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THE POST-PROJECT EVALUATION OF THE MINAMATA BAY ENVIRONMENTAL RESTORATION PROJECT

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The Minamata Bay Environmental Restoration Project was carried out in order to rehabilitate the Minamata Bay environment.

This study presents the process of planning and implementation of the project. We also evaluate the degree to which the environment was improved by the Minamata Project and the economic and societal effects of the project, and analyze the actual conditions of the environmental restoration like changes of mercury concentration in fish.

Key Words: Minamata Disease, mercury, dredging, removal standard, mercury concentration in fish

1. PURPOSE

The Minamata Bay Environmental Restoration Project was carried out in order to rehabilitate the Minamata Bay environment, thereby uprooting the cause of Minamata disease and invigorating the social economy of the region battered by the adverse effects stemming from the degradation of the environment. Hopefully, it is doubtful that the issue of toxic sediment removal due to industrial effluent will recur in Japan. However, it is thought that in developing countries, where the removal of toxic sediment is expected to become a practical problem. The object of this study is to evaluate the effects of the Minamata Project, which was an unprecedented great task of this type, and propose a valuable reference data for the implementation of similar projects that may be undertaken in the future.

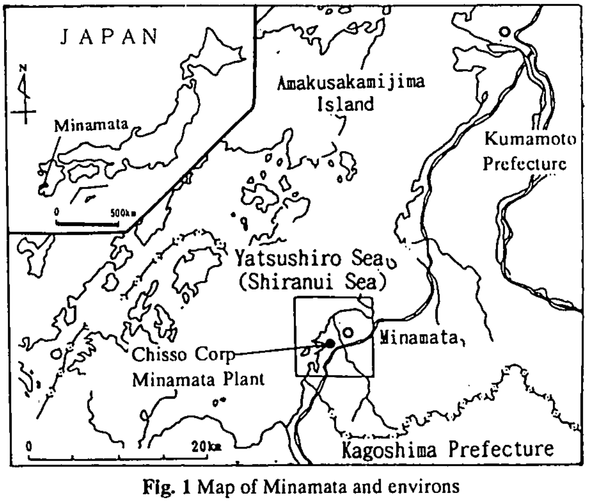

Fig. 1 Map of Minamata and environs

It is important to make the scheme of execution be able to remove the contaminated sludge safety,

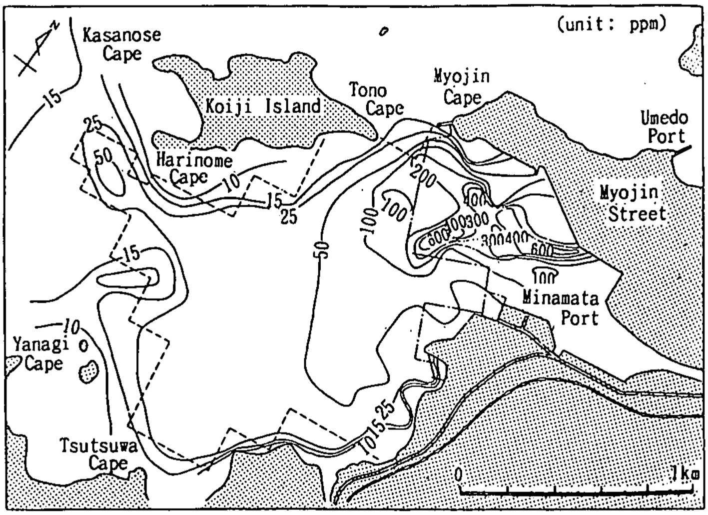

Fig. 2 Mercury concentration distribution in surface sludge

certainly and economically when optimizing the project. This point was reported by Hirose et al.[1] too. But no one has reported on the relations, which is important to economical efficiency in removing the sludge, between the standards for removal and the effect on improving the environment. No one has evaluated the rehabilitation of the Minamata environment by the ecological approach, such as the capturing and removal of contaminated fish from the area of sea covered by the project. Furthermore, it is necessary to optimize the project to revitalize the social economy of the region through the rehabilitation of the environment, in addition to optimization of the scheme of the execution.

In this paper we evaluate the degree to which the environment was improved by removal of contaminated sludge and ecological method, and also evaluate the social economy effects of the project. The evaluation was based on observed data of the environment quality before and after the project.

2. OUTLINE OF THE MINAMATA BAY ENVIRONMENTAL RESTORATION PROJECT[1]

(1) A summary of mercury pollution in Minamata Bay

Minamata City is located on the southwestern tip of Kumamoto Prefecture (see **Fig. 1**). Nippon Chisso Hiryo (today's Chisso Corporation) established a plant there in 1908. From 1932 until 1968, methyl mercury compounds, a by-product from the mercury used as a catalyst in acetaldehyde-synthesizing facilities, were released into Minamata Bay in wastewater from the company's factory. The total mercury released is estimated at 70-150 tons[2], while the total volume of methyl mercury released is not clear.

The "Minamata Disease" is a central nervous system disorder found in those who ingested large quantities of fish contaminated with organic mercury.

Mercury distribution in Minamata Bay according to the survey of 1974 is shown in **Fig. 2**. The concentration was higher towards the inside of the bay, where the factory's wastewater outlet was located, and lower at the mouth of the bay. Concentrations were 600 ppm at some areas on the inside of the bay and 15 ppm at the bay opening, serving as an indication of the way the contaminants were spread.

The results of a survey of seawater quality in Minamata Bay are shown in Fig. 3 and Table 13). The survey was carried out at 19 locations and found that the amount of total mercury on the inside of the bay measured a maximum of 0.002 mg/L(L: liter), exceeding Environmental Standards of 0.0005 mg/L.

The annual change of mercury concentration in fish caught in Minamata Bay is shown in **Fig. 4**[3]. In 1961, some species of fish carried total mercury concentrations of 10 ppm, but as measures were ta-

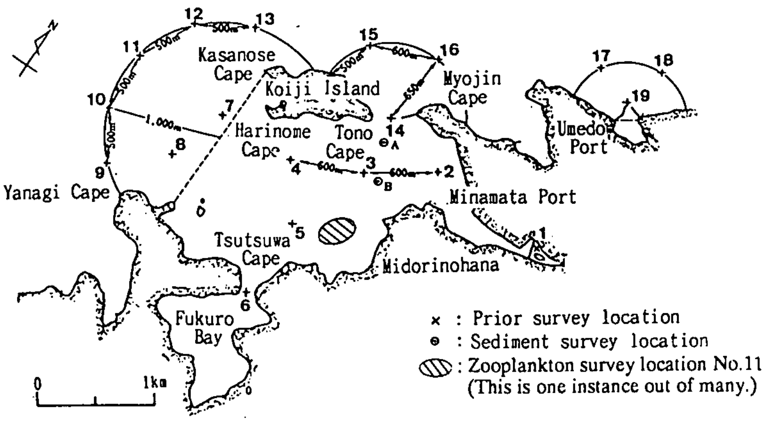

Fig. 3 Water quality survey locations

Table 1 Total mercury concentration in seawater

unit: μ g/L

Mercury Concentration	Location number 1	2	3	4	5	6	7	8	9	10
Maximum	2	2	0.6	0.4	0.5	2	0.5	0.4	0.5	0.5
Minimum	0.4	0.2	ND	ND	ND	ND	ND	ND	ND	ND
Mean	1	0.8	0.3	0.3	0.4	0.3	0.3	0.1	0.3	0.2

Mercury Concentration	Location number 11	12	13	14	15	16	17	18	19
Maximum	0.5	0.4	0.4	0.4	0.5	0.5	0.4	0.4	0.4
Minimum	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mean	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.3

