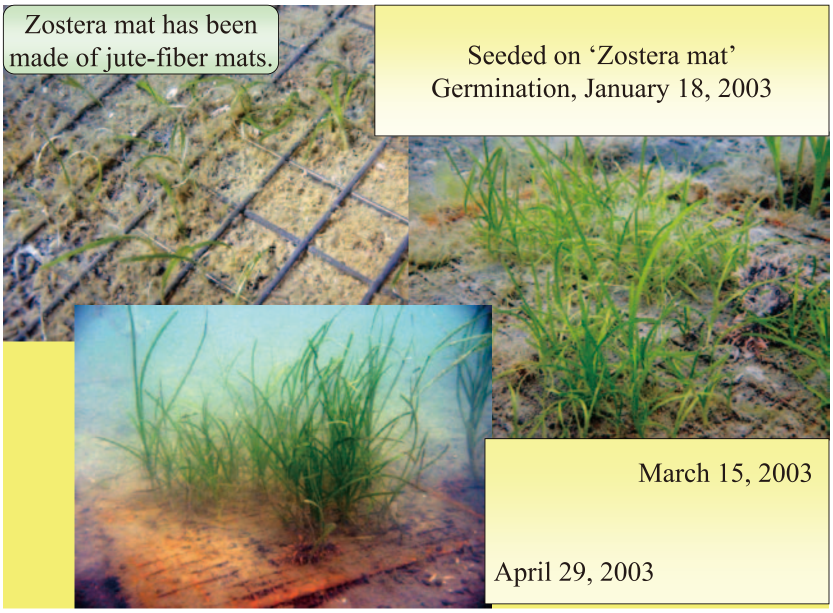

Fig. 6. Photographs showing the application of *Zostera* mats on which *Zostera* marina germinated and grown.

and inner parts of the bay to get information on the bay. The two FOS are established in line on the transverse section just inside the bay mouth.

The observation items of the WQOS are water temperature, salinity, chlorophyll fluorescence, dissolved oxygen and turbidity. The detector unit, in which the observation sensors are installed, goes up and down with a winch on the floating platform, and acquires the data for every water depth. In order to prevent biofouling, the detector unit is hauled up and is exposed to the air during the time between operations and goes down into water only during the time of measurement. This significantly reduced the frequency of maintenance and contributed to raise the time of operation. The WQOS has already been operated for more than three years, and attained an high operation rate of 90-95%, including the system stops at the time of typhoon attacks. The FOS consists of the seabed installation type ADCP and an acoustic modem that performs communication with the floating platform. The wireless communication system began to work in November 2005, however, the two ADCP had already been collecting data since July 2003. The analysis of the recorded data showed the effectiveness of the FOS to predict the variation of water quality in the bay (Figures 7 and 8).

The observation data of the WQOS and the FOS are transmitted to the Core Research Laboratory of the project at one hour intervals, using a cellular-phone network, and the data processed with the personal computer of the laboratory are immediately distributed to the Internet through the Web server. The homepage is actively accessed not only by researchers but also by pearl culture fishermen; consequently, it contributes to advertising the significance of the project to local residents (Figure 9).

Another objective of the environmental monitoring system is a short-term prediction of water quality. The observation data are used as the input data and the numerical simulation model under development is expected to perform the task. The dynamic behaviors of water quality in the bay have begun to be disclosed by the environmental monitoring system.

Development of hydrodynamic and ecosystem model for Ago Bay

Three different models are under development. They are a three-dimensional hydrodynamic model, a water quality model and a sedimentation model. The hydrodynamic model has characteristics that the vertical grid interval shrinks toward the sea surface. This aims at improvement of

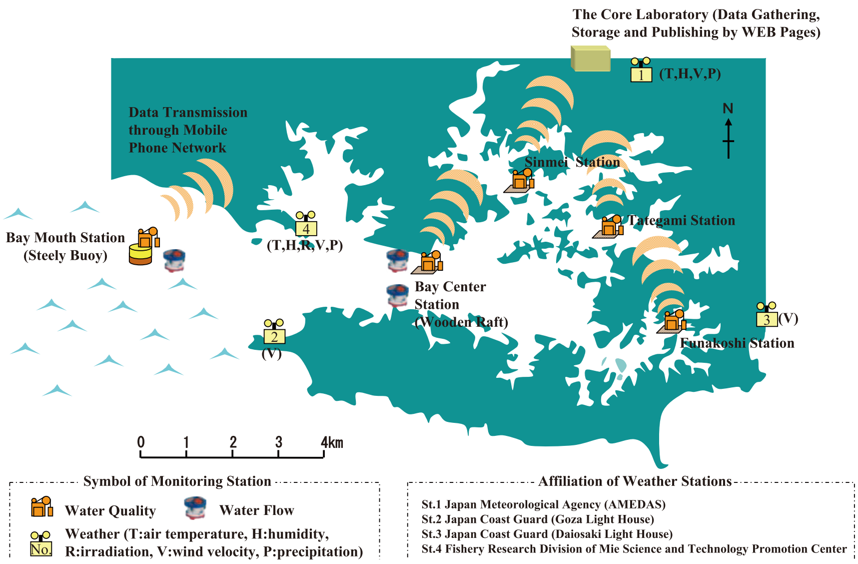

Fig. 7. Automatic environmental monitoring system of Ago Bay.

