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Large-scale restoration of tidal flats and shallows to suppress the development of oxygen deficient water masses in Mikawa Bay

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Abstract Development of hypoxia has been confirmed in the inner-part of almost every major bay of Japan on the Pacific coast from Tokyo southward. Mikawa Bay, where Japan's most serious hypoxia occurs, is used to this report to present the effects and causes of hypoxia, such as impact upon fisheries, historical development and nutrient budget between sediment and water. Although hypoxia basically results from an increase in nutrient load input, intense reclamation in Mikawa Bay of about 1,200 ha of shallows in the 1970s, including tidal flats, has drastically accelerated a deficiency in dissolved oxygen. This is mostly due to losses in the rich filter-feeding macrobenthic community that largely control the high water-purification capacity of those areas. Currently, oxygen deficient water masses in Mikawa Bay are large enough to strip the precious water purification capacity of the remaining shallows by killing the remaining filter feeders. Consequently, the considerable shallows have turned from being a purifier of water quality to a source of excess nutrients, thus sending the Bay into a spiral of deterioration. In order to break this vicious cycle, the dissolved oxygen deficiency of the Bay must be contained to the extent that the purification capacity of the shallows can be brought into full play. To this end, the first thing to do is to restore the tidal flats and the shallows having the effective depth so designed as not to be affected by oxygen deficient water masses, over an extensive area. This may be a more urgent imperative than reducing the nutrient load input. Since 1998 to 2001, about 350 ha of artificial shallows, including tidal flats, have been restored in Mikawa Bay using sand dredged from the Nakayama sea channel. Recovery of abundant benthic organisms, such as bivalves, has been confirmed already by monitoring. Additional tidal flat restoration is now in progress.

Key words: hypoxia, tidal flat, restoration, *Ruditapes philippinarum*

Effects of a dissolved oxygen deficiency on fisheries in Mikawa Bay

Mikawa Bay is a typical, partially mixed estuary located in the central part of Japan as shown in Fig. 1. The Bay consists of two inlets: The northwest part is Chita Bay into which the River Yahagi-gawa flows. The eastern part is Atsumi Bay into which the River Toyo-gawa flows. In its entirety, Mikawa Bay measures about 600 km^2 and is very shallow with an average depth of 10m.

Oxygen deficient water masses occur in Mikawa Bay on a large scale as seen in the example shown in Fig. 2 (Ishida and Hara, 1996) since about 1970. Oxygen deficiencies can last as long as four months, or more, from mid-June to mid-October.

Mikawa Bay was one of the best fishing grounds for commercial crustaceans (such as

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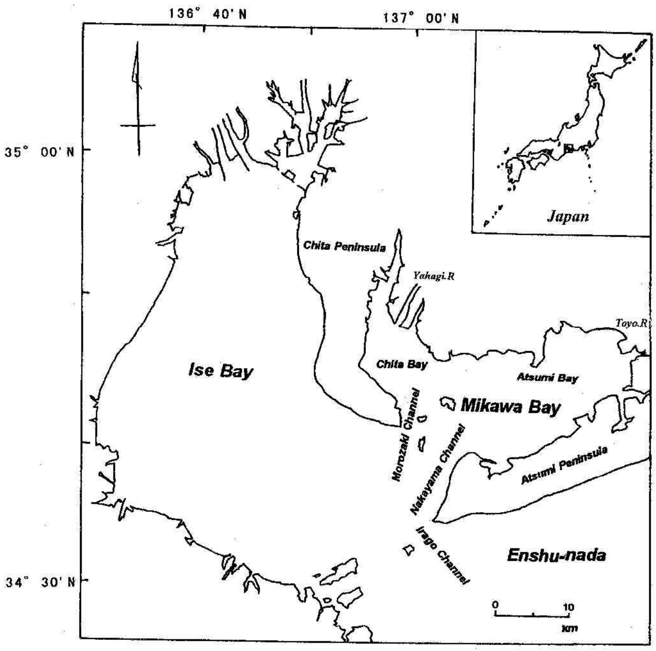

Fig. 1. Map of Mikawa Bay

kuruma-prawns, swimming-crabs), bivalves (such as short-necked clams, cockles) and benthic fishes (such as stone flounders) in Japan. For example, the catch of the short-necked clam (*Ruditapes philippinarum*) has been the best in Japan until today, contributing the largest share of about 36 % to the total yield. However, the total catch in Aichi Prefecture decreased from 20,000 ton year^{-1} to 11,000 ton year^{-1} from the latter half of the 1960s to 2001.

Since 1970, when dissolved oxygen deficiencies began to develop, the major fishing grounds of small-trawl fisheries of these species shifted from the middle of the bay towards the mouth. At present, the Mikawa Bay trawl fishery yield is rapidly declining.