ND: <0.1
1 μ g/L=0.001mg/L (L : liter)

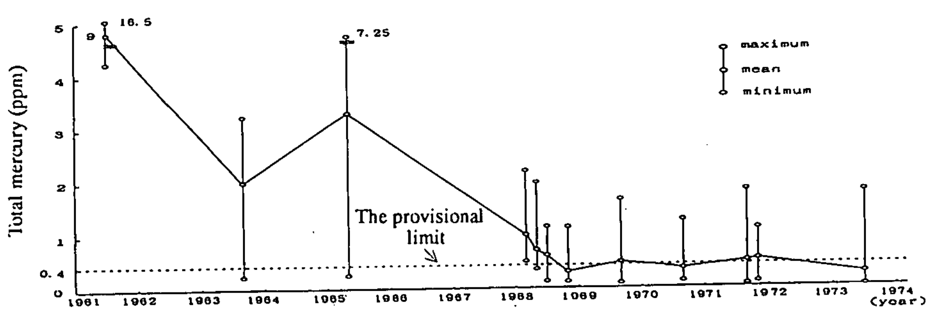

Fig. 4 Mercury concentration in fish in Minamata Bay

ken to deal with the effluent (complete recycling of effluent in the acetaldehyde production facilities in 1966, and discontinuance of the production of acetaldehyde using acetylene in 1968), mercury concentrations in fish decreased. In 1973, the average concentration in fish caught in Minamata Bay fell below the provisional limit (one type of environmental standard) of 0.4 ppm. Some species of fish, however, continued to maintain concentrations higher than 0.4 ppm.

(2) Outline of the Minamata Bay Sludge Treatment Project (the Minamata Bay Public Pollution Control Works)[3)]

The Minamata Bay Environment Restoration Project (here after referred to as simply the "Mi-

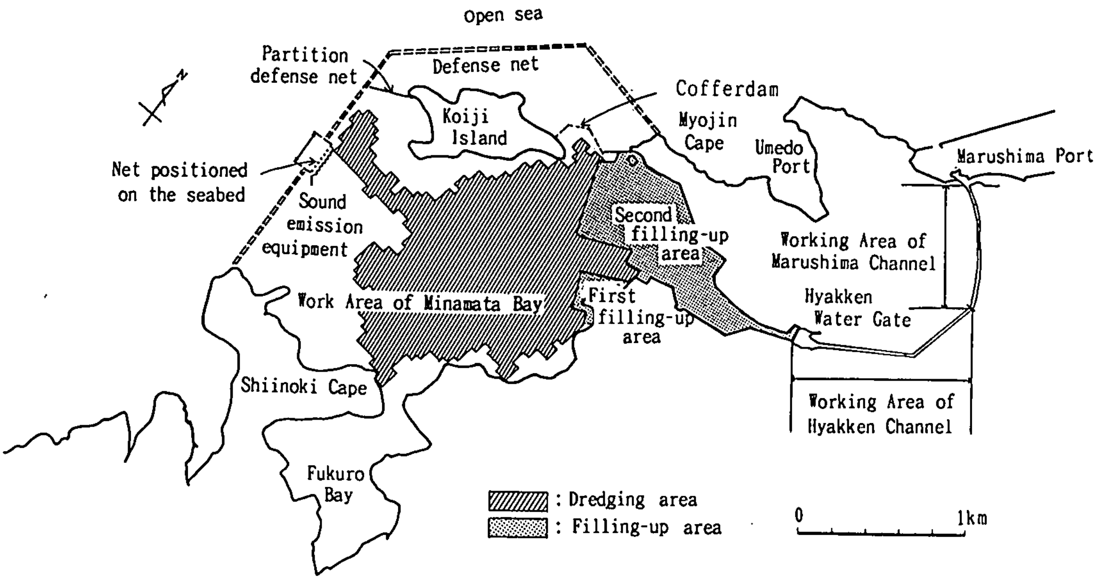

Fig. 5 Bay area covered by the project

namata Project") is the collective title given to two projects, namely 1) the Minamata Bay Sludge Treatment Project (the Minamata Bay Public Pollution Control Works), which involves the dredging and treatment of sediment sludge from Minamata Bay, and 2) a project dealing with fish and shellfish in Minamata Bay which aims at the resumption of commercial fishing. Both projects were executed by Kumamoto Prefectural Government and its related agencies.

The Sludge Treatment Project was carried out from 1977 to 1990 at a total cost of approx. 48.5 billion yen(see **Fig. 5**). The lead government agency for the project was Kumamoto Prefectural Government in conjunction with Minamata City Government. The Fourth Port Construction Bureau, Ministry of Transport, has executed the dredging and filling up project, having been commissioned by the Prefectural Government. Note that, however, the project actually got underway only in June 1980, due to an application for a provisional injunction against the dredging of sludge in Minamata Bay.

During the formulation of the project plans, diverse deliberations were conducted on the following issues:

1) Given the level of environmental contamination and the utility form of sea area, the extent to which the contaminated sediment would be removed (determination of a standard for removal),
2) The process to be used for removing the sludge (determination of sludge-removal method),
3) How to explain sludge-removal projects to local residents and other concerned parties, and how to gain their cooperation (forming a societal consensus),
4) How development in the region would be activated through marine environment restoration projects (regional development).

a) Determination of a standard for removal of contaminated sludge

The standard for removing sediment from Minamata Bay, which had spread beyond and extended past the bay, was established on the basis of a document entitled "Tentative Provisional Standards for Removal of Mercury-Contaminated Sludge" by the Water Quality Bureau, Environment Agency, 1973 (this document later became known as the Provisional Standards for Removal of Sludge, Water Quality Bureau, Environment Agency, 1975). The formula given is as Eq.(1)[4];

$$C = 0.18 \times \Delta H / J \times 1 / S \qquad (1)$$

Where

C: quantitative removal standard (ppm),

ΔH: mean tidal range (m),

J: desorption coefficient (−),
S: safety factor (−).

From Eq.(1), and based on the results from a survey conducted in 1973, it was decided to set the quantitative standard at 25 ppm by putting $\Delta H = 2.23$, $J = 1.6 \times 10^{-4}$ and $S = 100$.

b) Study of Sludge-Removal Methods

Following two plans were examined with the view of removing sludge certainly and efficiently, and preventing secondary contamination.

Plan 1) To completely seal off Minamata Bay, to establish harbor facilities outside the sealed area, and to cover the confined area to prevent leakage of mercury.

Plan 2) To seal off part of Minamata Bay to be treated with temporary cofferdam, and to treat the inside by dredging in part and by filling in part.

Regarding the plan 1) there was a danger that the pollution occurring as a result of the work would exceed the bay limits. It was also not appropriate because the water quality in the bay would deteriorate during the isolation, and because the project would be delayed. Additionally, the long-term effects of the covering work were uncertain, as it was not known to what degree wave action, the passage of ships, or ship anchorage would disturb the cover, or how benthos would affect fish species.

