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# Environmental Management in Aquaculture

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*Proceedings of the Twenty-first*
*U.S.-Japan Meeting on Aquaculture*
*Kyoto, Japan*
*November 26 and 27, 1992*

Kunizo Tanaka, Kooichi Konishi, James P. McVey and Marcia R. Collie (editors)

National Research Institute of Aquaculture
Fisheries Agency

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*Panel Chairmen:*
Kenji Takagi, Japan
James P. McVey, United States

*Under the U.S.-Japan Cooperative Program in Natural Resources (UJNR)*

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# PREFACE

The United States and Japanese counterpart panels on aquaculture were formed in 1969 under the United States-Japan Cooperative Program in Natural Resources (UJNR). The panels currently include specialists drawn from the federal departments most concerned with aquaculture. Charged with exploring and developing bilateral cooperation, the panels have focused their efforts on exchanging information related to aquaculture which could be of benefit to both countries.

The UJNR was begun during the Third Cabinet-Level Meeting of the Joint United States-Japan Committee on Trade and Economic Affairs in January 1964. In addition to aquaculture, current subjects in the program include desalination of seawater, toxic microorganisms, air pollution, energy, forage crops, national park management, mycoplasmosis, wind and seismic effects, protein resources, forestry, and several joint panels and committees in marine resources research, development, and utilization.

Accomplishments include: Increased communication and cooperation among technical specialists; exchanges of information, data, and research findings; annual meetings of the panels, a policy-coordinative body; administrative staff meetings; exchanges of equipment, materials, and samples; several major technical conferences; and beneficial effects on international relations.

Kenji Takagi - Japan
James P. McVey - United States

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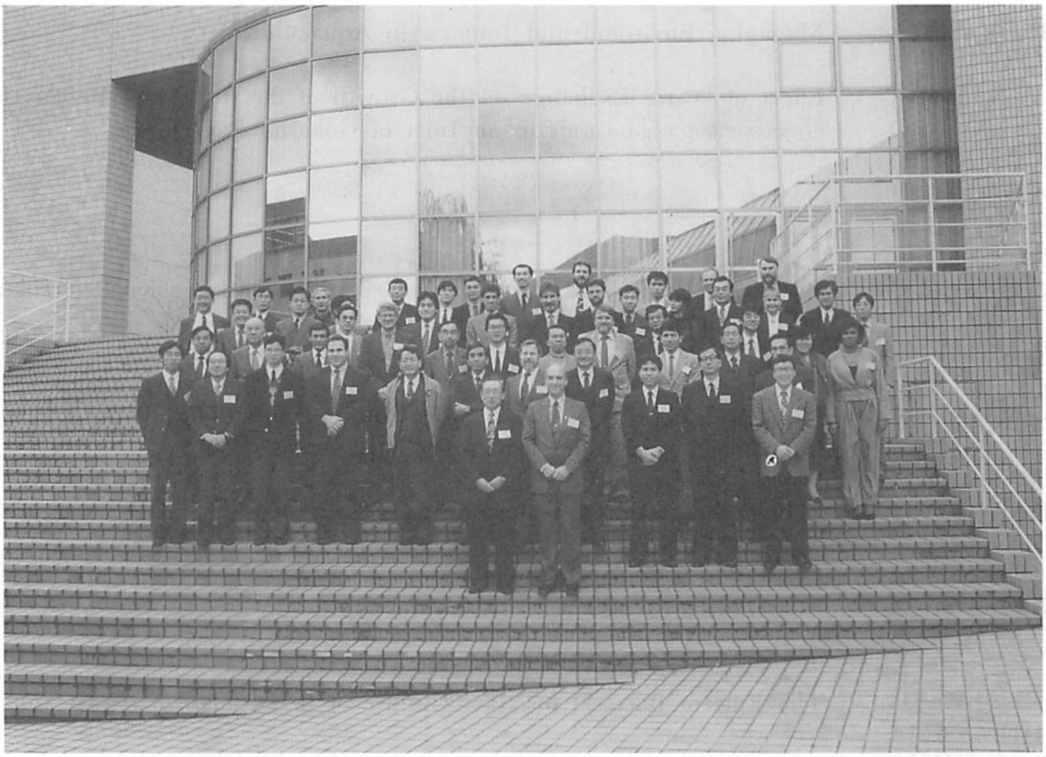

U.S. Side and Japan Side Attendance of the 21st Joint Meeting at Kyoto

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# INFLUENCE OF ORGANIC POLLUTION ON THE MACROBENTHOS IN AN URBAN ESTUARY

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## ABSTRACT

To clarify the effects of organic pollution on the macrobenthos in an urban estuary and to compare with previous surveys, quantitative samples were obtained from the rivers and the harbor area in Osaka, which are characterized by a large amount of sewage effluents and the extension of reclaimed lands in recent years. Ten benthic communities included in the past are recognized in this area. They are ordinated along the gradients of salinity and organic pollution. Comparison with the previous surveys suggests that the succession of the community occurred in the seaward area during the last 50 years. It is also suggested that the dominant *Capitella* sp. in the mouths of the rivers and the expansion of the area dominated by *Paraprionospio* sp. around Osaka Port are due to the increasing influence of the hypoxic water from organic pollution and the construction of reclaimed lands.

## INTRODUCTION

The species composition of macrobenthos changes along a gradient of increasing organic enrichment in an aquatic environment. The degree of organic pollution can be assessed by monitoring benthic faunas and communities.

The rivers and harbor area in Osaka are one of the most eutrophicated areas in Japan due to a large amount of sewage and industrial effluents. Investigations on the macrobenthos in this area were carried out first in the 1950's (Dept. Zoology Nara Women's Univ. and Osaka Pref. Fish. Exp. Stn. 1956; Kitamori and Funae 1959; Dept. Zoology Nara Women's Univ. 1960). Thereafter, reclamation has increasingly advanced around Osaka Port in order to develop real estate and harbor facilities or to dispose of garbage and industrial waste (Takamizawa et al. 1987). Recently, successive surveys on the macrobenthos have been conducted in this area (Yokoyama 1986; Yokoyama et al. 1985, 1986). In this paper, these results and unpublished data obtained by the author are synthesized to clarify the present state of the faunal composition and community structure in this area, and a comparison is made with results of the previous studies.

## METHODS

Surveys were carried out 12 times from August 1984 to February 1991 (Table 1). Samples were collected from 47 stations in the rivers and harbor area of Osaka City (Figure 1). Two replicate samples were taken at each of these stations with a 0.04-m$^2$ Ekman-Birge grab and a 1-mm mesh sieve. The collected animals were identified, counted, and their wet weight was determined after blotting with filter paper. Along with biological sampling, bottom water (0.5 – 1 m above the bed) and sediment samples were obtained for analysis of salinity, chemical oxygen demand ($COD_{Mn}$), biological oxygen demand (BOD) and dissolved oxygen (DO) of water, and grain size, ignition loss (IL), chemical oxygen demand ($COD_{sed}$) and total sulfide of sediment.

Table 1. Surveys conducted in the present study.

| Sampling date | Stations[a] | Reference |
|---|---|---|
| 27–29 Aug. 1984 | 5–32, L-O | Yokoyama et al. 1985 |
| 25–27 Feb. 1985 | 5–32, L-O | Yokoyama 1986 |
| 28 Aug. 1986 | 1–10 | unpublished |
| 9 Apr. 1987 | 1–10 | unpublished |
| 23–24 May 1985 | A-O | Yokoyama et al. 1986 |
| 26–27 Aug. 1985 | A-O | Yokoyama et al. 1986 |
| 25–27 Nov. 1985 | A-O | Yokoyama et al. 1986 |
| 19–20 Feb. 1986 | A-O | Yokoyama et al. 1986 |
| 10–14 May 1990 | A-O | unpublished |
| 7–10 Aug. 1990 | A-O | unpublished |
| 6–9 Nov. 1990 | A-O | unpublished |
| 5–8 Feb. 1991 | A-O | unpublished |

[a] See Figure 1.