Effects of dissolved oxygen deficiencies on the Mikawa Bay nutrient budget

A deficiency of dissolved oxygen not only affects the structure of a benthic community, but also its functionality. We have studied the temporal development of waters deficient in dissolved oxygen and the resulting benthic community changes (Suzuki *et al.*, 1998a). We have also studied how the nitrogen balance between the benthic sediment and seawater is affected, using a benthic ecosystem model (Suzuki *et al.*, 1998b) that was developed to quantify the nitrogen cycle of tidal flats in Mikawa Bay (Suzuki *et al.*, 1997). Those results are outlined below.

Fig. 3 shows the temporal changes in water temperature, salinity, and dissolved oxygen saturation percentage immediately above the bottom sediment in shallow areas (4 m depth expressed by chart) that were recorded in the inner part of Mikawa Bay, from June to the end of July 1996, and compared to changes in the benthic community (bacteria, benthic micro algae, meiobenthos, and macrobenthos).

A deficiency in dissolved oxygen was observed on 25-26 June, 28-29 June, and 10 July , but each time the occurrence was brief and the saturation level stayed at about 50 % until at least 20 July. Then, a deficiency in dissolved oxygen lasted through the period from July 20-

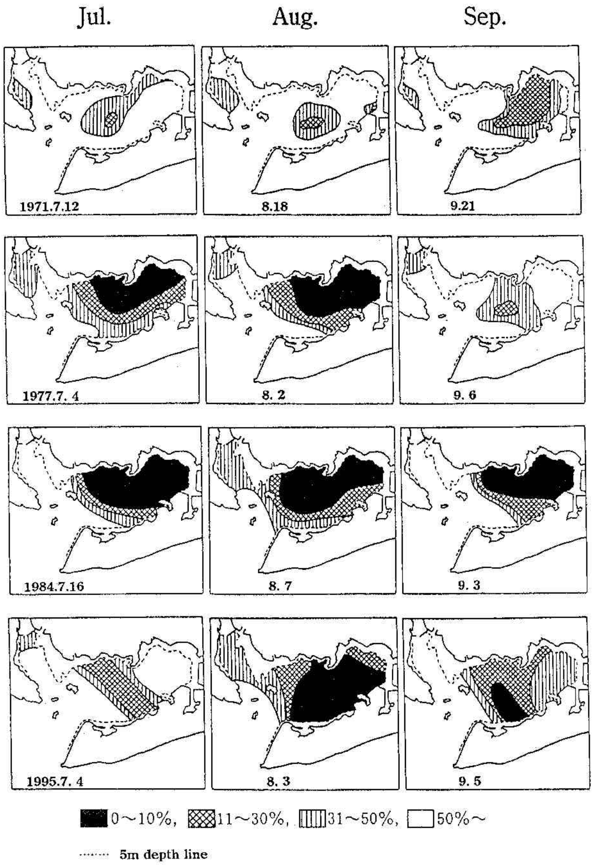

Fig. 2. Example of the distribution of dissolved oxygen deficient water masses in Mikawa Bay. Four legends denote the level of dissolved oxygen saturation percentage

29 and the frequency of anoxic conditions increased.

Different species reacted in different ways to low oxygen concentrations according to their tolerance limits, but eventually on July 29 the biomass of every species dropped sharply.

Fig. 4 shows a time-series chart of the nutrient flux between seawater and sediment calculated by a benthic ecosystem model. On the vertical axis, the flux from seawater to sediment is indicated as negative quantities.

Before 16 July, particulate organic nitrogen (PON) was being removed from the water at -561 to -962 mgN m^{-2} day^{-1} (-785 mgN m^{-2} day^{-1}, on average). Dissolved inorganic nitrogen (DIN) was eluting at 159 to 757 mgN m^{-2} day^{-1} (535 mgN m^{-2} day^{-1}, on average). On balance, Total nitrogen (TN) was removed from the water at -43 to -401 mgN m^{-2} day^{-1} (-250 mgN m^{-2} day^{-1}, on average). Then, from 16 to 22 July, both the PON removal rate and the DIN elution rate dropped rapidly, and on 29 July PON removal had almost ceased. Thus, after 22 July, the TN budget turned from negative to positive to about 240 mgN m^{-2} day^{-1}.