Deduced from the following, it is decided that the plan 2) was appropriate method on condition that it was carried out under careful monitoring to prevent secondary contamination, according to the "Provisional Guideline on the Removal and Treatment of Bottom Sediment" (Water Quality Bureau, Environment Agency, 1974). It was predicted that no secondary pollution would occur as a result of the dredging work, since 1) most of the mercury in the sediment sludge was mercury sulfide, which would not readily dissolve in water, and 2) according to forecasts of the spread of pollution, the use of cutterless suction dredgers would limit the spread of mercury out of the bay to within environmental standards (0.0005 ppm). The deep end of the bay (first and second filling-up area in **Fig. 5**), where the mercury concentration was high and the layer of contamination was thick, would be dealt with by

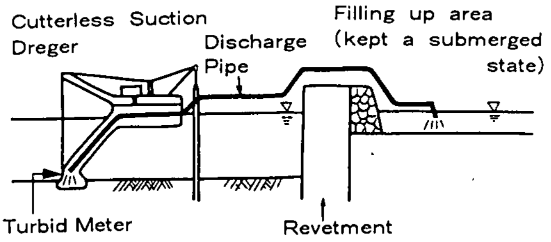

Fig. 6 Schema of the dredging

sealing it off, and the other areas would be dredged. This would dramatically reduce the amount of sludge to be dredged, and would also improve the safety of the work. The amount of sludge closed off within the fill area was equivalent to about 80% of the total mercury in the bay.

The revetment in the treatment area would have a high resistance to external forces, and would also prevent the toxic substances in the sediment from running out or leaking. On the northern end of the mouth of the bay, a temporary cofferdam would be built to halt the flow in the bay during construction.

As a result the plan 2) was adopted, and the treatment scale was determined to be approx. 2.09 million m^2 in area, 1.51 million m^3 in sediment volume, of which the area to be dredged would be 1.51 million m^2, the volume to be dredged 0.78 million m^3, and the area to be filled would be approx. 0.58 million m^2 (see **Fig. 5**).

c) Measures for preventing secondary contamination[5]

In addition to b) as stated above, a number of measures were taken to prevent secondary contamination caused by the migration and diffusion of mercury in sludge during dredging work:

1) A cofferdam was temporarily placed in a part of the bay to stabilize water in the bay, thereby preventing the spread of turbid water during the work, promoting sedimentation, and preventing the spread of mercury-contaminated sludge outside of the bay[2] (see **Fig. 5**).

2) In order to minimize turbidity during dredging, cutterless suction dredgers were employed. Additionally, turbid meters were used to continuously measure turbidity near the intake, and the dredgers operated accordingly[1] (see **Fig. 6**).

3) In order to avoid methylation of mercury by the

sludge's exposure to air[6], the filled areas were kept in a submerged state until discharged sludge was completely confined with mountain soil[2](see **Fig. 6**).

4) In order to prevent spreading out of mercury-contaminated sludge from the filled area, the contaminated sludge was covered and confined with mountain soil after casting the sludge into the area[1].

5) Water quality, fish and plankton were monitored regularly, based on a stringent monitoring plan, with all results being immediately reflected in the work[7].

6) In order to ensure the safety of aquatic biota in the sea outside the bay, a partitioning net would be positioned at the boundary between the work area and the open sea. Sound emission equipment was installed in the waterway, to control the movement of fish there[1](see **Fig. 5**).

d) Forming a societal consensus[8]

In the Minamata Bay case, almost all local residents were in favor of early implementation of the program. The Kumamoto Prefectural Government also worked towards the formation of a societal consensus regarding the work, by carefully studying work methods that prevent secondary pollution during the formulation of the work plans, as well as taking legal proceedings such as the public inspection of the application for reclamation work including evaluation of the project's effect on the environment. The government also conducted seminars in order to gain the backing of the local residents. Some local residents, however, feared the environmental risk of secondary pollution, and submitted an application for a provisional injunction against the work. Legally it would have been possible to proceed with the work, but emphasis was placed on obtaining the agreement of local residents, and thereby suspending the work for two and a half years. In spite of the application for an injunction being overruled, the agreement of local residents towards the program was obtained, thanks to the scientific discussions of risk conducted in court, and the introduction of work monitoring by a neutral committee.

In addition, after the resumption of work, the support and trust of local residents towards the work was reinforced by disclosure of field data.

e) Regional development

Minamata could not be revitalized without a resolution of the Minamata disease issue. A variety of efforts are currently underway to achieve this end, such as extending aid to patients. Meanwhile, it is also important that the implementation of the Minamata Project restores fertility to the sea and helps build a promising future for the region. From this standpoint, it was decided to aim primarily at the resumption of commercial fishing, to enhance the port and harbor facilities which play an important role in regional development, and to include in the program the creation of wide and open spaces through the construction of a reclamation site. During the planning stage, it had not been determined how to utilize the reclaimed land, but expectations were high that such a large tract of land would play a leading role in the development of the region.

(3) Results of the bottom sediment treatment

In order to implement monitoring aimed at preventing the occurrence of secondary pollution, surveys were conducted[9] to monitor water quality, bottom sediment, and marine life, in accordance with the master plan for monitoring activities. Survey results indicated that no secondary pollution occurred.

A survey was taken in 1987 to verify the completion of dredging. This survey found that the maximum mercury concentration was 8.75 ppm. It was, therefore, confirmed that treatment had brought the concentrations down to sufficiently low levels given the removal standard of 25 ppm (see **Fig. 7.1**, **Fig. 7.2**).

(4) Outline of the Project dealing with fishes in Minamata Bay

Since, even after the completion of the project outlined above, some species of fish still carried mercury concentrations of more than 0.4 ppm, the Kumamoto Prefectural Government established the Council for Minamata Bay Fish and Shellfish Treatment to study measures for dealing with contaminated fish in Minamata Bay. In response to the council's recommendations, Kumamoto Prefectural

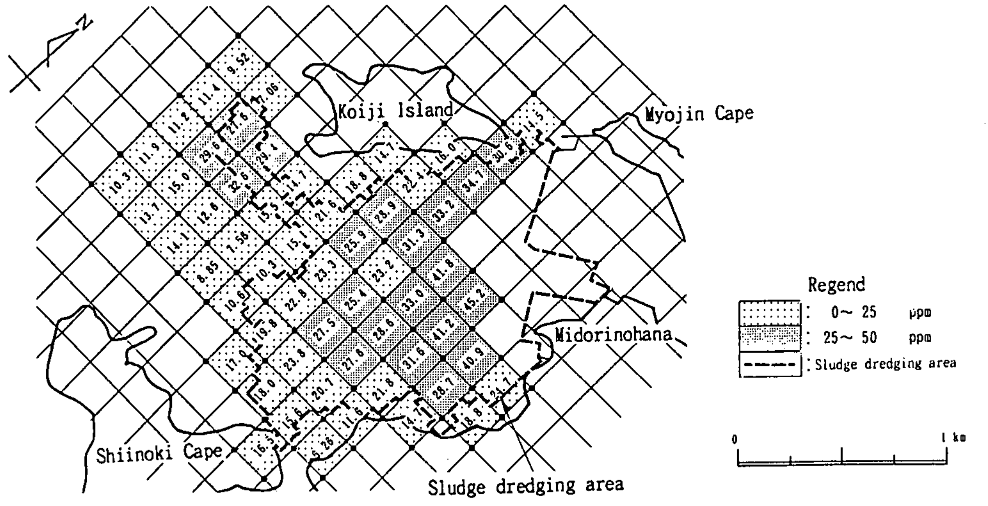

Fig. 7.1. Distribution of mercury concentration in the dredging area (Before dredging, 1985)