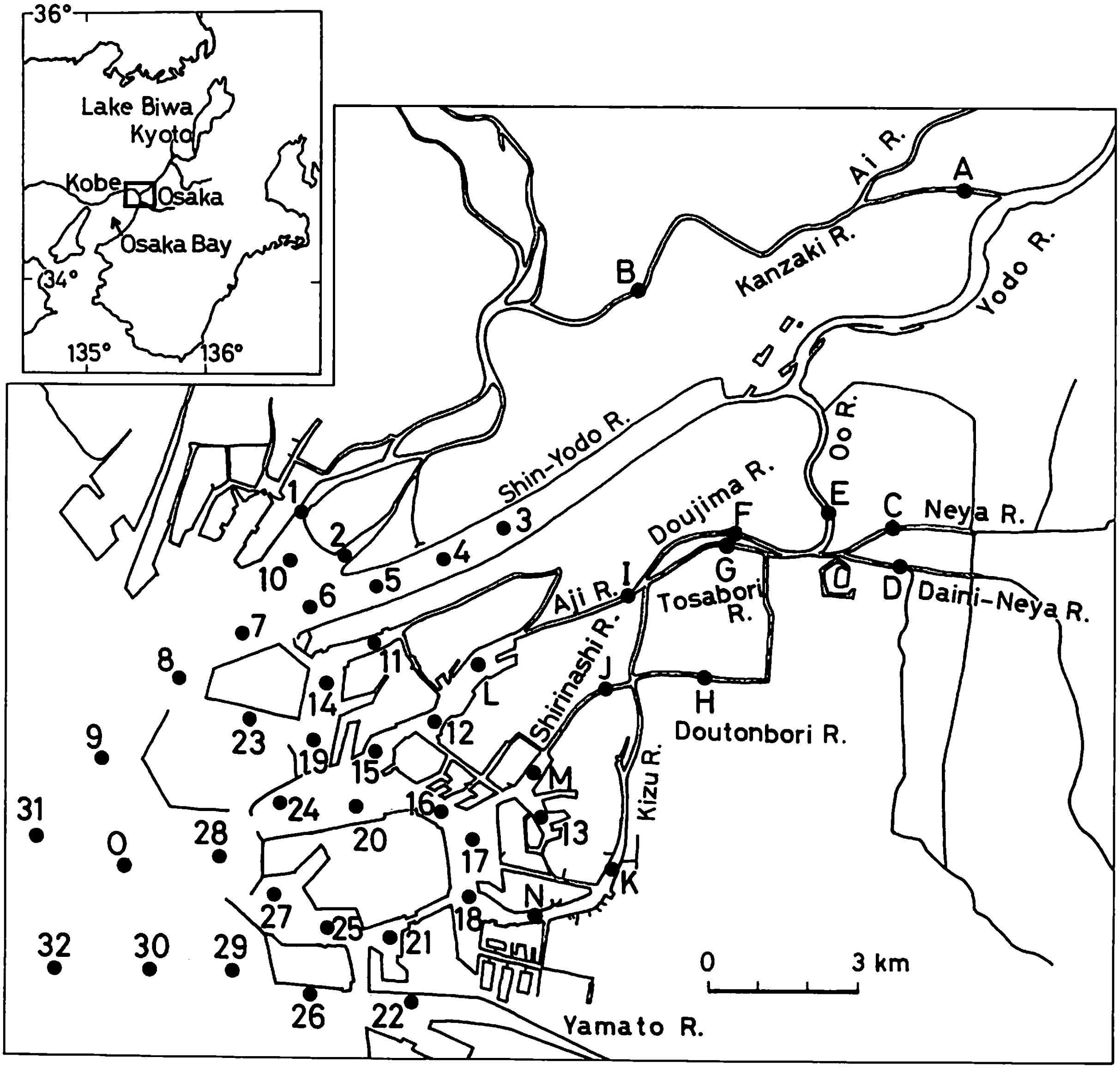


Figure 1. Map showing the study area and sampling stations.

## RESULTS AND DISCUSSION

### PHYSICAL AND CHEMICAL ENVIRONMENTS OF THE STUDY AREA

The study area is located around the mouth of the Yodo River, which originates from Lake Biwa (Figure 1). The Kanzaki River and the Oo River including its distributaries (the Doujima River, the Tosabori River, the Doutonbori River, the Aji River, the Shirinashi River and the Kizu River) branch from the lower Yodo River, flow through Osaka City, and pour into Osaka Port, which is located at the innermost part of Osaka Bay. The Oo River is joined with the Neya and the Daini-Neya Rivers whose basins are the east part of the Osaka plain.

An extensive part of the study area is under the influence of the tides, as shown by relatively high levels of salinity at the stations of the Kizu River (Station K, 18.8–30.5), the Aji River (Station I, 0.1–23.7), the Doutonbori River (Station H, 0.1–19.9), and the Sirinashi River (Station J, 0.1–14.2). The study area is also influenced by organic pollution caused by the industrial and domestic wastes from the congested areas of the Kyoto-Osaka districts. In particular, the water of the Neya and the Daini-Neya Rivers is heavily polluted (the yearly mean value of BOD, 7.8–9.3 mg $l^{-1}$; the yearly mean value of $COD_{Mn}$, 12–14 mg $l^{-1}$), mainly due to insufficient facilities for sewage treatment.

The innermost part of Osaka Port, i.e., the mouths of the rivers, is characterized by organically enriched sediments (ignition loss, >12%; $COD_{sed}$, >40 mg $g^{-1}$)

and thermohaline stratification, which cause hypoxic or anoxic conditions from late spring through autumn. Such deteriorated conditions are represented by extremely high values of sulfide in the sediment (>5 mg $g^{-1}$ dry sediment). Moving away from this area, pollution effects gradually decrease, but oxygen-deficient conditions (DO, <2 mg $l^{-1}$) at the outside of the harbor are often found in summer.

## FAUNAL COMPOSITION

A total of 139 species including 58 polychaetes, 23 bivalves, 20 crustaceans, 13 gastropods, 6 insects, and 4 oligochaetes were recognized from the study area. The species found commonly are listed in Table 2.

Table 2. Species found commonly in the study area.

Freshwater species
- Oligochaeta: *Branchiura sowerbyi, Limnodrilus* sp.
- Mollusca: *Sinotaia quadrata histrica, Unio douglasiae, Corbicula leana*
- Crustacea: *Asellus hilgendorfi*
- Insecta: *Psychora alternata*

Marine species
- Polychaeta: *Harmothoe* sp., *Sthenelais* sp., *Eumida sanguinea, Sigambra* sp., *Gyptis* sp., *Ophiodromus* sp., *Nectoneanthes latipoda, Nephtys polybranchia, Glycinde* sp., *Lumbrineris longifolia, Paraprionospio* sp. (form A), *Prionospio membranacea, Pseudomalacoceros* sp., *Pseudopolydora* sp., *Cirriformia* sp., *Tharyx* sp., *Cossura duplex, Mediomastus* sp. *Euchone* sp.
- Mollusca: *Alvenius ojianus, Ruditapes philippinarum, Mactra chinensis, Raetellops pulchella, Theora fragilis*

Estuarine species
- Polychaeta: *Neanthes succinea, Neanthes japonica, Schistomeringos* sp. *Polydora* sp., *Prionospio japonica, Prionospio pulchra, Pseudopolydora kempi japonica, Pseudopolydora paucibranchiata, Capitella* sp.
- Mollusca: *Musculista senhousia,*
- Crustacea: *Nebalia bipes, Corophium* sp., *Grandidierella japonica*

Faunal composition changed between the rivers and the seaward area. In general, in the rivers tubificid oligochaetes dominated, while in the harbor area polychaetes dominated. Several species were distributed characteristically in the mouths of the rivers. Such a large-scale pattern of faunal composition is considered to depend mainly on salinity in the bottom water. Macro-invertebrates inhabiting the study area can be classified into three groups; that is, freshwater species inhabiting the area with salinity of <2, marine species inhabiting the area with salinity of >27, and estuarine species inhabiting euryhaline environments (Table 2). The estuarine species can be divided into three subgroups; that is, species inhabiting the lower reaches of the rivers such as *Neanthes japonica* and *Prionospio japonica,* species inhabiting the seaward area including the mouths of the rivers such as *Neanthes succinea, Polydora* sp. and *Prionospio pulchra,* and species inhabiting exclusively the mouths of the rivers such as *Capitella* sp., *Corophium* sp., and *Nebalia bipes.*

Tsuda (1964) introduced the biomonitoring method using a saprobic system, in which freshwater organisms are ordered as oligosaprobic species, mesosaprobic species, and polysaprobic species along the gradient of increasing organic input, to assess water quality of rivers in Japan. According to this method, most of the rivers where the tubificid oligochaetes *Limnodrilus* sp. and *Branchiura sowerbyi* predominated belong to the polysaprobic zone except the Oo River, the Doujima River, and the upper reaches of the Kanzaki River where mesosaprobic species such as *Sinotaia quadrata histrica, Unio douglasiae,* and *Corbicula leana* are distributed.

In the coastal area, several species are often used as indicators of organic pollution. In Japan, *Capitella capitata* and *Paraprionospio pinnata* have been regarded as well-established pollution-indicators. However, the former species contains at least ten sibling species with distinct differences in life history (Grassle and Grassle 1976, Grassle 1980). *Capitella* species found in the present survey resembles closely *Capitella* sp. I, which can respond most rapidly to environmental disturbances by its opportunistic behavior (Grassle 1980). The spe-

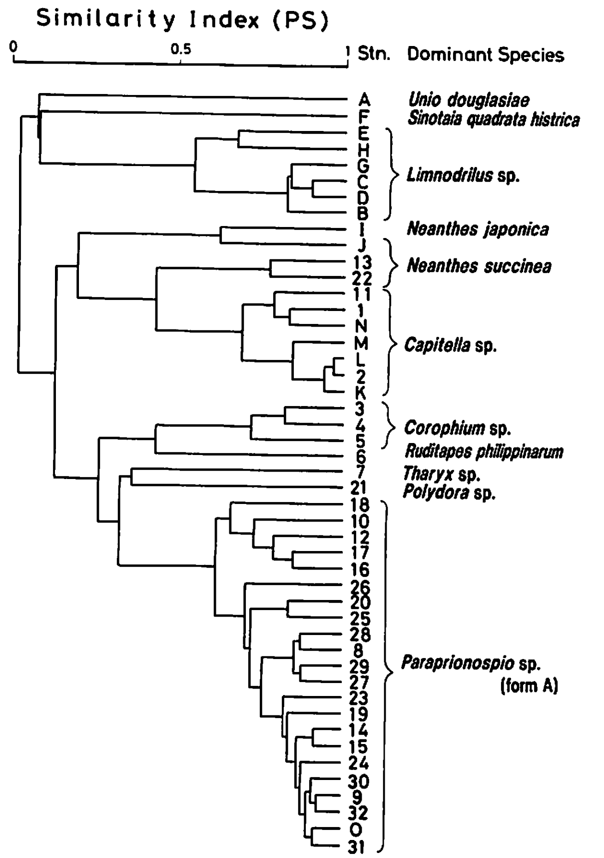


Figure 2. Dendrogram showing the similarity between the stations. The similarity index PS ranges from 0 (lowest) to 1 (highest similarity). Dominant species which was ranked highest in wet weight in each station are noted.

cies treated as *P. pinnata* in Japan was also revealed to contain morphological variations that allow it to be divided into four forms (Tamai 1981, Yokoyama and Tamai 1981). It is indicated that form A in this complex can respond to seasonal deoxygenation by acquiring a marked tolerance for hypoxia and by timing recruitment to the period of recovery of oxygen, although this species has a less opportunistic life-history (Tamai 1982, 1985; Yokoyama 1990). Yokoyama (1991) reported that larvae of this species were concentrated in water layers with oxygen levels below 1 mg $l^{-1}$ all day long and attributed the high abundances of this species in organically polluted sediments to the adaptation of larvae to hypoxic water. These ecological features suggest that *Paraprionospio* sp. (form A) is the useful indicator of hypoxic conditions.