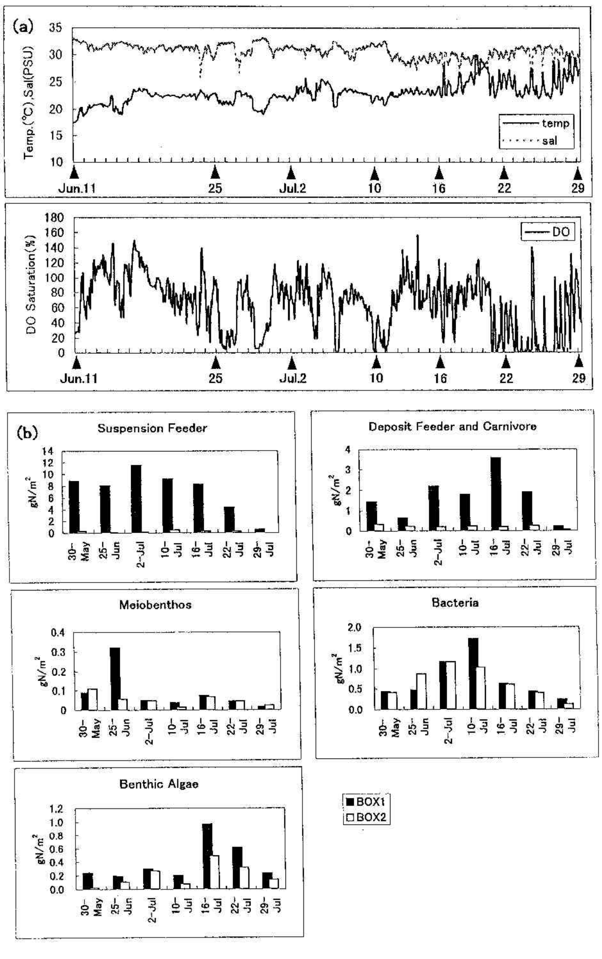

Fig. 3. Time-series changes in water temperature, salinity and degree of dissolved oxygen saturation percentage immediately above the bottom sediment in shallow areas of Mikawa Bay and changes in the benthic community (bacteria, benthic micro algae, meiobenthos, and macrobenthos) from June to end of July in 1996 (Suzuki *et al.*, 1998a)

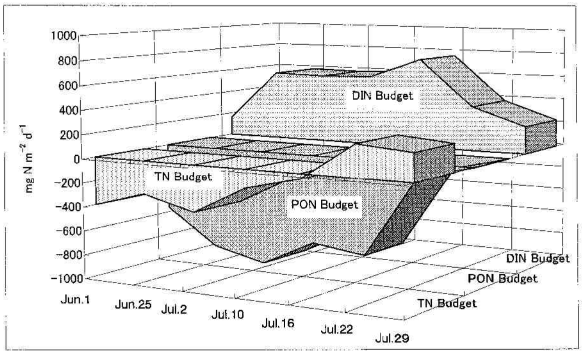

Fig. 4. Change of the nitrogen budget between sea water and sediment on the shallow area of the inner Mikawa Bay from 1 June to 29 July, 1996 (Suzuki *et al.*,1998b)

The analytical results from the benthic ecosystem model indicate that the shallows usually have the capacity to reduce particulate organic matter at a higher rate of efficiency than the rate of elution of inorganic nutrient salts. However, this so-called "water purification capability" functions only if ambient oxygen conditions are normal. If a large oxygen-deficient water mass develops in the offshore sea bottom to a scale that can affect the shallows under certain wind and tide conditions, the situation changes completely.

First, the macrobenthic biomass of suspension-feeders decreases, resulting in a lower rate of removal of particulate organic matter from the water. Then, the rate of removal of organic sediment matter by macrobenthic deposit-feeders, which balances with the rate of sedimentation of PON, also drops. Subsequent deterioration in water transparency near the sea bottom hinders the growth of benthic microalgae and seaweeds, which slows down the absorption rate of inorganic nutrient salts. Then, the amount of oxygen generated by photosynthesis also falls, accelerating the development of the anaerobic condition near the sea bottom.

Circulation of nutrient salts within the bottom sediment becomes heavily dependent on bacteria, although this system is also hindered by a reduction in bacterial biomass. Although this means a reduction in nutrient elution from sediment to seawater, the TN budget of PON and DIN shifts from a sink (−) to a source (+). Consequently, the shallows that were a highly efficient water column purifier become a source of nutrients, and this further exacerbates the dissolved oxygen deficiency.

It is estimated that benthic organisms usually abundant in shallow sea areas above 5 m in depth are wiped out by the deficiency of dissolved oxygen in about one third of the total shallow area under the worst circumstances. This results in nitrogen elution of 11 tons day^{-1}, which amounts to about 27 % of the nutrient load input to Mikawa Bay. This means that countermeasures to reduce the nutrient input, such as construction of sewage treatment plants, would make little difference unless the hypoxic condition is improved first.