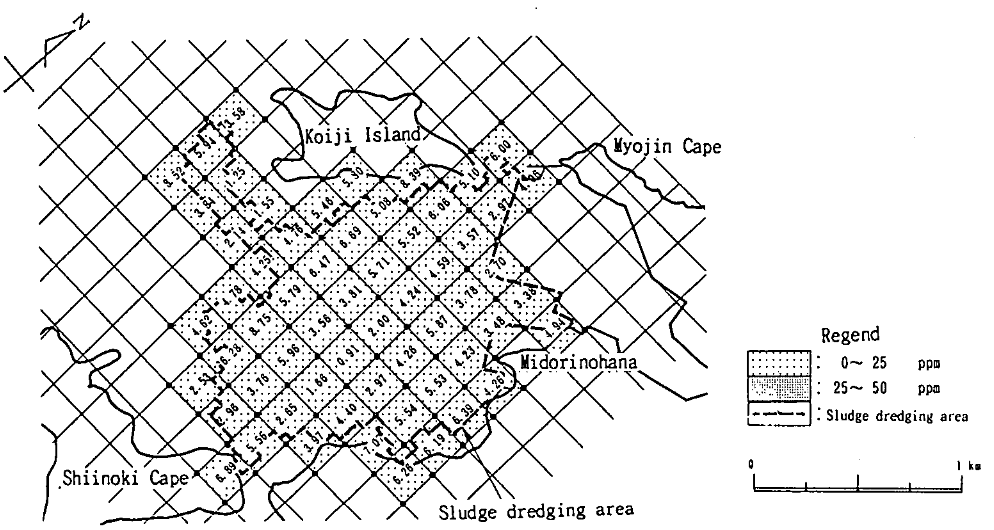

Fig. 7.2. Distribution of mercury concentration in the dredging area (After dredging, 1987)

Government aggressively carried out the capture of contaminated fish in order to lower the mercury concentrations in the fish.

3. PURPOSES AND EVALUATION OF EFFECT OF THE MINAMATA BAY ENVIRONMENTAL RESTORATION PROJECTS

Sludge-removal is a means of restoring the Minamata Bay environment, and true objectives of the Minamata Bay Environment Restoration project are the six as follows.

This section evaluates the effect of the Minamata Bay Environment Restoration Project, according to each of the six objectives as follows.

(1) To prevent the potential fear from the Minamata disease spreading further, and to prevent the spread of contaminated sludge outside of the bay

By the time the Minamata Project commenced in 1977, fishery products from Minamata Bay were no longer being supplied for human consumption. If, however, one considers it possible for the disease not to attack in other areas through the flow of polluted material out of the bay or the migration of contaminated fish out of the bay, then the projects

Table 2 Species-specific total mercury concentration before and after the project (average in edible parts)

unit: ppm

Species	Before * 1978~1980	After 1989 First Half	1989 latter half	1992 first half	1992 latter half	1994 first half	1994 latter half	1995 first half
Stingray	–	0.99	0.47	0.57	0.89	0.51	0.30	0.36
Silver Whiting	–	0.95	1.04	0.87	0.79	0.49	0.39	0.35
Scorpionfish	1.11	0.83	0.68	0.56	0.53	0.31	0.31	0.25
Black Sea Bream	0.88	0.38	0.63	0.55	0.26	0.26	0.20	0.19
Bambooleaf Wrasse	0.57	0.31	0.40	0.26	0.25	0.18	0.20	0.16
Rock Fish	0.34	0.22	0.28	0.27	0.22	0.15	0.14	0.06
Japanese Sea Bass	0.42	0.30	0.27	0.15	0.07	0.15	0.10	0.12

*1987 : completion of the dredging work

can be evaluated as having had a effect in contributing to the prevention of further casualties. Mercury concentrations in the bottom sediment had fallen to below 25 ppm, which means that the source of the pollution was reduced and the danger of contaminated sludge spreading outside the bay was eliminated.

(2) To lower mercury concentrations in fish and to rehabilitate fishing grounds to their previous fertile states

One of the objectives of the project was to, through the dredging of sludge, lower mercury concentrations in fish down to levels permitting the resumption of commercial fishing in the bay.

Table 2 shows a comparison of mercury concentrations in fish caught in Minamata Bay prior to and subsequent to the implementation of the project[9),10)]. The reduction rates of mercury contamination differed according to fish species, but even the Stingray and the Silver Whiting, which were the last to exceed limits, finally fell to below 0.4 ppm in 1994, and currently the average value does not exceed 0.4 ppm in any fish species. After the lapse of ten years (1994) from the completion of the dredging work, the partitioning net was removed and commercial fishing in the bay was resumed.

Putting aside the issue of whether a duration of ten years (1987-1997) is long or short, the success in lowering mercury concentrations in fish to within allowable limits through the project, and the fact that the regeneration of the previously fertile fishing grounds in Minamata Bay have emerged, should be evaluated positively.

(3) To protect fishing grounds in the vicinity of Minamata Bay

For a time, due to growing interest in environmental pollution all over the country, the price of fish caught in Minamata Bay and nearby fishing area outside the bay declined sharply. Measures were taken to prevent the spread contaminated fish outside the bay, by isolating the bay fish from other fish, in January 1974. In addition to the installation of partitioning nets surrounding the port area, a 3 meter-high net was installed on the seabed with sound emission equipment to assist in preventing the migration of fish at the entrance to the waterway.

The fact that, due to the installation of partitioning nets and the prevention of migration of the bay's fish, the price of fish outside the bay was normalized despite having once plummeted, shows that the measures had a considerable effect in removing the public's fears and consequently protecting fishing grounds in the vicinity of Minamata Bay. The measures had the effect of preventing the migration of contaminated fish from Minamata Bay.

(4) To make possible the revitalization of programs utilizing Minamata Bay

The cargo handling volume in Minamata Port grew at a faster pace before the project, and existing facilities were cramped due to the lack of large wharfs. The construction of new facilities, however, was impossible because of the concern for secondary pollution due to the construction work.

The Minamata Project expanded existing port facilities and constructed a new harbor with larger wharfs using reclaimed land. This has contributed to the expansion of economic activity in the region.

Minamata Bay has always been an area of scenic beauty, and offers potential for tourism. Now it will be possible to develop this potential and construct new facilities at Minamata Bay and environs without the fear of secondary pollution. The Minamata Project can thus be said to have had a profound effect on improving the environment, in terms of the maritime utilization of Minamata Bay.

(5) To invigorate regional development utilizing land reclamation

The reclamation site already serves as a quay, and construction and preparations are underway for a planned "Minamata Ecological Kenko (health) Park." Minamata has relatively small flat land. The birth of a 58 hectare land area in the form of a reclamation site will have an extremely significant impact as a nexus for the rehabilitation and recreation of the environment. The efforts to revitalize the region through the construction of a reclamation site, made as a product of the Minamata Bay Sludge Treatment Project, are held in regard.

(6) To improve the image of Minamata-city and Minamata Bay

Since the occurrence of the Minamata Disease, the negative image of pollution has haunted Minamata and stagnated the local atmosphere. Needless to say, the victims of Minamata Disease continue to suffer from their disease. For the victims, Minamata Disease is not a closed issue, nor has their past been settled. However, the fact that commercial fishing has resumed symbolizes that Minamata Bay has become a "Sea of Life," bringing nature's bounty to the region. The beneficial effect of the Minamata projects in rehabilitating the image of Minamata City and Minamata Bay is significant.

Therefore, as six objectives of the project have almost been brought to fruition, the hard work of those involved in the Minamata Bay Environment Restoration Project should be greatly appreciated.

4. DISCUSSION ON THE ENVIRONMENTAL RESTORATION FOR THE PROJECT

It is important to determine a removal standard when restoring a marine environment by removing sediment. This is because the removal standard significantly affects the effect and cost of such a project.

The Japanese standard for sludge removal is defined, to be such that there are no adverse effects on the human metabolism if consumed, when the mercury concentration in sludge is below the removal standard, considering the safety factor(10～100). **Fig. 8** shows a flow chart of the factors affecting the determination of a numerical removal standard.