*Capitella* sp. and *Paraprionospio* sp. (form A) appeared as overwhelming dominant species in the mouths of the rivers and in the seaward area, respectively. *Neanthes succinea, Lumbrineris longifolia, Prionospio pulchra, Raetellops pulchella, Theora fragilis,* and *Nebalia bipes,* which were main constituent species in the study area, have been reported as species associated with organic-enriched sediments in the Japanese coastal waters (Kikuchi 1991). Such species composition indicates that the study area has faunas typical of the organically polluted bottom of rivers, estuaries, and coastal waters in Japan.

Yearly mean features of species composition at each station are obtained by accumulating wet weights of each species, and the similarities between stations are

Table 3. Mean values of biomasses and densities of main species in each community.

| Community (Stations) | Species | Biomass[a] (g $m^{-2}$) | Density (individuals $m^{-2}$) |
|---|---|---|---|
| *Unio*-community (A) | *Unio douglasiae* | 111.5 | 6 |
| | *Sinotaia quadrata histrica* | 19.9 | 16 |
| | *Limnodrilus* sp. | 1.9 | 1750 |
| | all animals | 137.2 | 2030 |
| *Sinotaia*-community (F) | *Sinotaia quadrata histrica* | 621.8 | 302 |
| | *Limnodrilus* sp. | 0.8 | 520 |
| | *Neanthes japonica* | 0.5 | 48 |
| | all animals | 623.4 | 952 |
| *Limnodrilus*-community (B, C, D, E, G, H) | *Limnodrilus* sp. | 41.4 | 18200 |
| | *Branchiura sowerbyi* | 5.4 | 415 |
| | all animals | 48.0 | 18700 |
| *Neanthes*-community (I, J) | *Neanthes japonica* | 3.0 | 83 |
| | *Neanthes succinea* | 2.6 | 28 |
| | *Limnodrilus* sp. | 0.7 | 469 |
| | *Capitella* sp. | 0.2 | 120 |
| | all animals | 6.7 | 861 |
| *Capitella*-community (1, 2, 11, K, L, M, N) | *Capitella* sp. | 31.9 | 6290 |
| | *Polydora* sp. | 2.1 | 361 |
| | *Neanthes succinea* | 1.9 | 21 |
| | *Nebalia bipes* | 1.0 | 338 |
| | *Prionospio pulchra* | 0.5 | 644 |
| | all animals | 39.7 | 8090 |
| *Corophium*-community (3, 4, 5) | *Corophium* sp. | 39.9 | 9900 |
| | *Polydora* sp. | 6.4 | 2050 |
| | *Euchone* sp. | 5.0 | 885 |
| | *Paraprionospio* sp. (form A) | 4.0 | 182 |
| | *Grandidierella japonica* | 3.3 | 398 |
| | all animals | 53.3 | 15700 |
| *Paraprionospio*-community (8, 9, 10, 12, 14, 15, 16, 17, 18, 19, 20, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, O) | *Paraprionospio* sp. (form A) | 20.9 | 2060 |
| | *Lumbrineris longifolia* | 2.2 | 292 |
| | *Euchone* sp. | 1.1 | 881 |
| | *Neanthes succinea* | 1.0 | 28 |
| | *Sigambra* sp. | 0.6 | 355 |
| | *Prionospio pulchra* | 0.3 | 1140 |
| | all animals | 30.9 | 5700 |

[a] Wet weight including shell. Animals heavier than 1 g were included.

determined by the index of percentage similarity (PS) proposed by Whittaker (1952). The results are shown as a dendrogram which is represented by the method of Mountford (1962) (Figure 2). The dendrogram indicates that seven communities exist in the study area. The communities are designated here as *Unio*-community in the upper reaches of the Kanzaki River, *Sinotaia*-community in the Doujima River, *Limnodrilus*-community in most of the rivers, *Neanthes*-community in the Aji and the Shirinashi Rivers, *Corophium*-community in the Shin-Yodo River, *Capitella*-community in the mouths of the rivers, and *Paraprionospio*-community in the harbor area. Species composition and abundances of main species in each community are summarized in Table 3.

## BIOMASSES AND SEASONAL CHANGES OF BENTHIC COMMUNITIES

Biomasses of the seven communities are indicated as "biomass curves" of Horikoshi et al. (1977), which are represented by plotting all values of the biomass obtained in each community cumulatively from the minimum value to the maximum value (Figure 3). This shows that *Limnodrilus*-community had small biomasses except in the Neya River (Station C) and the

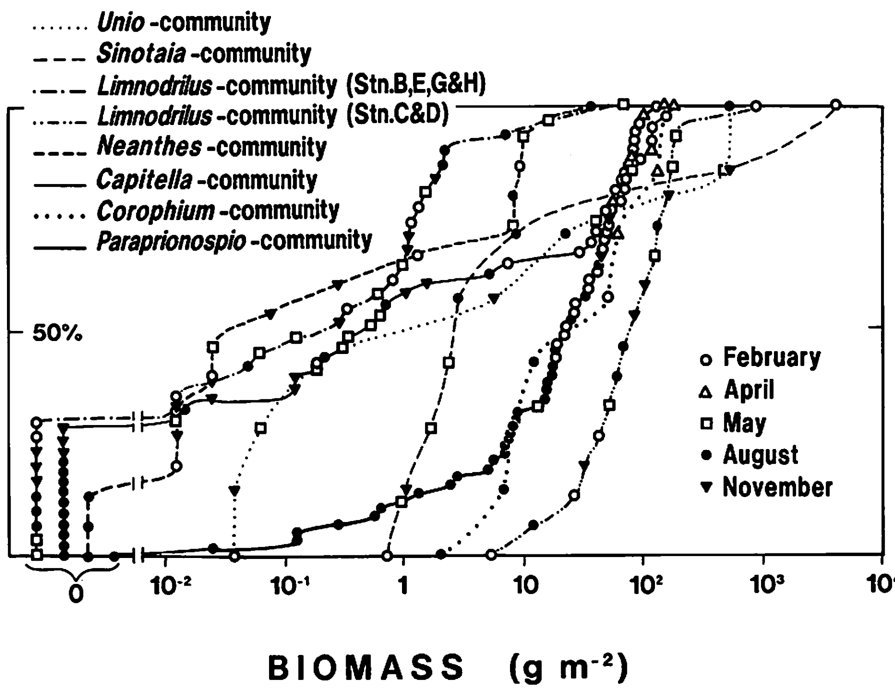


Figure 3. Biomass curves in seven communities in terms of wet weight (including shell) of all individuals (including animals heavier than 1 g) collected from each station.

Table 4. Mean values of environmental factors in each community.

| Community | Bottom water | | | | Sediment | | | |
|---|---|---|---|---|---|---|---|---|
| | Salinity | $COD_{Mn}$[a] mg $l^{-1}$ | BOD mg $l^{-1}$ | DO[b] mg $l^{-1}$ | Mdø | IL[c] % | $COD_{sed}$[d] mg $g^{-1}$ | TS[e] mg $g^{-1}$ |
| *Unio*-community | <0.1 | 5.4 | 2.7 | 7.6 | 2.1 | 1.2 | 2.1 | <0.01 |
| *Sinotaia*-community | 0.2 | 5.5 | 2.2 | 6.3 | 2.3 | 4.2 | 9.0 | 0.08 |
| *Limnodrilus*-community | 1.2 | 9.2 | 5.2 | 3.8 | 3.4 | 9.0 | 22.9 | 1.3 |
| *Neanthes*-community | 6.9 | 6.0 | 3.1 | 4.9 | 5.0 | 13.1 | 49.0 | 3.3 |
| *Capitella*-community | 30.1 | 3.0 | 1.2 | 0.8 | 6.0 | 14.0 | 42.9 | 6.3 |
| *Corophium*-community | 28.6 | 4.4 | — | 3.2 | 2.3 | 2.6 | 4.6 | 0.4 |
| *Paraprionospio*-community | 31.7 | 2.0 | 0.6 | 2.5 | 7.2 | 10.5 | 16.1 | 1.8 |

[a] Chemical oxygen demand measured with the acidic $KMnO_4$ method.
[b] Dissolved oxygen in August.
[c] Ignition loss during 2 hrs at 600°C.
[d] Chemical oxygen demand measured with the alkaline $KMnO_4$ method (15 min at 100°C) in terms of mg of oxygen per g of dry sediment.
[e] Total sulfide in terms of mg of sulfur per g of dry sediment.