Historic record and causes of dissolved oxygen deficiencies

An oxygen deficient water mass is formed when oxygen demand exceeds oxygen supply. The main cause of high oxygen demand is the increase in the amount of particulate organic matter in the water or organic sediments on the bottom.

Fig. 5 shows the transition in transparency and the nitrogen load through time. Transparency rapidly decreased from 1955 to 1970, corresponding to annual fluctuations in the nitrogen load. During that period, the nitrogen load doubled and phosphorus tripled. However, from about 1970 to 1983 as shown in Fig. 6, red tides became a notable feature after that period. The development of dissolved oxygen deficiencies also increased steeply from about 1970. Red tides and associated hypoxia rarely occurred before 1970.

Thus, historically, eutrophication in Mikawa Bay can be divided into Phase I (1955-1970) in which transparency decreased considerably as a result of the increased nutrient load; and Phase II (1970 and after) in which fisheries were severely damaged by red tides and oxygen-deficient water masses. The question now is, apart from the increase in nutrient inputs, what caused the intensification of eutrophication between Phase I and Phase II?

One likely cause is the intense reclamation throughout the extensive shallow areas. During the 1970s in Atsumi Bay, in the eastern-part of Mikawa Bay, about 1,200 ha of shallows, including tidal flats, were reclaimed to prepare for constructing a harbor (see Fig. 7). The appearance of red tides, accompanied by oxygen deficient water masses, coincides exactly with that reclamation of the shallows. This fact is very important in regard to hypoxia in the estuary. Tidal flats and shallows have a high water-purification capability due to filtering by macrobenthic suspension-feeders. Incidentally, benthic suspension feeders (mainly bivalves) living on the Isshiki tidal flat of Mikawa Bay, are estimated to filter seawater at a rate of 3.4 (Aoyama and Suzuki, 1997) to 5.0 m^3 m^{-2} day^{-1} (Sasaki, 1994). From the reclaimed 1,200 ha, this totals to about 500 m^3 sec^{-1}. This value is calculated by assuming that the standing stock of the benthic suspension feeders in the reclaimed area in 1970s is equal to that of the present Isshiki tidal flat area. However, it is possible that this value is underestimated because the reclaimed area was the richest clam fishing ground in Mikawa Bay. The standing stock of short-necked clams in the reclaimed area was estimated at 3.4 times as much as that in the present Isshiki tidal flat, according to the past catch statistics of Aichi Prefecture. Using this revised value, the reclaimed 1,200 ha of shallows are estimated to filter seawater at a rate of 1,700 m^3 sec^{-1}. Since the rate of exchange of seawater at the mouth of Mikawa Bay is 1,169 m^3 sec^{-1} (Unoki, 2000) to 2,600 m^3 sec^{-1} in the summer (Sasaki, 1989), the lost seawater filtration rate equals 19 % to 43 % of the exchange rate of seawater in the case of 500 $m^3 sec^{-1}$ and 65 % to 145 % in the case of 1,700$m^3 sec^{-1}$.

It seems likely that the reduced capability of seawater filtration drastically reduced the capacity to remove suspended organic matter from the water and consequently, accelerated the development of water masses with a dissolved oxygen deficiency, followed by severe red tides.

There is another possibility besides intensive reclamation. It is the development of water resources in the catchment basin. In Mikawa Bay, the River Toyo-gawa is the most important river in regard to density flow and seawater exchange of the Bay.

In 1968, Toyo-gawa canal was completed, which diverts about 20 % (in an average year) to 40 % (in a dry year) of the total flow of the River Toyo-gawa. The chief purpose of the canal is irrigation of farmlands on the Atsumi Peninsula, for which 72 % of the diversion is used. There is speculation that this large reduction in the river flow, due to the canal diversion, reduces the density flow in the bay and exchange of seawater proportionally by 20 % to 40 %. However, this subject needs further study, since a lower estimation of the decline rate of exchange of seawater has been made in an analysis using a numerical model (Suzuki *et al.*, 1986). Nevertheless, it is certain that the hindrance to seawater exchange slows the ejection of suspended organic matter to the exterior of the Bay; and reduces the supply of dissolved oxygen from the mouth of the Bay.

We surmise that the reduction in the filtration rate of seawater, caused by reclamation of the shallows around 1970s, was what mainly accelerated the occurrence of red tides and dissolved oxygen deficient water masses. As mentioned above, Oxygen-deficient water masses in Mikawa Bay have become large enough to strip the precious water purification capability of the remaining shallows. Unfortunately, the shallows have turned from being a water purifier to a source of nutrients sending the Bay into a spiral of deterioration. This phenomenon, triggered by hypoxia, is very similar to the catastrophic degradation of lake ecosystems caused by several external forces.