When determining a removal standard, it is important to deepen understanding regarding the various phenomena indicated in the flow chart. Therefore, in this section we will consider the improvement of water quality through the Minamata Project and the extent to which mercury concentrations in fish were lowered.

The IPCS (International Programme on Chemical Safety) describes how the ingestion of mercury-contaminated seafood affects the human body. Henceforth the assumption will be that it is necessary that the mercury concentration in fish is less than 0.4 ppm.

(1) Changes in mercury concentration of seawater

From the implementation to the completion of the project, the mercury concentration in seawater was found to be less than 0.0005 mg/L (0.5 μg/L) which was the detection limit at that time and also the equivalent in the environmental standards. Meanwhile, the mercury concentration in fish was gradually reduced as a result of the project. This was anticipated to be because, although the initial mercury concentration in the seawater was less than the detection limit and higher than normal level, it continued to decrease gradually, thanks to the implementation of the project.

According to William et al.[13], the concentration factor of mercury in maritime fish is 1.7×10^3. It may be estimated to be 1,000[4] according to the for-

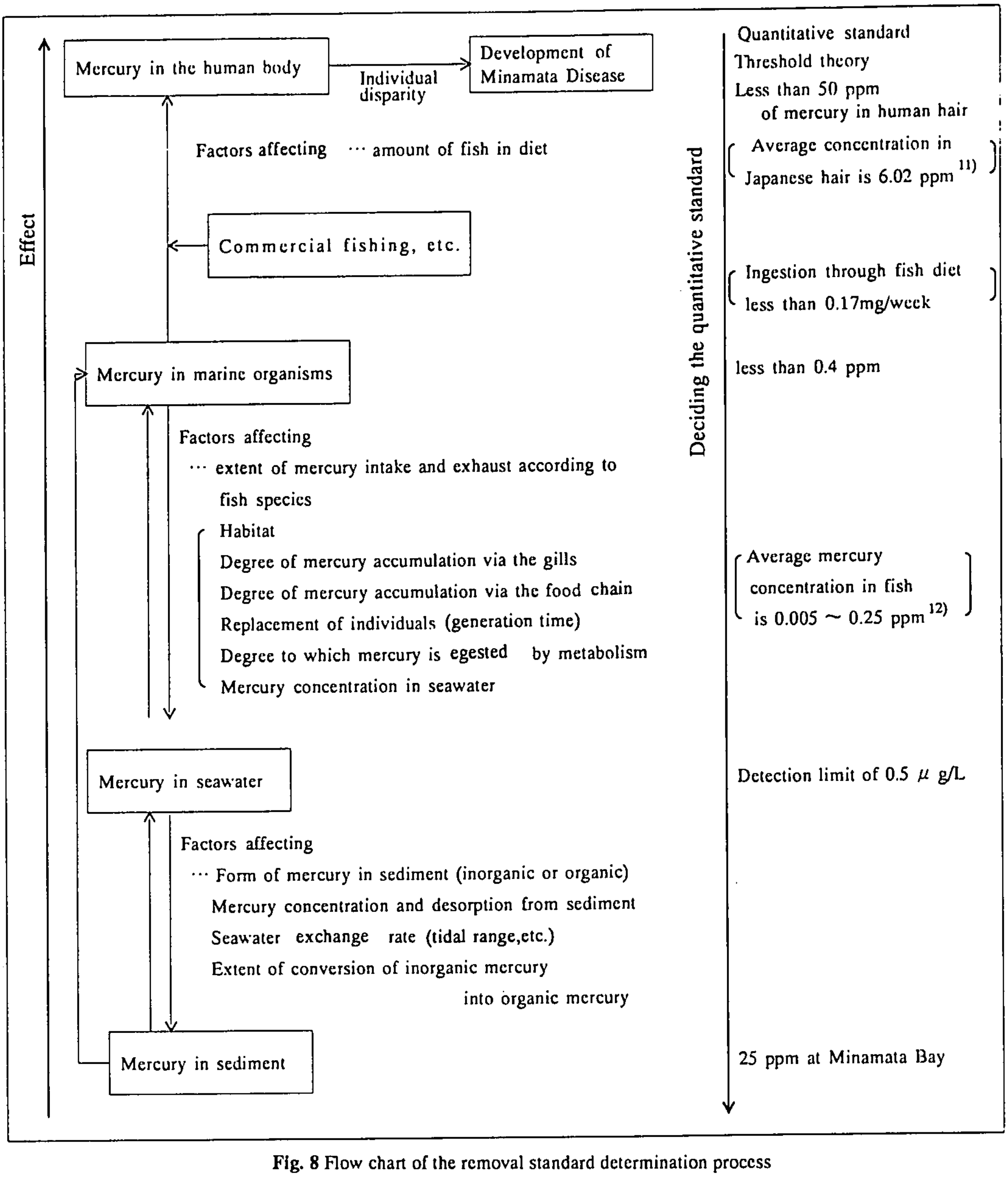

Fig. 8 Flow chart of the removal standard determination process

mula given in "Tentative Provisional Standards on the Removal for Mercury-Contaminated Sludge". In this case, if the supposition is made that the detection limit at that time of 0.0005 mg/L of mercury is contained in the seawater (Mercury concentration in Minamata Bay at that time might be much lower than 0.0005 mg/L as shown in **Table 3**), the use of a concentration factor of 1,000 would mean that 0.5 ppm of mercury is concentrated in the fish, exceeding the provisional limit of 0.4 ppm. In other words, the possibility exists that dissolved mercury, at levels less than the detection limit, has an influence on mercury concentration in fish. Hence, it is necessary to estimate the effect of restoration through the determination of a lower concentration than the detection limit for mercury in seawater.

Because the direct measurement of such a low concentration of mercury in seawater could not be carried out at that time, the concentration was estimated through the use of a bioconcentration process

Table 3 Mercury concentrations of seawater estimated from mercury concentrations in zooplankton

unit: μ g/L

Survey period	Survey district No.11
Before Dredging (1974/8~1983/4)	0.029
During Dredging (1983/6~1987/12)	0.012
After Dredging (1992/2~)	0.005

1 μ g/L=0.001mg/L (L : liter)

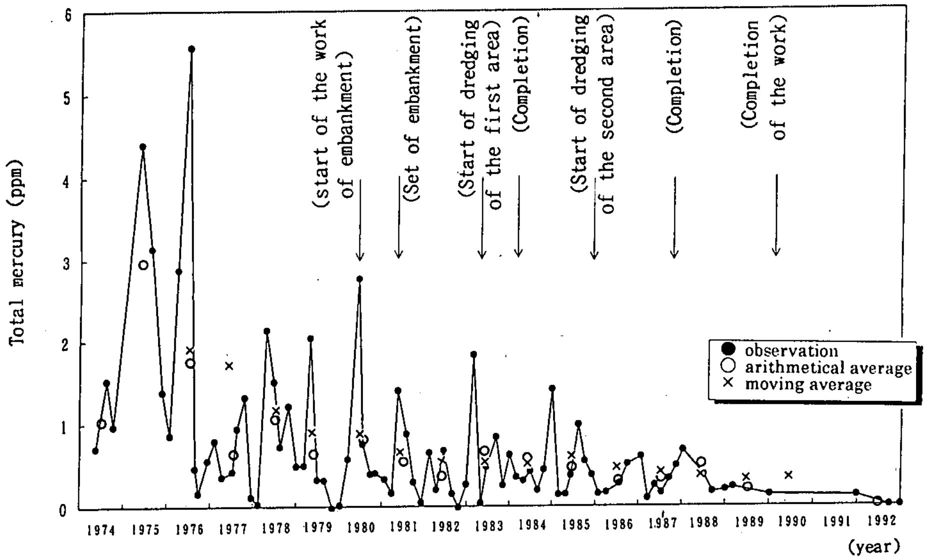

Fig. 9 Annual change in Zooplankton mercury concentrations (district No.11)

presented in this paper. The estimation was carried out by using Zooplankton of which the intake rate was fast and whose mercury load during a short duration in the planktonic body can be estimated because of a rather short life (several months).