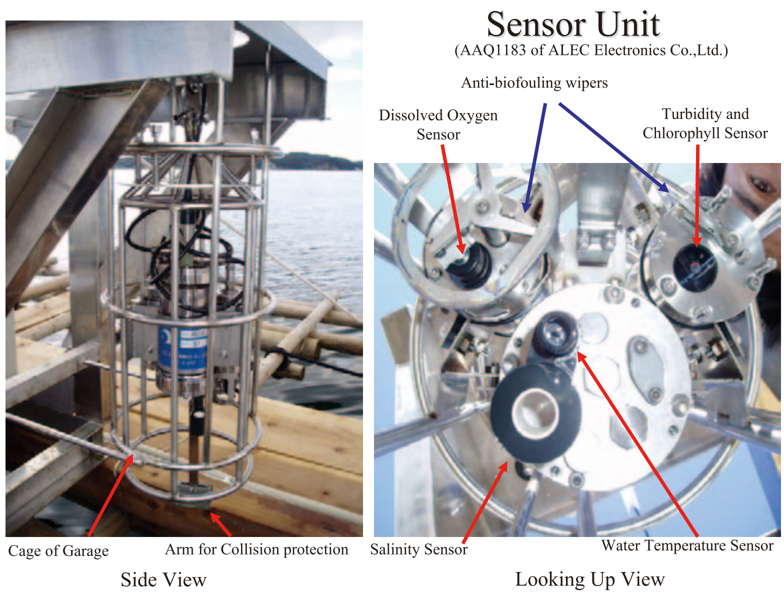

Fig. 8. Photographs showing the structure of a sensor unit.

computational accuracy of salinity, which has a strong vertical gradient near the sea surface. According to the analyses already done, the river plume that spreads on a sea surface was clearly captured, and density stratification in summer season was reproduced quite accurately. Since the nutrient inflow from the land area is conveyed by the river plume, the models are also expected to improve the accuracy of water quality calculation.

The water quality model includes dynamics of plankton and nutrients, and the physiological characteristics of pearl oysters. Nineteen compartments are included in the model, which allows the competition of phytoplankton species between a diatom and a dinoflagellate. The concentration of carbon, nitrogen and phosphorus are carefully implemented in the model so that the computational results can be utilized in the investigation of material circulation. The sedimentation model also has 19 compartments and takes into consideration the circulation of carbon, nitrogen, phosphate, iron, manganese, sulfur and oxygen. It is one of the targets of the present study to couple the water quality model with the sedimentation model and to perform analyses that reproduce the existing phenomenon as correctly as possible.

To obtain basic data for the numerical models, oceanographic observations and experiments with the sediments have been conducted over three years. In addition to that, a biological experiment for developing a physiological model for pearl oysters has been conducted. The water quality data measured by the environmental monitoring system since September 2003 also created a huge data base. All of those data will be effectively utilized to complete the integrated Ago Bay model (Figure 10).

A short-term prediction of the water quality is planned in the project. The real time observation data of the environmental monitoring system is utilized and is read into the numerical models with use of the data assimilation technique. This will be tried after the completion of the development of the numerical models.

Closing Remarks

Results of the study and development of the technology during the course of the project including development of functional tidal flats, a new method for recovering *Zostera* beds, real time environmental monitoring systems and environmental forecasting technology to be established are expected to contribute to establish

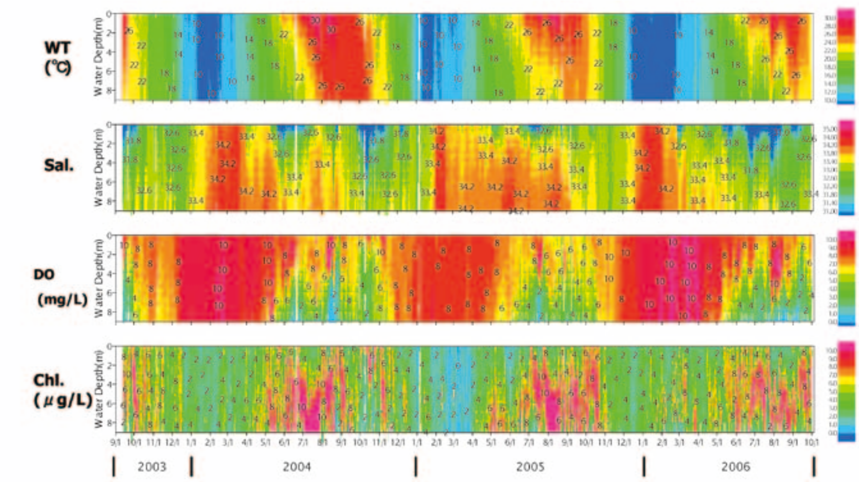

Fig. 9. Display of monitoring data during three years (water temperature, salinity, dissolved oxygen and chlorophyll from above) at Tategami Station.