Takamura (2002) reports in order to maintain a healthy lake ecosystem, it is necessary to distinguish between acceptable change and changes to avoid. The most important factor affecting this distinction is the concept of "re-

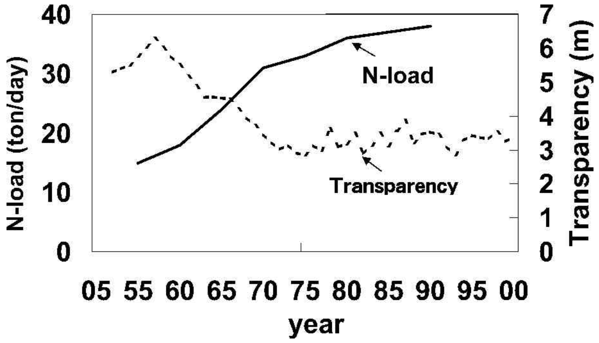

Fig. 5. Transparency and nitrogen load in Mikawa Bay

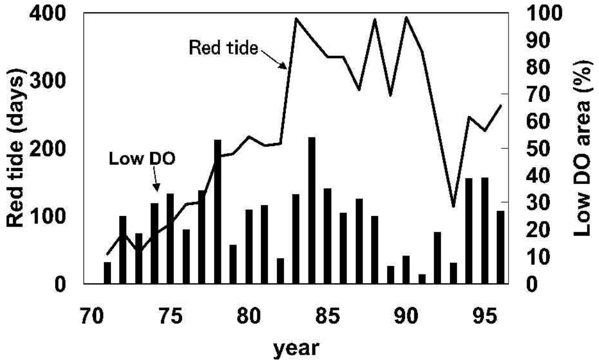

Fig. 6. Total number of days of red tides observed and the areal proportion of oxygen deficient water with less than 30 % saturation in Mikawa Bay

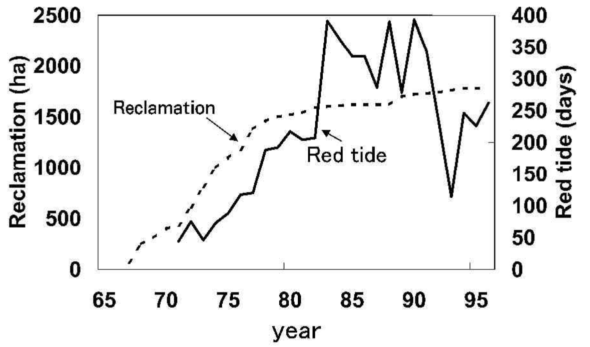

Fig. 7. Total number of days red tides observed and the area of reclaimed land in Mikawa Bay

silience". Takamura (2002) defines lake ecosystem "resilience" as the ability to sustain certain structures and functions of the lake ecosystem against several external forces, and changes that can damage this resilience (catastrophic change) must be avoided.

There are reports in the literature that, through their feeding activities, the macrobenthic community controls the structure of the planktonic community and nutrient concentrations of seawater. They also exert a strong influence on nutrient circulation in the bay (Cloern, 1982; Cohen *et al.*, 1984; Carlson *et al.*, 1984). Thus, in Mikawa Bay, it may be said that abundant bivalves that lived in the reclaimed area provided the Bay with its "resilience". Ironically, the drastic environmental deterioration caused by intensive reclamation projects in Mikawa Bay proved the importance of the benthic community in providing that resilience function.

Restoration of tidal flats and shallows

In order to break the vicious cycle of eutrophication, the dissolved oxygen deficiency of water masses in Mikawa Bay must be contained to the extent that the purification capability of the shallows can be restored to a sufficient level. To this end, the first thing to do is to restore tidal flats and shallows having the effective depth so designed as not to be affected by oxygen deficient water masses, over an extensive area. This may be a more urgent imperative than reducing the nutrient load input.

The Aichi Prefectural Federation of Fisheries Co-operative Associations (APFFCA) organized a technical society to study environmental improvement methods for Mikawa Bay from 1995 to 1997. APFFCA published a proposal titled "The necessity to artificially develop tidal flats and shallows for the improvement of Aichi prefectural sea areas" in 1997. The proposal stated that aggressive restoration of the water purification capability in the Bay would