Daini-Neya River (Station D), where extremely large biomasses and high densities (the maximum values; 920 g wet wt $m^{-2}$, 270,000 individuals $m^{-2}$) were found throughout the year. Figure 3 also shows relatively large biomasses in *Paraprionospio*-community and *Corophium*-community, a wide range of variation in *Unio*-community, *Sinotaia*-community, *Limnodrilus*-community, *Neanthes*-community, and *Capitella*-community, and seasonal reduction of the biomass except in the three freshwater communities.

Environmental factors in each community are shown in Table 4. *Limnodrilus*-community is situated at the most advanced stage of organic pollution in the three freshwater communities. The largest biomasses at Stations C and D, which resulted from a dense population of *Limnodrilus* sp., may depend on organic enrichment in water, providing a rich food source, but does not result in serious depletion of oxygen due to strong river current.

In the harbor area, the biomass in summer decreased gradually as the station shifted landward, then an azoic situation was found at the innermost part of the harbor. Figure 3 shows that this situation lasted from May through November. In winter, however, the innermost part of the harbor was inhabited by dense populations of *Capitella* sp. and several estuarine species, which brought large biomasses and a clear faunal boundary between *Capitella*-community and *Paraprionospio*-community. The reduction of biomasses in summer was also found in *Paraprionospio*-community, but that was not so prevalent in *Capitella*-community.

At the innermost part of the harbor, a long-term accumulation of organic substances in sediments and stagnant conditions caused by the enclosed topography, halocline stratification lead to deoxygenation (Table 4), and subsequent elimination of the macrofauna. Prolonged anaerobic conditions limit the constituent species to opportunists such as *Capitella* sp. that have an ability to reproduce rapidly in a short life span. Deteriorated conditions are improved in the seaward area. However, even this area often suffers reduced oxygen concentrations $<2$ mg $l^{-1}$ in summer, which may lead to the occurrence of *Paraprionospio* sp. (form A), an indicator of hypoxic conditions, as a dominant species.

## SUCCESSION OF BENTHIC COMMUNITIES

The benthic survey conducted in 1960 revealed an afaunal situation at Asahi-bashi in the Neya River, which was thought to result from the heavy organic pollution of the water (Dept. Zoology Nara Women's Univ. 1960). In 1960, yearly mean value of BOD in this river showed 32 mg $l^{-1}$, which is extremely high as compared with the value of $<10$ mg $l^{-1}$ in recent years (personal communication, the municipal office of Osaka City). In the study area, the river water began to be polluted in the 1950's (Uno 1961), and peak levels were found around 1970 (Oda et al. 1980). Thereafter, water quality has been gradually improved by enforcing the Water Pollution Prevention Act and equipping facilities for sewage treatment. The faunal recovery in the Neya River found in the present survey seems to be a result of improved water quality.

The previous surveys conducted in Osaka Port in 1955 (Dept. Zoology Nara Women's Univ. and Osaka Pref. Fish. Exp. Stn. 1956) and in 1957–1958 (Kitamori and Funae 1959) showed that the benthic fauna in the mouths of the rivers was also impoverished in summer because of hypoxic conditions. Both in 1955 and 1958, recovered benthic fauna in winter or in spring was

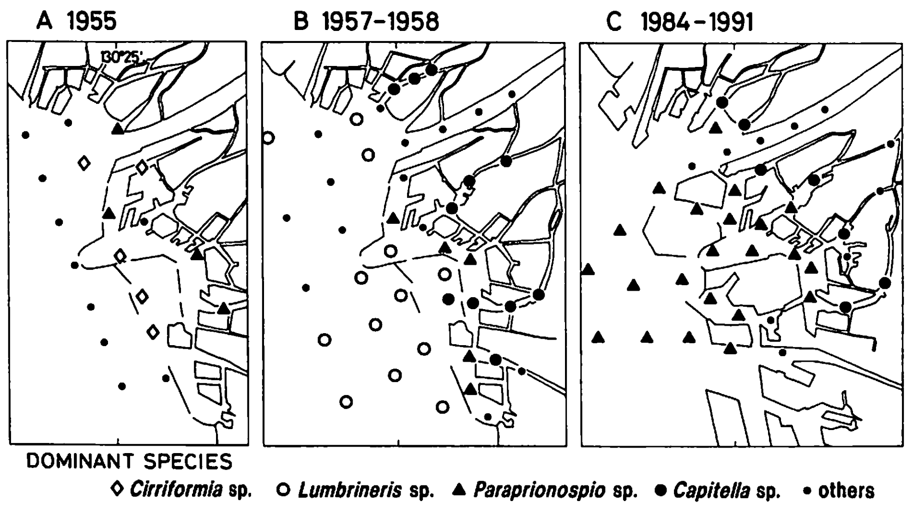


Figure 4. Succession of dominant species around Osaka Port during thirty years. (A) after Dept. Zoology Nara Women's Univ. and Osaka Pref. Fish. Exp. Stn. 1956; (B) after Kitamori and Funae 1959; (C) the present study.

revealed, but a change of the dominant species was found there during this period (Figure 4). In 1955, *Paraprionospio* sp. dominated in the mouths of the rivers, while in 1958 *Capitella* sp. dominated there. If *Capitella* sp. indicates short-lived, highly disturbed conditions, the domination of this species in the mouths of the rivers suggests the protoraction of an anaerobic period there, resulting in an impediment of recruitment of *Paraprionospio* species.

Successive alternation of the dominant species also have been found around the harbor area. First surveys in Osaka Bay conducted from 1937 through 1939 showed the dominant occurrence of the polychaete *Spiochaetopterus costarum* at depths of <15 m off the northern and eastern coast of the bay (Miyadi 1940). Inside the harbor, the polychaete *Cirriformia tentaculata* dominated in 1955, but this species was replaced by *Paraprionospio* sp. or *Lumbrineris* species in 1957–1958 (Figure 4). The area dominated by *Paraprionospio* sp. was confined within the breakwaters in Osaka Port before 1958. However, the present investigation reveals that the area dominated by this species has expanded to outside the harbor, where *Lumbrineris* appeared as a dominant species at the time of the 1957–58 survey. The domination of *Paraprionospio* sp. along the northeast coast of Osaka Bay is also confirmed by the surveys conducted after 1968 (Joh et al. 1969, 1978; Tamai 1981; Yamanishi 1990). The expansion of the area dominated by *Paraprionospio* sp. in recent years, which indicates the occurrence of seasonal hypoxic-conditions (Tamai 1982; Yokoyama 1990, 1991), may reflect the expansion of the area suffering seasonal deoxygenation.

The succession of the dominant species observed during the last 50 years around Osaka Port suggests the effects of increasing organic-pollution in this area, although the river water has been improved after the 1970's. Such a tendency is probably due to the increasing organic matter in sediments that originated in the river water or red-tide organisms in the sea and to stagnant conditions caused by the expansion of the reclaimed land in Osaka Port.

## CONCLUSION

Ten benthic communities included in the past are recognized in the study area. They are placed in the gradients of salinity and organic pollution (Figure 5). In the freshwater area, three communities, i.e., *Unio*-community, *Sinotaia*-community and *Limnodrilus*-community are present; *Unio*-community is located in the less-polluted area, while *Limnodrilus*-community is located in the most-polluted area (Table 4). *Neanthes*-community and *Corophium*-community are present in the euryhaline environment. The former is characterized

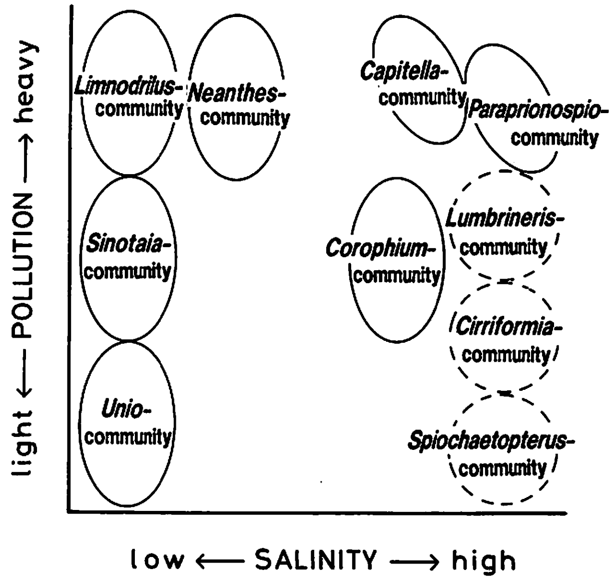


Figure 5. Ordination of ten benthic communities in gradients of salinity and organic pollution. Communities enclosed with a solid line are existing in the study area; those with a broken line are not detected in the present.

by its organically polluted habitat in oligohaline conditions, while the latter develops on the clear, well-sorted sand bottom in the estuary. Five communities are recognized in the seaward area. *Capitella*-community tends to develop in a less-saline environment as compared with other four marine communities. Comparison with the previous surveys suggests that the succession of the community in order of *Spiochaetopterus*-community, *Cirriformia*-community, *Lumbrineris*-community, *Paraprionospio*-community and *Capitella*-community occurred in the seaward area during the last 50 years as levels of organic pollution increase. Only the latter two communities are found in the present.