The mercury concentrations in Zooplankton (see **Fig. 9**) in the survey district, No.11, shown in **Fig. 3**, have been divided by a mercury concentration factor of 3.3×10^4 for marine invertebrates given by William et al.[13] to estimate the mercury concentration in seawater. The estimated values are displayed in **Table 3**. (The mercury concentration factor for Zooplankton varies considerably between different species of plankton. Since the extraction of only a single species of zooplankton was difficult, there is a limit to evaluating the accuracy of the mercury concentration of seawater in this manner.)

Table 3 shows how the mercury concentration in seawater, estimated from the mercury concentration in Zooplankton, though less than the 0.5 μ g/L limit, decreased throughout the project implementation period.

One phenomenon is the considerable decrease of the fluctuation in mercury concentrations in zooplankton in 1986, the year after the innermost area of the bay—the sediment of which had high mercury concentrations—was sealed off with a revetment (see **Fig. 9**). This is thought to be due to the two effects of,: a) isolation of the marine area with a high mercury concentration by the revetment, and b) the isolation and elimination of the tidal flats, where the methylation of inorganic mercury is thought to have occurred.

Mercury concentration was the further decrease and smaller fluctuation in 1988, the year after dredging was completed (see **Fig. 9**).

These facts signify that the removal and treatment of sludge had a considerable effect on lowering seawater mercury concentrations in Minamata Bay.

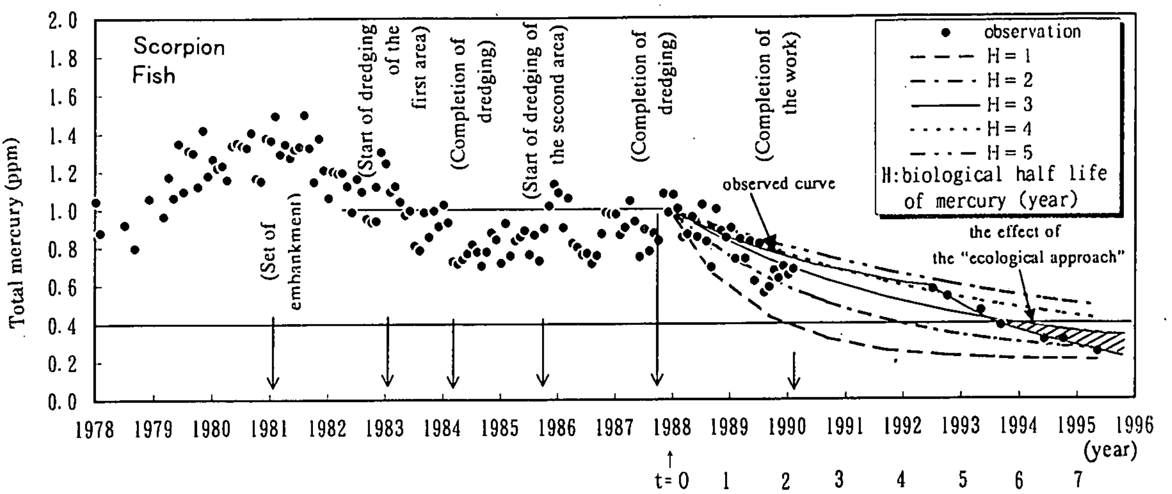

Fig. 10 Changes over the years in mercury concentration in the scorpionfish

(2) Thoughts on the actual conditions of the lowering of mercury concentrations in fish

Fig. 10 shows how mercury concentrations in the scorpionfish (*Sebastiscus marmoratus*) have changed from 1978 to the present. (The species of fish which were the last to exceed the limit were the Stingray and the Silver Whiting (see **Table 2**), but as no data existed for these species from before the implementation of the project, in **Fig. 10**, the scorpionfish was given as an example of a species in which the time required for a drop in mercury concentration was relatively long.)

As stated above, although the Minamata Bay Sludge Treatment Project improved water and sediment quality, mercury concentration in the fish did not lower suddenly, but lowered gradually with the lapse of time. This was because it took time for mercury to be discharged from the fish.

The monitoring of mercury concentrations in fish, which continued even after the completion of the sludge treatment project, revealed that in the later 1994, for the first time, concentrations fell to below the provisional limit 0.4 ppm in all of the species.

In other words, seven years had to elapse after the completion of the dredging operation before lowering the mercury concentration in fish to the extent below the provisional limit (see **Table 2**).

Mercury concentrations in fish within the bay are thought to decrease in the two following ways.

1) A reduction of the amount of mercury ingested by each fish to a level below the amount egested, due to the purification of the sea.
2) A decrease in the proportion of fish with high concentrations of mercury, due to their death, capture, or migration out of the bay.

The absorption of mercury by fish occurs relatively rapidly, but no established theory exists for the egestion rate of mercury. Nonetheless, it seems that there is agreement on magnitude, i.e. that the half-life of mercury in fish with high mercury concentrations ranges from several years to a decade.

This suggests the following: Purifying the sea does not lead to an immediate decline in the mercury concentration levels in fish; a certain time-delay is inevitable. Therefore, the projects should not be viewed skeptically because of the time-delay. If Minamata Bay is taken as an example, even though seven years lapsed after the completion of dredging, the success in lowering the mercury concentration in fish below the objective of 0.4 ppm should be accorded due regard. The effects of the capture and disposal of contaminated fish also were reflected in the lowering of the mercury concentration levels in fish. No definitions are made here regarding the proportion to which the clean up of the sediment contributed to the lowering of mercury concentrations in fish. (It was considered that the migration of contaminated fish to the open sea could be minimized by installing partition nets and catching the fish inside the netted-area.)

As it is a significant aspect of the project to be able to determine how many years is required for the concentrations to be reduced, further studies are necessary concerning the rate at which mercury is dissipated from fish (biological half life of mercury), and on the life-span of the fish.

Kumamoto Prefectural Government stepped up the capture and disposal of contaminated fish in 1992. An examination of the measured values in scorpionfish shows that the mercury concentration in the fish after 1992 falls more rapidly than prior to that year. This shows that direct action on the fish — capturing and disposal of polluted fish (the "ecological approach") —had an effect in lowering the mercury concentration in fish.

(3) Simulation of Mercury Concentration in Fish by Using of a Modeling Formula

a) Outline of simulation

To evaluate the effectiveness of marine environment restoration projects further, using a formula for modeling changes in piscine concentration due to the purification of the sea.

In the previous section, it has been stated that the lowering of mercury concentrations in fish has a time lag in response to the lowering of mercury concentration in the water.