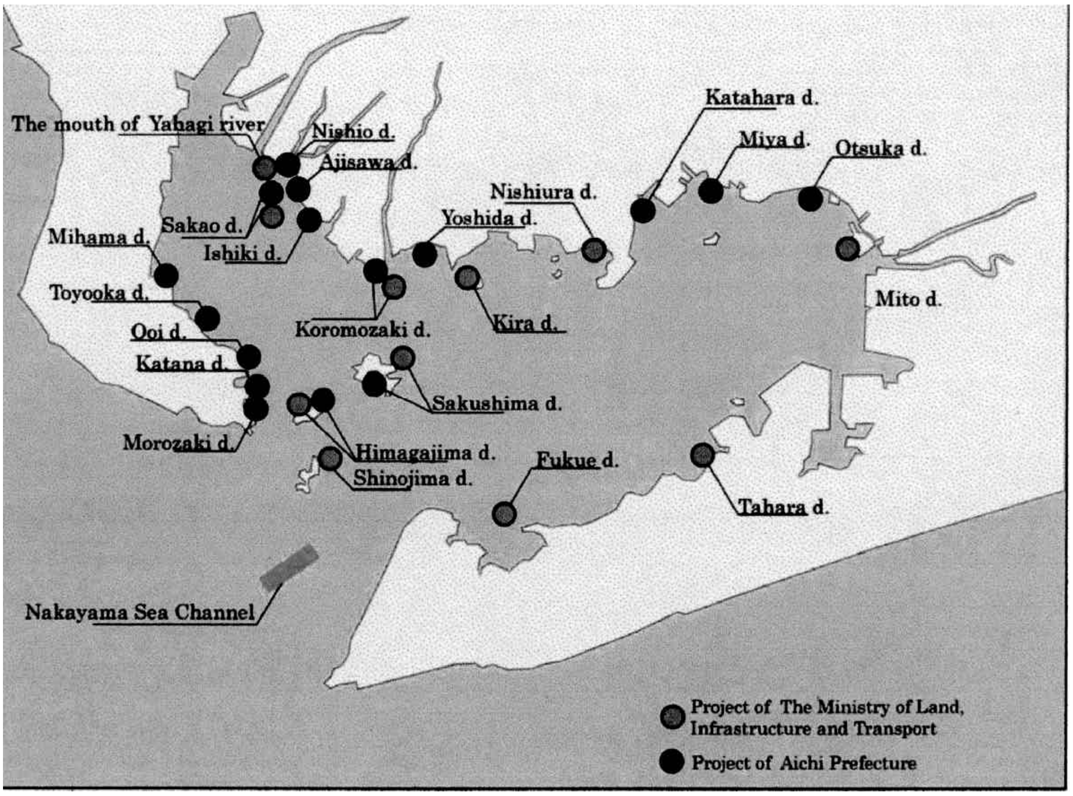

Fig. 8. Locations of the sites restored by 2001

be the most effective way to improve the hypoxic conditions, and then it would be necessary to enhance biological diversity and the productivity of fisheries.

At first, it was thought that realization of this proposal would be very difficult because of the high cost and the large sand volume, given that the APFFCA proposal stated that it would be necessary to restore a large area of over 1,000 ha to significantly suppress hypoxic conditions.

The Nakayama sea channel, located at the entrance of Mikawa Bay, is important to marine traffic accessing the ports in Mikawa Bay. However, the navigation of vessels in the area is limited, because of patchy shoals (the most shallow point is −8.6m) and sunken rocks that interfere with the economical operation of vessels. To improve navigability of the channel, the Ministry of Land, Infrastructure and Transport (MLIT), Chubu Bureau, made the "Nakayama Channel Line improvement plan" in 1980. APFFCA has consistently objected to this plan because this area has been a good fishing ground. As a result of many negotiations between APFFCA and MLIT, it was agreed that all dredged sand (6.2×10^6 m^3) would be used to restore tidal flats and shallows in Mikawa Bay. After this agreement, artificial development of tidal flats and shallows to improve Mikawa Bay accelerated drastically under a joint effort between MLIT and Aichi Prefecture. Fig. 8 shows the locations of the restored sites, in which 11 sites were created by MLIT and 16 sites by Aichi Prefecture. In total, tidal flats and shallows of 350 ha have been restored already using the sand of 3.4×10^6 m^3 from 1998 to 2001. The use of the remaining 2.8×10^6 m^3 is scheduled to restore tidal flats and shallows by 2004.

Effect of the restoration

At some of the restored tidal flats and shallows, monitoring surveys have been conducted on environmental conditions such as water quality, sediment quality, benthic community diversity and abundance of fishery organisms by MLIT and Aichi Prefecture. As the investigations are still going on, we cannot show the results in detail yet. However, parts of the interim results are given in the following:

At the Nishiura site (12 ha) where a tidal flat was created in 1999, many bivalves have been observed-even immediately after construction. In an investigation using a small trawl shell-net (0.59 m width) conducted about 3 years after the tidal flat creation, many megabenthic species, including commercial species, were observed as shown in Table 1. These values are comparable to those of natural tidal flats in Mikawa Bay. Before the creation of the artificial tidal flat, these megabenthic species were not found in this area in summer.