The present study gives an instance of the biomonitoring of an estuary pollution with macrobenthos. Further studies in other localities should be conducted to clarify the ordination of benthic communities in the gradient of pollution and to use the biomonitoring method for assessing aquatic environments.

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# EFFECTS OF MUSSELS, *MYTILUS GALLOPROVINCIALLIS*, TO THE EUTROPHICATION OF THE COASTAL ENVIRONMENT OF OSAKA BAY

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## ABSTRACT

The marine mussel, *Mytilus galloprovinciallis* Lamarck, is one of the most abundant sedentary organisms in the littoral zone of the coastal structure around Japan. From 1989 to 1991 some areal investigations were conducted along the coast of Osaka Prefecture and effects of a *Mytilus* population on the coastal bottom environment were examined on the basis of their distribution, growth, mortality and nitrogen budget.

Osaka Bay, about 1480 $km^2$ in area, is a semi-closed bay. It is located on the eastern end of the Seto Inland Sea. The east and innermost parts of the bay, both less than 20 m in depth, are dominated by river discharge water which mostly originates from the Yodo and Yamato Rivers (Figure 1). The waters from such rivers contain substantial amounts of nutrients, being involved in outbreaks of red tide, decrease in transparency, and occurrence of oxygen-deficient water in the bottom layer of the bay (Joh et al. 1984; Yamochi 1989). Average nutrient concentration of the surface water at the inner part of Osaka Bay in 1980–1991 exceeded 20 $\mu gat \cdot l^{-1}$ for dissolved inorganic nitrogen and also surpassed 0.5 $\mu gat \cdot l^{-1}$ for dissolved inorganic phosphorus.

A survey conducted in 1989 revealed that the length of coastline for Osaka Prefecture was ca.260 km and 95%

Table 1. Total biomass of *Mytilus galloprovinciallis* along the coast of Osaka Prefecture in July 1990.

| Coastal feature | Area | Total mussel weight* (t) | Wet flesh weight (t) | Dry flesh weight (t) | Dry flesh nitrogen (t) | Length of coast line (km) |
|---|---|---|---|---|---|---|
| Vertical wall | north | 8758 | 4028 | 761 | 63 | 115.2 |
| | central | 521 | 222 | 53 | 4.3 | 13.7 |
| | south | 313 | 136 | 35 | 2.9 | 8.9 |
| | sum | 9592 | 4386 | 849 | 70 | 137.8 |
| Block mound | north | 1379 | 558 | 111 | 9.4 | 27.8 |
| | central | 554 | 234 | 58 | 4.5 | 11.3 |
| | south | 495 | 212 | 37 | 3.5 | 16.4 |
| | sum | 2428 | 1004 | 206 | 17.4 | 55.5 |
| Rubble mound | north | 159 | 73 | 16 | 1.5 | 13.4 |
| | central | 10 | 4 | 0.7 | 0.07 | 3.5 |
| | south | 47 | 20 | 3 | 0.3 | 9.3 |
| | sum | 216 | 97 | 20 | 1.9 | 26.2 |
| Gentle | south | 27 | 11 | 2 | 0.19 | 1.9 |
| slope mound | sum total | 12263 | 5498 | 1077 | 90 | 221.4 |

*: Wet shell weight+wet flesh weight.

Table 2. Estimated nitrogen production and elimination of the mussels, *Mytilus galloprovinciallis* on the vertical wall of Ozaki Harbor, Osaka Bay from May to September 1990.

| Age | Production ($gN \cdot m^{-2}$) | | | | | Elimination ($gN \cdot m^{-2}$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Flesh | Gamete | Shell | Byssus | Total | Flesh+Gamete | Shell | Byssus | Total |
| 0 | 20.1 | 14.1 | 5.9 | 0.7 | 40.8 | 32.0 | 5.5 | 0.7 | 38.2 |
| 1 | 5.7 | 15.9 | 4.0 | −1.5 | 24.1 | 57.6 | 10.8 | 1.9 | 70.4 |
| Total | 25.8 | 30.0 | 9.9 | −0.8 | 64.9 | 89.6 | 16.3 | 2.6 | 108.6 |

of the coastline was unnatural. Vertical walls and block mounds accounted for 69% and 22% of the whole coastline. This means the coastal features of Osaka Bay dramatically changed over the past 40 years. Therefore, emphasis should be placed on environmental improvement of the vertical walls at the northern coasts together with the preservation of natural rocky shore and sand beach on the southeastern coasts.

*Mytilus galloprovinciallis* predominated on vertical walls or block mounds of the northern and eastern coasts of Osaka Bay, but drastically decreased in number at the mouths of the Yodo and Yamato Rivers. This is probably due to low salinity there. The maximum standing stock of *M. galloprovinciallis* reached 230.4 $kg \cdot m^{-1}$ in wet body weight at a breakwater outside Osaka South Outer-Port in July 1990. In addition, the total biomass along the coast of Osaka Prefecture in July 1990 was estimated as ca. $1.2 \times 10^4$ t in wet body weight, ca. $5.5 \times 10^3$ t in wet tissue weight. and ca. 90 t in dry tissue nitrogen (Table 1). The population density and biomass of *M. galloprovinciallis* markedly declined in Ozaki Harbor in late summer. As a result, elimination of the mussels exceeded their production by 1.7 times in May to September, 1990 (Production: 64.9 $gN \cdot m^{-2}$, Elimination: 108.6 $gN \cdot m^{-2}$; Table 2). These findings suggested that the bulk of the mussels was deposited and decomposed on the sea bed in summer when dissolved oxygen concentrations of the bottom seawater were low.

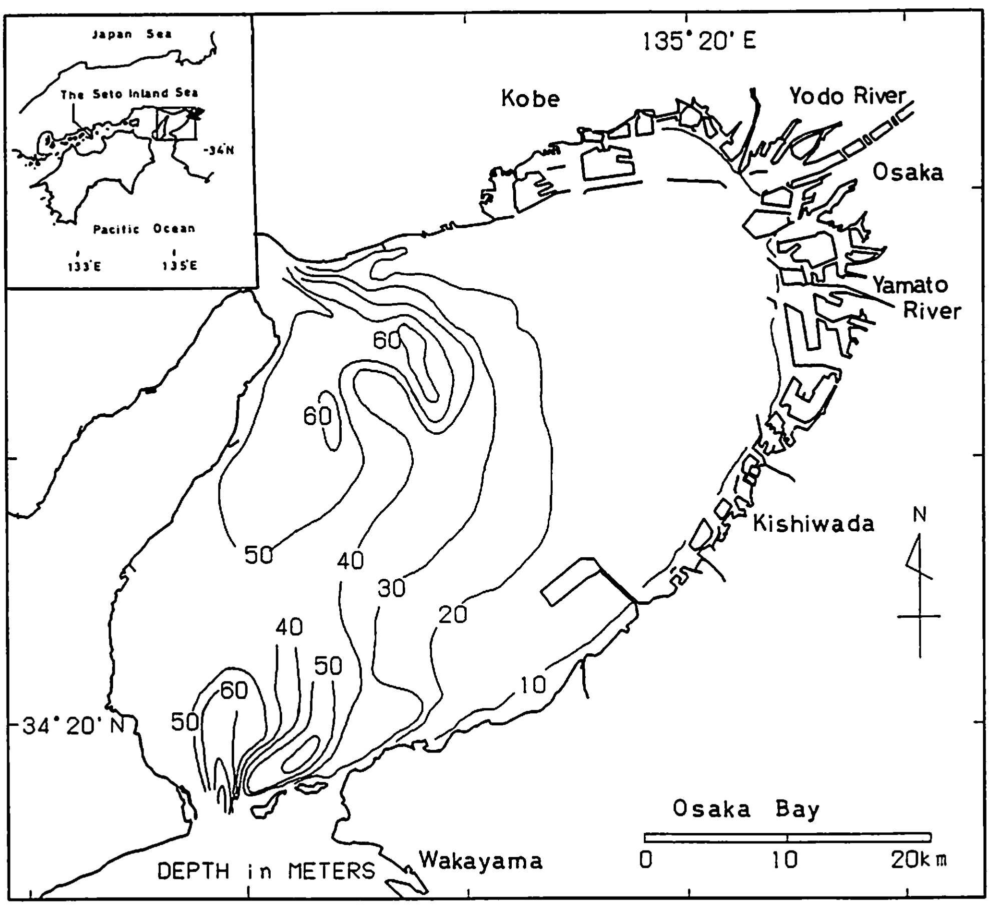


Figure 1. Map of Osaka Bay

As for *M. galloprovinciallis,* densely populated on the vertical walls of the eutrophic Osaka Bay, more attention should be paid to the negative effects to the sea bottom environment by their mortality and decomposition in the summer, rather than the positive effect through their filtering and purifying functions of sea water.

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# MANAGING ENVIRONMENTAL IMPACTS IN AQUACULTURE

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## ABSTRACT

As aquaculture has grown, so has the potential for increasing impacts on the environment and for increasing conflicts over the use of natural resources. The relationships between different forms of aquaculture and the environment are reviewed in this paper. Some examples of the form and magnitude of the environmental impacts caused by aquaculture operations are presented and analyzed. Strategies for minimizing the negative environmental impacts of aquaculture operations are discussed, including those of site selection and integration with other agricultural or industrial activities, input management, and water treatment and reuse.