In this section, the changes in mercury concentrations in fish through the reduction of mercury concentrations in seawater are studied. The conditions for changes in the mercury concentrations in the seawater were given, and an equation for estimating changes in the mercury concentration in fish was derived from a concentration factor and decrease rate, or biological half-life, of mercury in fish.

b) Construction of the equation

As long as the mercury concentration in the seawater is steady, the mercury concentration in fish is also steady, to equilibrate with the rate of decrease in mercury concentrations in the fish (half-life). In this case, the mercury concentration in fish C_f is equal to the mercury concentration in water C_w multiplied by the concentration factor N as given in Eq.(2) and Eq.(3). However, if the mercury concentration in the seawater has been lowered due to sediment removal work, the mercury concentration in fish decreases until equilibrium is reached. After completion of the work (it is assumed that the work is completed instantly after commencing), the concentration of mercury in the fish after a period of t years is $C_f(t)$. Assuming that the decrease rate for the difference of $C_f(t)$ and C_{fe} is the first order reaction as given in Eq.(4), and that the difference of $C_f(H)$ and C_{fe} at the time t=H(half-life) is shown as Eq.(5). Then $C_f(t)$ is equal to the remaining amount after t years, i.e. the difference in mercury concentration in fish before the work C_{f0} and when equilibrium has been reached C_{fe}, plus C_{fe}, Eq(6).

$$C_{f0} = N \times C_{w0} \quad (2)$$

$$C_{fe} = N \times C_{we} \quad (3)$$

$$-\frac{d(C_f(t)-C_{fe})}{dt} = \lambda\,(C_f(t)-C_{fe}) \quad (4)$$

$$C_f(H)-C_{fe} = (C_{f0}-C_{fe})\times 1/2 \quad (5)$$

$$C_f(t) = C_{fe} + (C_{f0} - C_{fe}) \times 2^{-(t/H)} \quad (6)$$

Where

- $C_f(t)$: mercury concentration in fish after t years (ppm),
- C_{f0} :mercury concentration in fish before the work has been completed (ppm),
- $C_f(H)$:mercury concentration in fish after H(half-life) years (ppm),
- C_{fe} :mercury concentration in fish when equilibrium has been reached (ppm),
- C_{w0} :mercury concentration in the water before the work has been completed (mg/L),
- C_{we} :mercury concentration in the water after the work has been completed (mg/L),
- H :decrease rate of mercury in fish (biological half-life) (year),
- N :concentration factor of mercury in fish (concentration relative to seawater).

This can be schematically expressed as shown in **Fig. 11** (provided that C_w is expressed by mg/L because of mg/L ≒ ppm).

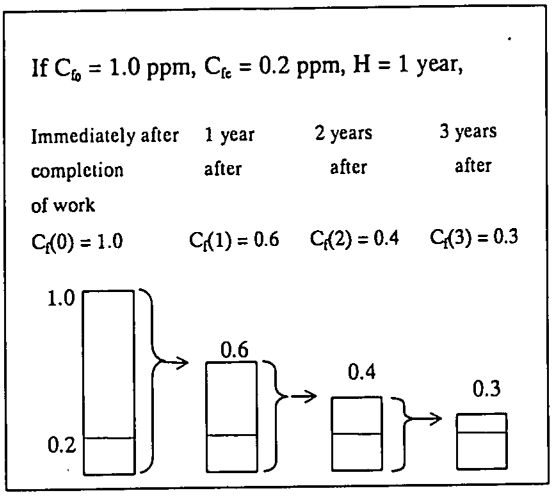

Fig. 11 Schema of the formula

c) Parameters for estimation

Requisite parameters were set down as follows.

- Prior to completing the work concentration of mercury in seawater, C_{w0}, is constant.
- Prior to completing the work concentration of mercury in fish, C_{f0}, is constant.
- The mercury concentration in seawater is instantly lowered to C_{we} by completing the work and becomes uniform. The value of C_{we} is selected appropriately in view of the mercury concentration in each fish species.
- The intake of mercury by fish is instant, and the concentration factor N is 2,000 (based on the concentration factor of mercury in fish proposed by William et al.[13] of 1.7×10^3). The relation, mg/L ≒ ppm, is assumed.

The concentration of mercury in fish after a period of t years, $C_f(t)$, is affected by C_{f0}, C_{fe}, C_{w0}, C_{we}, H, and N for each fish species. In Minamata Bay, $C_f(t)$ and C_{f0} have been measured, but the other variables have not been measured adequately (C_{w0} and C_{we} for each fish species, which are necessary for reliable estimation, cannot be estimated because they are lower than the detection limit. Information available on the ecological habits of each fish species is now limited). Mercury concentration in the benthos, which is necessary for estimation of the influence of food, has not been measured, either.

By reason of the above mentioned, assumptions are required for the value of C_{w0}, C_{we} and N. Estimation was carried out using by this equations unwillingly, because it is important to presume the process for changing of mercury concentration in fish.

d) Simulated Results on Decreases in Mercury Concentration in Scorpionfish

The scorpionfish is one of the fish species that showed high mercury concentrations before the implementation of the project. The scorpionfish is susceptible to mercury contained in the seabed sediment because this species is highly sedentary and dwells near the seabed.

Fig. 10 shows a curve representing changes in mercury concentration in the scorpionfish. Based on measurement results, by putting C_{f0} = 1.0ppm, C_{w0} is 0.0005mg/L since C_{f0}/C_{w0} = N = 2,000, here, C_{we} was assumed 0.0001mg/L. The biological half-life of mercury in fish, H, was calculated on 1, 2, 3, 4, 5 years.

Note that the equation for the estimation takes into account only the "reduction of the amount of mercury ingested by each fish to a level below the amount egested, due to the purification of the sea. " It is evident from the calculation results that the mercury concentration in fish is gradually lowered.

According to the method of estimation, the decrease rate is reduced with the time, and hence the curve of the rate of decrease in concentration forms is a convex towards the bottom; the value asymptotically approaches, 0.2 ppm, which is $C_{we} \times$ N: (0.0001 ppm × 2,000). The calculated results on H=3 are fitted into mercury concentrations measured in 1989 and 1990.

However, an examination of the measured values in scorpionfish shows that the mercury concentration in the fish after 1992 falls more rapidly than prior to that year. Kumamoto Prefectural Government stepped up the capture and disposal of contaminated fish from 1992. The difference between the estimated and the measured values is thought to be attributed to the effects from the capture of contaminated fish.

This shows that direct action on the fish — capturing and disposing polluted fish (the "ecological approach") — is effective to lower the mercury concentration in fish.

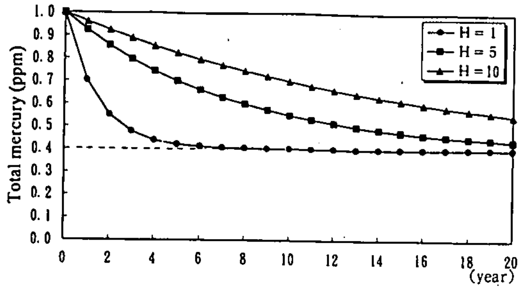

Fig. 12.1 Estimation in mercury concentrations in fish (C_{we}=0.0002)

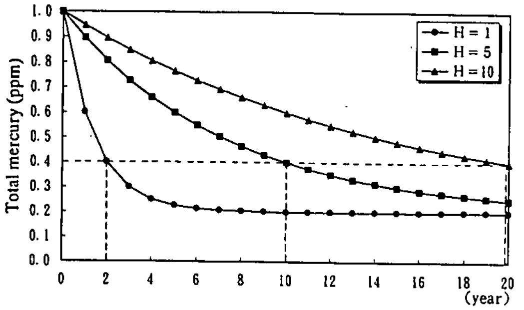

Fig. 12.2 Estimation in mercury concentrations in fish (C_{we}=0.0001)