Fig. 9 shows the transition in the numbers of benthic species at the Mito site (10 ha). Initially, the biota consisted mainly of polychaetes (unpublished data by MLIT). As time passed, many additional bivalves appeared such that the biota has become diversified. Improvement of the water purification capacity is expected due to the increase of bivalves because they have a high water filtration capability. At present, the most dominant species, on a wet weigh basis, is *Mactra chinensis* as is likely at the Nishiura site. The particulate organic nitrogen purification capability of this site has been estimated at 136 mgN m^2 day^{-1}, based on the monitoring results of June 2000 (unpublished data by MLIT). This value, estimated 21 months after the artificial creation, is equivalent to about 60% of the nitrogen purification ability of Isshiki tidal flat, which was estimated at 227 mgN m^2 day^{-1} by Aoyama and Suzuki (1997).

At the Isshiki site (26 ha), a lot of juvenile flounders were caught using a standard sledge net (Koshiishi *et al.*, 1999). The most dominant species was the stone flounder (*Platichthys bicolorantus*), which appeared mainly from March to May. A sledge net was towed along three transects on the tidal flat and one transect off the tidal flat at high water. Observed individuals ranged between 3,278-

13,489 inds ha^{-1} (7,156 inds ha^{-1} on average) in March, 2,647-7,037 inds ha^{-1} (5,571 inds ha^{-1} on average) in April and 216-3,315 inds ha^{-1} (1,390 inds ha^{-1} on average) in June, respectively assuming that the efficiency of catch is 0.4-0.7 estimated from the body size (Koshiishi *et al.*, 1999). The values on the restored tidal flat are larger than that of the outside of site. Although the Isshiki site was created in August 2000 and less than one year had passed, these values are almost equal to, or larger than, the density (1,620-8,192 inds ha^{-1}) observed in the natural estuary, of Gamou of Sendai Bay in mid April from 1992 to 1996 (Yamashita *et al.*, 1999). However, there are some sites of artificial shallows where good results that were expected have not been obtained. In summer, at the innerpart of Mikawa Bay, serious hypoxia is frequently observed near the bottom, even in shallows above 4 m in depth. Therefore, the aim of developing a new shallow area should be to avoid hypoxia.

Imao *et al.* (2001) proposed a method to determine the depth necessary to avoid hypoxia at a new artificial shallow area. They proposed that the depth of the artificial shallow should be where the survival rate for the short-necked clam will be over 70 % under the severest hypoxic conditions (hereafter called the "survival depth"). Imao *et al.* (2001) sampled the macrobenthos, water temperature and dissolved oxygen concentration successively in nine coastal areas of Mikawa Bay. Then they estimated each survival depth using a numerical model to forecast the survival rate of short-necked clams against hypoxia (Suzuki *et al.*, 1998c). The results showed that the survival depth is different for each area within a range of D.L. −1.3 m to D.L. −4.0 m. Unfortunately, however, in the actual tidal flat creation, civil engineers, who tend to plan uniformly without reflecting the local hypoxic features, have not yet acknowledged the importance of this method.

We suggest that the depth of the artificial tidal flat creation was slightly lower than the

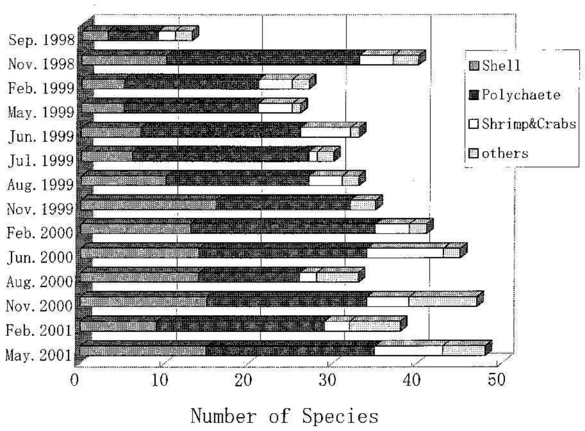

Fig. 9. Numbers of the benthic species at the Mito site (unpublished data by MLIT)

Table 1. Megabenthos caught by a small trawl shell-net (0.59m width) in summer 2002 (21 June; 13 August; 26 August) at Nishiura artificial tidal flat (12 ha) created in June 1999

Species name		inds. m^{-2}	wet. g. m^{-2}
(*Pelecypoda*)			
Mactra chinensis	(bakagai)	2.3-17.2	73-614
Mactra quadrangularis	(shiohukigai)	0.7-22.7	9-194
Ruditapes philippinarum	(asari)	3.4-72.9	21-678
Scapharca subcrenata	(sarubou)	1.2-4.2	6-42
(*Gastropoda*)			
Neverita didyma	(tsumetagai)	0.3-1.5	14-68
Rapana venosa	(akanishi)	0-0.1	0-11
(*Crustacea*)			
Portunus trituberculatus	(gazami)	0-1.0	0-14
Charybdis japonica	(ishigani)	0-0.1	0-1

survival depth at some unsuccessful sites.