## INTRODUCTION

The growth of the aquaculture industry has become an international phenomenon. There are examples of extraordinary growth throughout the world. Worldwide production of salmon increased from 7,149 metric tons (mt) in 1980 to 235,563 mt in 1991 (Folsom and Sanborn 1992); the shrimp industry throughout the world went from insignificant production in the mid1970's to producing 697,000 mt or 28% of worldwide shrimp sales in 1991 (Weidner and Rosenberry 1992). In some areas of the world, the growth and magnitude of the industry has reached a point where substantial environmental impacts have occurred. These impacts have resulted in reductions in production, in disease outbreaks in cultured and in wild populations, and in an increase of regulatory restrictions being placed on aquaculture operations. Environmental impacts can take on many faces and can include issues of recreation and aesthetics, as well as the uses of resources and the discharge of nutrients and organic matter into the environment (DeVoe et al. 1992). The discussion of environmental impact in this paper is limited to considerations of water use and the release of nutrients and organic matter. Ultimately, however, engineers are responsible for developing "good" designs for aquaculture systems, where "good" has been defined in terms of: "right scale, simplicity, efficient use of resources, close fit between means and ends, durability, redundance, and resilience, (that) are often place specific ..." (Orr 1992). In the general context, then, the issues discussed in this paper are only part of what an engineer, designer, manager, or regulator needs to consider when assessing the environmental impact of an aquaculture operation.

Analysis of the potential environmental impact of an aquaculture operation is an essential component of planning for and responding to regulatory decisions that will be made with regard to the future of that aquaculture venture. Existing and future aquaculture operations should be developed and managed with explicit consideration of how particular choices of the facility's size, its technology, and chosen site will affect the impact of the operation on the surrounding environment. Concern about the environmental impact of aquaculture operations is already evident in many of the areas where industry growth has been most dramatic. The concern has resulted from observed and perceived degradation in environmental quality that is thought to have been caused by aquaculture operations. In some cases, the result of this concern has been the promulgation of regulations restricting the size of farms, the locations where farms may be developed, the amount of water used in a farm, the concentration of certain substances (such as nutrients, suspended solids or biochemical oxygen demand (BOD)) in the effluent water, and in some cases the total amount of a particular substance that may be released from an aquaculture facility. In other cases, environmental degradation has resulted in substantial reductions in water quality for the aquaculture operations themselves, causing disease outbreaks and drops in production (Boyd 1991).

The objective of this paper is to review the relationships between aquaculture and the environment in a general sense by looking at overall mass balances for various substances and for different types of aquaculture operations.

## RESOURCE COSTS OF AQUACULTURE PRODUCTION

Mass balances are convenient tools for examining the possible impact of aquaculture operations on the environment. These mass balances can also be used to examine how changes in the operation of an aquaculture system will affect its possible impact on the environment. In general terms, the flow of mass through an aquaculture operation can be represented as in Figure 1. The mass balance presented is for aquaculture systems in which the cultured animals are fed with concentrated feeds as opposed to systems in which fertilizers are used and food production is carried out inside the culture system. Inputs include feed, water, air or oxygen, and energy. Outputs include fecal and metabolic wastes, uneaten feed or the products of its decomposition, water, and fish biomass. This generalized mass balance can be defined in more detail for nutrients or substances that are most likely to have significant effects on the environment. These include primary nutrients (nitrogen and phosphorus), dissolved oxygen, and organic matter.

### NITROGEN

A generalized mass balance for nitrogen can be analyzed from Figure 1, where overall inputs and outputs to a culture system are shown. For a nutrient like nitrogen, the input to the system is through the feed provided to the fish. Bioenergetics estimates are available for the various fractions of the feed nitrogen that are fixed into fish biomass, excreted as ammonia, as fecal matter, or as undigested feed. The numbers shown in Figure 2 illustrate the partitioning of feed nitrogen for salmonids (after Beveridge et al. 1991 and Colt and Orwicz 1991). A very important contribution to the

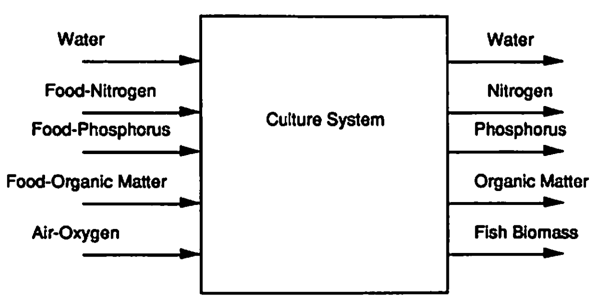


Figure 1. Simplified schematic diagram showing some of the critical inputs and outputs to an aquaculture production system. Nutrients (nitrogen and phosphorus) in the output will be present in organic matter and fish biomass in addition to inorganic forms in the water or sludge.

nitrogen release from an aquaculture operation can come from uneaten feed. The amount of uneaten feed is highly dependent on the culture practices used, the species of fish cultured, and on the type of feed. Beveridge and co-workers (1991) report a range between 1 and 30% for uneaten feed, with the lower values corresponding to pelleted feeds and the larger numbers to trash fish. There is, however, a strong economical incentive for reducing the quantity of uneaten feed, and the amount tends to be small in well-managed operations.

For the purposes of analyzing the impact that an aquaculture operation is likely to have on the environment, it is important to know not only how much, and in what form the nitrogen is being excreted by the fish, but also how those factors are likely to change within the system. Figure 3 illustrates how nitrogen discharge from an aquaculture operation may be partitioned. Water-borne nitrogen may include both dissolved and particulate forms of nitrogen, and each of those may include both organic and inorganic fractions. The differentiation between dissolved and suspended solids is based on standard glass fiber filtration with a filter of 1.5 $\mu$m pore size (APHA et al. 1989). The inorganic forms are ammonia, nitrite, and nitrate. The relative amounts of the three inorganic forms depend to a large extent on the amount of nitrification taking place within the system. In a flow-through system such as a raceway, most inorganic nitrogen will be present as ammonia. In a system in which there is some degree of water reuse and biofiltration, most inorganic nitrogen will be present as nitrate.

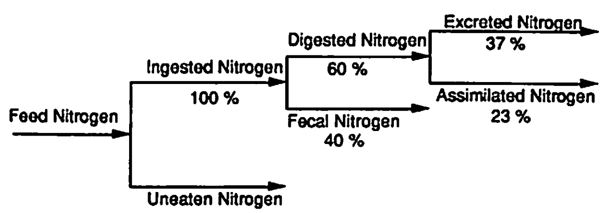


Figure 2. Partitioning of nitrogen fed to salmonid fish. All percentages are expressed with respect to the nitrogen in the feed that is ingested by the fish.

Sludge-borne nitrogen is that nitrogen present in a sludge or high-solids fraction that is separated within the system prior to discharge. The sludge may be formed in settling tanks or ponds, in screen filters, or in particulate media filters where solids produced in the system are concentrated and removed from the system separate from the water flow. Sludge-borne nutrient removal may not be present in all systems; a system in which there is no separation of solids prior to discharge will not have one.

The nitrogen present in fish biomass is the third route by which significant amounts of nitrogen exit the system. A goal of nutritionists (and farmers alike) is to minimize the ratio between nitrogen applied in the feed and nitrogen present in fish biomass. An indirect measure of this relationship is the food conversion ratio (FCR). For example, an overall FCR for the salmon industry in the Nordic countries is between 1.4 and 1.6 (Enell and Ackefors 1992; Beveridge et al. 1991), a typical nitrogen content of salmonid feed ranges between 6.1 and 8.5% (Enell and Ackefors 1992; Beveridge et al. 1991; MacMillan 1991; Weston 1991), and the nitrogen content of fish flesh between 2 and 3% (on a wet weight basis; Beveridge et al. 1991; Boyd 1991; Schroeder et al. 1991). Taking these numbers into account, the proportion of nitrogen fed that is actually converted to fish biomass is between 15 and 31%.

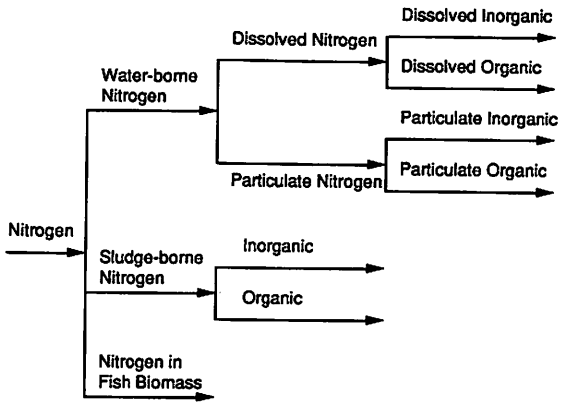


Figure 3. Forms in which nitrogen can be discharged from an aquaculture production system. In some cases, nitrogen volatilization (e.g., as nitrogen gas) can constitute an additional avenue for discharge.

In addition to the avenues for nitrogen discharge shown in Figure 3 and discussed above, nitrogen may be released as nitrogen gas ($N_2$), the end product of denitrification. This nitrogen release form was not included here because it is rare to see an aquaculture production system in which there is significant denitrification. From Figure 3 and the discussion above, one may conclude that reducing the overall amount of nitrogen released to the environment can only be achieved by lowering the fish biomass under cultivation or by increasing the proportion of the nitrogen fed that is fixed as fish biomass. Water treatment processes that may be added to a culture system may affect the partitioning of the nitrogen forms that are released (Figure 3) but will not affect the total amount released, as will be discussed below.