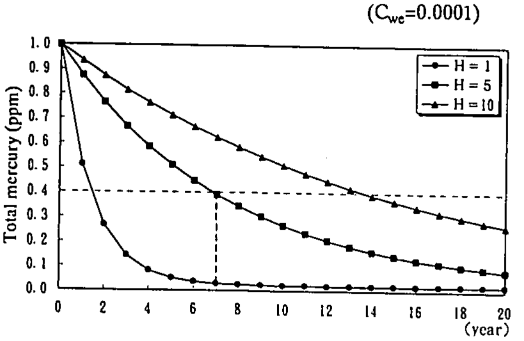

Fig. 12.3 Estimation in mercury concentrations in fish (C_{we}=0.00001)

e) Considerations on the Effect of Mercury Concentration in Sea Water on Mercury Concentration in Fish

Equation (4) was used to examine the effects of the mercury concentration in the seawater and the rate of decrease in mercury concentration in the fish after the project on the variation trend of the piscine concentration. The piscine concentration before the project, C_{f0}, was assumed to be 1.0 ppm. The mercury concentrations in the sea water after the project, C_{we}, of 0.0002, 0.0001, and 0.00001 mg/L, and the rates of decrease in mercury concentration in the fish (half-life H) of 1, 5, and 10 years were also assumed. The changes of piscine concentrations thus obtained are shown in **Fig. 12. 1-Fig. 12.3**.

One of the things **Fig. 12. 1-Fig. 12.3** show is that the time required for reaching equilibrium varies considerably depending on the half-life. For example, in **Fig. 12.2**, which shows the case of C_{we} = 0.0001 mg/L, the time required for the piscine concentration to decrease to a safe level (below 0.4 ppm) (expected duration for attaining objective T_s[in years]) is 2, 10, and 20 years, respectively. These results indicate that the half-life, which is thought to be dependent on such factors as metabolism, causes considerable variations of T_s among fish species.

Examination of changes in mercury concentration in each fish species reveals that if the half-life of a fish species is 5 years, in the cases where the mercury concentration in the sea water has been lowered to 0.0001 mg/L and 0.00001 mg/L, the time required for the piscine concentration to fall to below 0.4 ppm is about 10 and 7 years, respectively. However, in the case of the mercury concentration in the sea water of 0.0002 mg/L, the piscine concentration does not fall to below 0.4 ppm even after the lapse of 20 years (in the case where the mercury concentration in the sea water is 0.0002 mg/L and the concentration rate 2,000, the mercury concentration in the fish is 0.4 ppm, which is theoretically lowest of concentrations). This indicates, although it is quite obvious, that when planning and implementing a project for the purpose of lowering the piscine concentration, it is necessary to consider the concentration factors of the fish species involved and purify the sea so that the piscine concentrations can be lowered to below the target level.

Comparison of the rates of decrease in the two cases involving the mercury concentrations in the sea water of 0.0001 mg/L and 0.00001 mg/L reveals that the values of T_s for the two cases are about 7 and 10 years, respectively, and that despite the tenfold difference in mercury concentration in the sea water, the difference in the rate of decrease is smaller. This means that although the mercury concentration in the seawater can be effectively lowered to a certain level through the implementation of a project of a certain scale, an additional project of a greater scale will not make much difference in the piscine concentration. The 10-fold difference in the mercury concentration in seawater will lead to a considerable difference in project costs.

From those mentioned above, the following conclusions can be drawn with respect to the planning and implementation of a project aimed primarily at lowering mercury concentrations in fish:

1) Mercury accumulation and egestion characteristics of a fish species are greatly affected by such factors as the habitat, feeding habits, and metabolic characteristics of the species.
2) The rate of decrease in mercury concentration varies widely depending on the characteristics (especially C_{f0} and H) of the fish species concerned. When considering the expected duration for attaining objectives (T_s), therefore, it is necessary to conduct a study for each fish species in order to identify which fish species is critical.
3) T_s is infinite unless the mercury concentration after the project falls to below a certain limit. Achieving higher water quality (i.e., a mercury concentration much lower than a certain limit) will make T_s shorter, but too high of a water quality standard is not very effective in shortening T_s.
4) From the example above, it can be concluded that in order to shorten T_s effectively or minimize the project cost, it is important to make use of an appropriate combination of the technological approach of purifying the sea by means of sediment removal, etc., and the ecological approach including the capturing and rejecting of contaminated fish. The project cost can be reduced significantly by removing sediment containing mercury concentrations exceeding a certain limit, which is determined as a limit to lower the concentration of the almost fish species to 0.4 ppm in view of factors such as chemical form changes of mercury and the dissolution rate of mercury, and by intensively capturing and rejecting of specific fish species of which mercury concentration is critical (giving accumulation and egestion).

(4) On the removal standard of 25 ppm at Minamata

The removal standard affects directly and profoundly both the cost of the project and the effectiveness of the project. The Minamata Bay sediment removal standard was determined by the formula, Eq.(2); it was decided to dredge sediment containing more than 25 ppm of mercury at a total cost of approximately 48.5 billion-yen. The formula handled numerous variables using a safety factor, and now that experience has been gained from the Minamata project, several problems regarding the formula can be pointed out.

The mercury concentration in the fish fallen below 0.4ppm in seven years, and resumption of the commercial fishing was in ten years after the completion of the dredging work. This fact supports the suitability of the value of 25 ppm. It can also be said that this figure will be used as a guideline for sludge-removal in other contaminated sea areas.

The value, used for Minamata Bay (25ppm), should be regarded as a range of standards whereby proposed projects can compare the conditions of their sea areas to those of Minamata, and arrive at an appropriate removal standard. On the basis of the comparison and taking the results reported here into consideration, changes in mercury concentration in each fish species should be predicted, and a removal standard should be determined accordingly.

5. CONCLUSIONS

Based on observed data on the quality of the environment before and after the Minamata Project, this paper has made a post-project evaluation of the project, studied the state of the environmental remediation.

In the study, the following were clarified:

1) While improvement of the environment is the foremost purpose of environmental restoration projects, it is also important to, through the projects, help the economic and societal rejuvenation of a region adversely affected by a deterioration of the environment.
2) Even if most of the mercury in sediment is mercury sulfide, not readily dissolvable in water, the removal of contaminated sediment has an effect on the improvement of the water quality.
3) Even if the removal of sediment is carried out,

the mercury concentration in contaminated fish is not lowered immediately; there is a time lag of several years to a decade. In order to estimate the time lag in advance, it is necessary to carry out ecological research on the biological half-life of mercury in fish and on the generation time of fish.

4) In order to promote the lowering of mercury concentrations in fish, it is effective to pursue an ecological approach, involving the capture and elimination of contaminated fish, in addition to the engineering approach, i.e. the removal and disposal of contaminated sediment.

5) The determination of a removal standard is an important factor in the removal of sediment. In future similar projects, the removal standard of the Minamata Project, 25 ppm, should be of reference. Changes in mercury concentration in each fish species should be predicted, and a removal standard should be determined accordingly.

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水俣湾環境復元事業の事後評価について

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水俣湾環境復元事業は，水銀で汚染された水俣湾の環境の復元を行ったものであり，熊本県等が行った水俣湾等堆積汚泥処理事業（水俣湾等公害防止事業）と漁業の再開を目指した水俣湾の魚介類対策のための事業からなる．

本研究は，様々な事業目的を達成するために慎重な検討と工夫がなされた水俣事業の計画・事業過程を示すとともに，水俣事業の実施前後の環境質の観測データ等をもとに，同事業の環境改善効果，経済的・社会的効果などの事業効果の評価、魚体中水銀濃度の変化等の環境改善の実態について分析を行ったものである．