There are some problems to solve in addition to the acknowledgement of survival depth. The first is the supply of the sand. As mentioned, we must restore at least 1,200 ha to supress the hypoxic condition in Mikawa Bay effectively, but we can restore only half of 1,200 ha by 2004. After 2004, we shall not be able to get the enough sand to restore. So, we are now studying the alternative materials including the artificial sand such as granulated blast furnace slag, urgently.

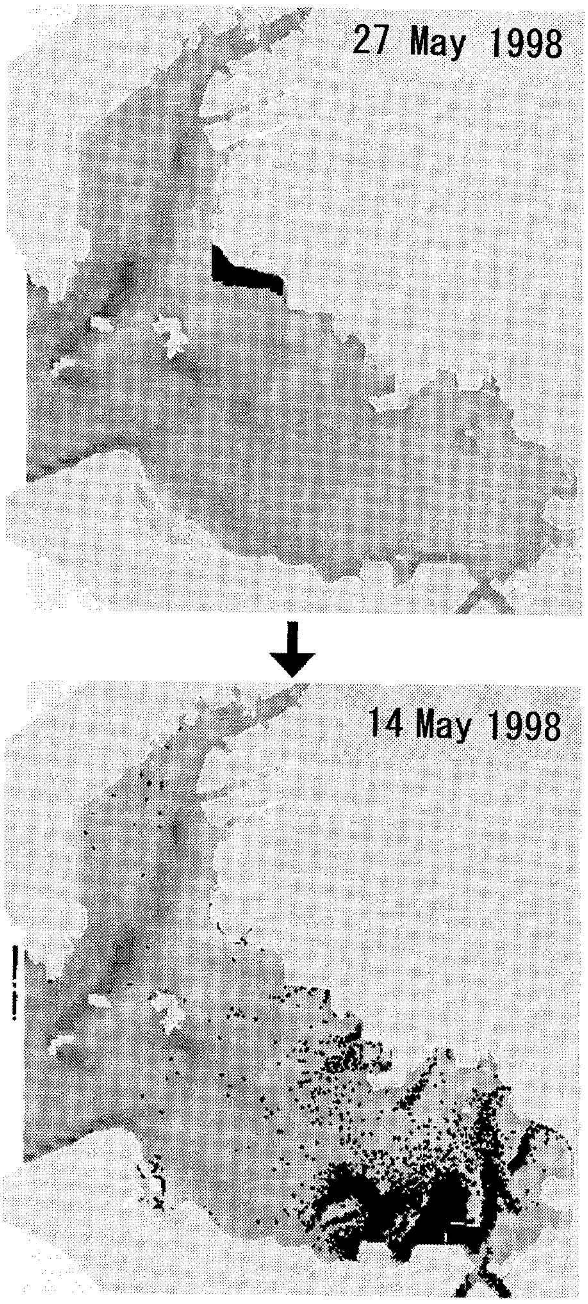

Fig. 10. The example of the final horizontal distribution pattern of pelagic larvae calculated by receptor mode model. Upper figure shows the initial distribution (Suzuki *et al.*, 2002)

The second is the proper selection of the site location. It is important to choose areas that will be the most effective for the recruitment or supply of bivalve's pelagic larvae. To that end, we selected the short-necked clam (*Ruditapes philippinarum*) as a target species, and observed the vertical distribution pattern of the larvae. Then, using a receptor mode model, we are trying to predict trajectories of the pelagic larvae (Suzuki *et al.*, 2002). Receptor mode model is the simulation technique to trace the drift particles in the inverse time mode. Fig. 10 is one of the examples of the calculations (the case calculated at the period from 27 May to 14 May, 1998). Isshiki area where the initial distribution of pelagic larvae was given, is the most important fishing ground of short-necked clam in Mikawa Bay. Pelagic larvae supplied to this area was estimated by receptor mode model, supposing that the drift period is two weeks from the water temperature and the larvae distribute around the mid-depth from the observation. As the model result, it was suggested that the inner part of Atsumi Bay is the most important origin and perhaps it may be the proper site location in future.

Although there are some problems to solve, we will be able to confirm the suppression of hypoxic conditions in future by an increase of the water purification capability, as long as the restoration of tidal flats and shallows progresses smoothly and the existing reclamation plans are abandoned.

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