## PHOSPHORUS

Phosphorus is often considered to be the nutrient limiting algal growth and eutrophication in natural systems. As a result, it is sometimes used as the basis on which the aquaculture industry is regulated (Beveridge et al. 1991) or will be regulated in the future (MacMillan 1991). The movement of phosphorus through a culture system has some similarities to that of nitrogen, but there are important differences as well. As was the case for nitrogen, phosphorus is introduced into the system through the feed, and the effluent can be partitioned as in Figure 3. Typical salmonid feeds have a phosphorus content of 0.9 to 2% (Enell and Ackefors 1992; Weston 1991), of which between 25 and 42% can be expected to be fixed as fish biomass (for fish flesh phosphorus contents of 0.4 to 0.6% of wet weight as indicated by Boyd, 1991 and by Schroeder et al. 1991). In the effluent, there tends to be a smaller proportion of the phosphorus present in the inorganic soluble form than was the case for nitrogen.

## DISSOLVED OXYGEN AND ORGANIC MATTER

The importance of dissolved oxygen in the context of an environmental impact stemming from aquaculture operations arises due to the oxygen demand that may be present in aquacultural effluents, rather than from the effluent dissolved oxygen concentration. Dissolved oxygen concentration in the effluent from aquaculture operations is, by the very nature of the operation, sufficient to sustain fish life. The oxygen demand created by the presence of organic matter, on the other hand, may be such that oxygen depletion in the receiving waters could occur. A mass balance on organic matter can, once again, be represented schematically as shown in Figure 2. There are, however, significant differences between the partitioning of the organic matter and nitrogen and phosphorus in the effluent. The difference is caused primarily by the fact that some of the oxygen demand of the organic matter in the feed can be exerted inside the system: by the fish themselves, and by microbial degradation. The removal of organic matter is, therefore, associated with the operation of any type of biological treatment or with a process like solids removal, where the organic matter may stay in the system for a certain period of time during which there is some degradation of the organic matter and a reduction in biochemical oxygen demand (BOD). In some systems, notably ponds, there may be a net production of organic matter due to photosynthesis (Boyd 1991; Tucker 1991). The increased BOD from those systems will be in the form of algal cells.

In most aquaculture systems, organic matter is associated primarily with the solids fraction (suspended solids) of the effluent. As such, measurements of suspended solids are often used as indicators of the organic matter released from an aquaculture operation. In addition, suspended solids concentrations in effluents are used as criteria on which aquaculture farms are regulated. As an example, trout farms on the Snake River Valley in Idaho are limited to suspended solids concentrations of 5 mg/L (MacMillan 1991). Because most of the organic matter in aquaculture effluents tends to be in particulate form, solids removal is probably the most common water treatment operation undertaken in aquaculture.

## RELATIONSHIP BETWEEN AQUACULTURAL OPERATIONS AND THE ENVIRONMENT

In this section, examples of types of aquacultural operations will be examined using the mass balance approach described above. Where there is enough information available, the analysis will be presented for a whole industry rather than a particular operation.

### CAGES

Analysis of the relationship between the cage aquaculture industry and the environment will be described with the "Nordic" (Denmark, Finland, Iceland, Norway, Sweden, and The Faroe Islands) salmon culture as the example. The extraordinary growth of the Nordic salmon industry is well known: 1,580 mt in 1974, to 8,000 mt in 1979, to 34,500 mt in 1984, and to 155,000 mt in 1989 (Enell and Ackefors 1992). The industry growth was accompanied by improvements in feeds and feeding technology. Industry-wide feed conversion ratios were reduced from 2.0–2.5 in 1974 to 1.8 in 1984, to approximately 1.4 by 1989, and the value projected for 1994 is 1.3 (Enell and Ackefors 1992). The drop in the overall feed conversion ratio was accompanied by changes in the nitrogen and phosphorus content of the feeds from 6.1–8.5% N and 1.5–2% P in 1974 (all are proportions of wet weight) to 6.8–7.2% N and 0.9–1.2% P in 1989 (Enell and Ackefors 1992).

Fish production in 1989 was approximately 98 times the production in 1974 (after Enell and Ackefors, 1992). The amount of nitrogen released to the environment during the same time rose by a factor of 58 (from 200 mt to 11,600 mt) and phosphorus by a factor of 50 (40 mt to 2,000 mt) (after Enell and Ackefors 1992). The difference between the increase in fish production and the rise in nitrogen and phosphorus release is explained by the improvements in feed conversion ratios and feeding practices mentioned above. It is important to note that improvements were not caused by treatment, containment, or separation of part of the waste stream, but by making changes in the amount and form in which nutrients were input to the system (feed quality and feeding practices). This approach, as opposed to efforts to treat the wastes produced, is understandable given the special characteristics of cage aquaculture and the difficulties that would be associated with containing, conveying, and treating waste products from a cage.

### PONDS

Catfish Production in the United States takes place almost exclusively in earthen ponds. The ponds are usually shallow (less than 1.5 m deep) and range widely in size (to over 15 ha). Production is spread over many areas in the United States, but the largest producer is the state of Mississippi, with 1989 production of approximately 116,000 mt, and 1990 production of 120,000 mt (Anonymous 1991). This production takes place in approximately 37,000 ha, with an industry wide average of just over 3200 kg $ha^{-1}$ (Anonymous 1991).

Identifying the values for partitioning the effluent from catfish ponds is considerably more difficult than was the case with cages and raceways. As was mentioned earlier, there are many transformations of nutrients and of organic matter that occur inside a pond, and these depend on how the pond is managed and on site specific conditions of climate, soil properties, and background water quality. Boyd (1991) proposed some generalizations that are useful in the context of this paper: approximately 17% of the organic carbon, 25% of the nitrogen, and 25% of the phosphorus in the feed are converted to fish flesh. Boyd's (1991) estimates are based on a feed conversion ratio of 1.6, a feed with a nitrogen content of 5%, a phosphorus content of 1%, and a 90% dry matter content of which 10% is ash. Some of the nitrogen and phosphorus not fixed into fish biomass is lost from the pond as inorganic nutrients. Nitrogen may volatilized as ammonia, or as nitrogen gas if there is active denitrification in the pond, or it may leave the pond with the effluent in the form of ammonia, nitrite, or nitrate. Phosphorus tends to be less mobile and may be, lost to the pond sediments (Boyd 1991; Tucker 1991). Substantial amount of nitrogen and phosphorus may, however, be lost from the pond in the form of organic matter, some of it actually produced in the pond. Boyd (1991) estimates that the production of 1 mt of catfish results in the production of 3 mt of algal organic matter. As a result of the transformations of nutrients that take place inside a pond, overall estimates of nutrient release into the environment from catfish aquaculture are very difficult to obtain. An estimate obtained by difference (i.e., nutrient input in feed minus nutrient fixed as biomass) is possible: 7,200 mt of nitrogen and 1,450 mt of phosphorus were applied in the feed and were not fixed as fish biomass in 1990. It is important to reiterate that substantial proportions of this nitrogen and phosphorus are not actually released with effluents, but will be released either to the atmosphere by volatilization, or will be trapped in organic and inorganic forms in the pond sediments.

## RACEWAYS

The rainbow trout industry in the state of Idaho is responsible for almost 60% of the total trout production for direct human consumption in the United States (Chew and Toba 1990; Anonymous 1989). Production in Idaho is almost exclusively carried out in raceways with flow-through of high quality spring water. Raceways are often in series, with some form of aeration (and in some cases solids removal) between them, achieving improved water use efficiency over single raceways. Even with this increased efficiency of water utilization, total water use by the industry is very high. A single company with 4 production facilities (Clear Springs Trout Company) used 22.6 $m^3$ $s^{-1}$ of spring water at 15°C and produced 8,200 mt of trout in 1990 (MacMillan 1991). This farm's production constitutes approximately 45% of the total output from the state of Idaho (MacMillan 1991; Chew and Toba 1990).

There is probably more information about nutrition and nutrient use by trout than by any other species. Even with all these data, it is difficult to come up with an industry-wide view of the nutrient output. Feed used is normally very high in protein, and food conversion ratios are relatively low. The corresponding values for the Clear Springs farms are 42% and 1.56 (MacMillan 1991). Using these numbers as indicators for the whole industry, and for a yearly production of 18,000 mt of fish, one can estimate that the total amount of feed applied is 28,080 mt per year, containing 1,900 mt of nitrogen and 280 mt of phosphorus (at an estimated phosphorus content of 1% (Weston 1991)). Of the nitrogen and phosphorus applied in the feed, approximately 360 mt and 72 mt are fixed as fish flesh (Boyd 1991), resulting in a net release of 1,540 mt of nitrogen and 208 mt of phosphorus into the environment. Using concentration increases in effluents from Idaho farms that use settling basins (0.1 mg $L^{-1}$ total N; 0.04 mg $L^{-1}$ total P, the maximum values reported by Brannon, 1991), and from an overall estimate of water used based on Clear Springs Trout Company's use and its proportion of the total production for the state of Idaho ($(1/0.45) \cdot 22.6\ m^3\ s^{-1} = 50.2\ m^3\ s^{-1}$), one can estimate that total nutrients released in the effluents as 158 mt of nitrogen and 63 mt of phosphorus (or approximately 10% of the total nitrogen and 30% of the total phosphorus release into the environment). Most of the nutrients not released in the effluent are contained in the solids removed in settling basins. These solids have been analyzed recently by Olson (1991), who found an average total nitrogen concentration of 4.13 mg $L^{-1}$, a total phosphorus of 2.15 mg $L^{-1}$, and a moisture content of 88%. These solids are currently being used as agricultural fertilizers (MacMillan 1991; Olson 1991), but there are no estimates of the amount of solids produced. Using phosphorus as a basis for calculation and assuming that the difference between the phosphorus not fixed as fish biomass and the phosphorus present in the farm effluents will be present in the solids, one can calculate the volume of sludge produced by the trout industry as 2.14 $m^3$ $s^{-1}$ or just over 4% of the water flow rate.