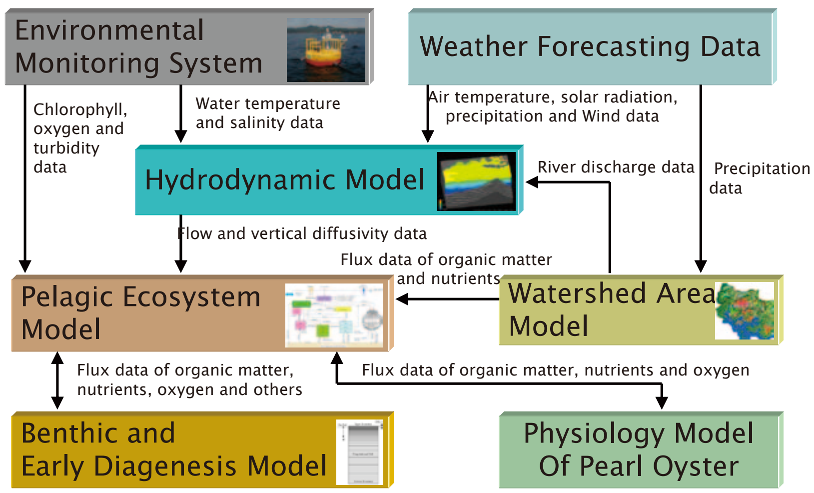

Fig. 10. Structure of prediction model by integration of the environmental monitoring system and other models being developed.

sustainable *Sato-Umi* through effective environmental restoration in the Ago Bay area. Recent attempts of environmental restoration in this area with broader cooperation among a variety of stakeholders can be a model of environmental restoration of small scale enclosed coastal seas with particular emphasis to environmental education for the next generation and sustainable environmental management by local people and local municipalities. The concept of *Sato-Umi* may help realize the motto of the project: "Better life through wise and sustainable use of coastal environments" in Ago Bay.

Acknowledgment

The author appreciates members of the project, in particular of Dr. Tadaya Kato, Professor Emeritus of Mie University, Dr. Miyuki Maegawa of the same university, Dr. Satoshi Chiba of Yokkaichi University, Mrs. Hideki Kokubu and Hiroyuki Okumura of Mie Prefecture, Dr. Dabwan Ahmed and Mr. Daizo Imai of Mie Industry and Enterprise Support Center, for providing valuable information and data.

References

Chiba S. *et al.* 2006. Contribution of environmental monitoring system to the solution of environmental problems. Proceedings of the 16th Joint Symposium by Cooperation Council for Coastal Environment-related Society in Japan (ENKANREN), pp. 5-12. (in Japanese)

Imai T. *et al.* 2006. New technology for treating muddy dredged sediment. Proceedings of the 16th Joint Symposium by Cooperation Council for Coastal Environment-related Society in Japan (ENKANREN), pp. 37-39. (in Japanese)

Kokubu H. *et al.* 2006. New technology for developing tidal flat. Proceedings of the 16th Joint Symposium by Cooperation Council for Coastal Environment-related Society in Japan (ENKANREN), pp. 49-55. (in Japanese)

Matsuda O. 2007. Overview of Ago Bay restoration project based on the new concept of "*Sato-Umi*": a case of environmental restoration of enclosed coastal seas in Japan. Proceedings of 1st International Workshop on Management and Function Restoration Technology for Estuaries and Coastal Seas (ed. by Jung K. T.), KORDI, pp. 1-6.

Matsuda O. 2007. New approach for the integrated aquaculture management from the view point of multi-functional role of fisheries and aquacultures. Bull. Fish. Res. Agen. No. 19, pp. 167-171.

Maegawa M. 2006. New technology for developing *Zostera* bed. Proceedings of the 16th Joint Symposium by Cooperation Council for Coastal Environment-related Society in Japan (ENKANREN), pp. 34-36. (in Japanese)

Okumura H. *et al.* 2006. Environmental education in elementary school developed in Ago Bay area. Proceedings of the 16th Joint Symposium by Cooperation Council for Coastal Environment-related Society in Japan (ENKANREN), pp. 20-24. (in Japanese)