There is a great deal of uncertainty associated with the figures used to carry out the calculations shown above for the trout industry, and the numbers are meant to serve solely as an illustration. The important point, however, is that nutrients are conservative quantities, and mass balances must be satisfied. All the nitrogen and phosphorus entering a fish farm must leave it as fish biomass, in the water, or as a sludge, or be released to the atmosphere, or accumulate inside the farm. In the particular case of trout farming in raceways, there tends to be minimal transformation or treatment of the nutrients inside the system, especially of phosphorus. As a result, large volumes of relatively low strength wastes (both the water effluent and the sludge from the settling basins) are produced that are difficult and expensive to treat or dispose of.

## INTENSIVE TANK SYSTEMS WITH WATER REUSE

Intensive tank systems with water reuse can have significant impacts on the quantities of water that are used and on the volume of water and solid wastes that are produced from an aquaculture operation. In addition to the reduction in water use achieved by treating and reusing the water, there may be significant changes in the amount of nutrients and of organic matter that are exported from the system as water effluent or solids. Chen and coworkers (1991) discussed the possible effect of biological treatment on the amount of solids produced from an aquaculture operation. They proposed an equation to calculate the solids produced from a system that includes water treatment. The equation takes into account the production of particulate organic matter by microbial action on dissolved organics, as well as the reduction of the particulate organics by endogenous respiration. They also concluded that, although the volume of sludge produced is greater than for other livestock on a unit mass of live weight (beef and dairy cattle, poultry, and swine), the suspended solids and total nitrogen output were lower for fish.

In an aquaculture system that incorporates substantial amounts of water treatment and reuse, the major changes in the waste output will be in the overall concentrations in the water and in the forms in which the wastes exist. Inorganic nitrogen will be present in the water primarily as nitrate, rather than ammonia. If denitrification is included in the water treatment, there will be a reduction in the overall export of nitrogen in the water and solids. The overall mass balance for phosphorus is not likely to change very much with respect to a system without water reuse. The changes will be primarily in the concentrations present in the water and sludge rather than in the total amounts. Overall organic matter output from a system with water reuse is likely to be substantially different from a non-treated system. There will be a reduction in the dissolved organic fraction, and there may be an increase or a decrease in the particulate organic fraction depending on endogenous respiration rates and other factors (Chen et al. 1991).

## STRATEGIES FOR MANAGING THE ENVIRONMENTAL IMPACT OF AQUACULTURAL OPERATIONS

A general statement that can be made from the mass balance equations presented above is that the production of a certain amount of fish results in the release of nutrients, the consumption of oxygen, and the introduction of organic matter into the water. Managing the environrmental impact of aquaculture operations is usually limited to reducing the amount of water used and the amount of nutrients released, or of reducing and controlling the negative effects that nutrients released may have on the environment. These goals may be achieved by selecting sites where nutrients and organic matter released can have minimum negative impact or actually constitute a useful resource, by improving feeds and feeding technologies and reducing the amount of water used, and by treating and concentrating the wastes prior to release from the aquaculture operation (Boyd 1991; Brown 1991).

### SITE SELECTION AND INTEGRATION WITH OTHER ACTIVITIES

Site selection will affect the background concentrations of nutrients, the presence of other environmental "stressors" that may be impacting the overall quality of the ecosystem. Site selection will also affect the "tolerable" levels of nutrient release. The definition of what is tolerable will depend on other uses of the ecosystem, on how those users may affect the quality of the ecosystem, and on the changes in the ecosystem that those users or other interested parties are willing to accep.

Site selection should be taken into account not only for nutrient releases and overall water quality changes, but also for issues such as the possible transmission of diseases. True quarantines are not technically practical or economically feasible in many aquaculture operations.

Aquaculture has been described as a non-consumptive user of water (e.g., MacMillan 1991). The rationale behind this assertion has been that water used in aquaculture is released to the environment while still being of very high quality, and approximately the same amount of water that is taken in by the aquaculture operation is released. An argument that can be made based on the premise of non-consumptiveness is that aquaculture is a benign water user and that effluents from aquaculture operations can be used in agriculture or other industrial applications. Although this may be true in many cases, it is important to consider the overall flow of various substances through aquaculture systems in order to develop a more comprehensive understanding of how aquaculture might impact the environment. In the case of integrating aquaculture with agriculture, one looks at aquaculture effluents as a resource and considers the environmental impact of aquaculture as the combined impact of the aquaculture and associated enterprises.

### INPUT MANAGEMENT

A reduction of nutrient inputs has been shown to be an effective strategy for lowering the amount of nitrogen and phosphorus released into the environment, particularly in Europe (Enell and Ackefors 1992; Beveridge et al. 1991; Brown 1991; Weston 1991), and is being proposed in the United States (e.g., MacMillan, 1991). The research has focused on improving the match between the nutrient requirements of the fish and the nutrient composition of the feed, on improving the physical properties of the feed pellets, and on improving the method of delivering the feed to the fish. A symposium was held recently on this topic, and the readers are referred to the proceedings for further detail (Cowey and Cho 1991).

The European experience proves the effectiveness of feed management in reducing nutrient release into the environment. Success depends not only on results of scientific research, but also on the quality of the ingredients and techniques used for feed preparation and on high quality management of aquaculture operations. The reduction in nutrient inputs may come in the form of improved feeds: lower feed conversion ratios and more efficient utilization of nutrients in the feed (e.g., nitrogen and phosphorus).

### WATER TREATMENT AND REUSE

When water is treated and reused in an aquaculture operation, the total water use and discharge are greatly reduced. The concentration of nutrients in the water discharged tends to be higher than in flow through systems. Of particular importance is the increase in nitrogen (as nitrate). But the major form of disposal of waste products from a system with water reuse may no longer be the water but some form of sludge. The sludge is accumulated in some form of solids removal unit of the reuse system and will include uneaten feed, fecal material, and biological sludge from biofilters (Chen et al. 1991). The nutrient content and overall properties of the sludge depend on how it is accumulated and on how much treatment it undergoes within the system. If the sludge is allowed to remain in the system for long periods of time, substantial amounts of the organic matter may be decomposed and inorganic nitrogen, carbon, and phosphorus will be released into solution. If, on the other hand, the sludge is removed frequently from the system, the organic matter and nutrients will be removed with it.

By having water treatment and reuse, the tendency is to shift from high volume-low strength wastes to relatively low volume-high strength wastes. In addition, the production of a sludge serves to concentrate further the nutrients and organic matter facilitating the treatment to reduce the uncontrolled release of organic matter and nutrients in the effluent. Even in cases in which the concentration of nutrients (such as nitrogen and phosphorus) and organic matter in the water increases as a result of water reuse practices, the reduction in water use results in a net drop in the amount of those substances released in the effluent water.

## SUMMARY AND CONCLUSIONS

Aquaculture, like other livestock rearing enterprises, results in the production of discharges that include substantial amounts of nutrients (nitrogen and phosphorus) and organic matter. Mitigation of the overall negative impacts that aquaculture may have on the environment can be accomplished by a combination of input and output controls on nutrients, organic matter and water use. Continued development of the industry requires that attention be given to improving the efficiency of utilization of the nutrients in the feed and to the fate of the effluent components that may have negative effects on the environment. Farmers have economic incentives for reducing the amount of feed required to produce a kilogram of fish, but those incentives are not necessarily tied to the overall efficiency of nutrient utilization. Farmers in many areas also have strong economic incentives to reduce the amount of water used in their operations. There are, however, few incentives for most farmers to reuse their water or institute water treatment operations that result in the concentration of the wastes from their farms and a reduction in the total amount of nutrients and organic matter that is discharged with the water. There are some notable exceptions to this assertion, such as self-preservation of the industry in estuarine areas where the shrimp industry has caused such a decline in water quality that shrimp production is no longer feasible (Boyd 1991) and self-preservation by meeting regulatory restrictions on nutrients used an/or released into the environment as in various areas in Europe and North America.

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# EFFECT OF WATER EXCHANGE ON THE GROWTH OF THE RED-TIDE DINOFLAGELLATE *GYMNODINIUM NAGASAKIENSE* IN AN INLET OF GOKASHO BAY, JAPAN

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## ABSTRACT

We investigated the seasonal changes in water exchange and annual cycles of the motile cells of the noxious dinoflagellate *Gymnodinium nagasakiense* from January 1989 to September 1990 in an inlet (Hazama-Ura) of Gokasho Bay in central Japan. We examined the effect of water exchange on the growth of this organism. Using a reservoir model, we analyzed the salinity budget and calculated the residence time of the inlet. The residence time ranged from 1.6 to 11.1 days and was negatively correlated with precipitation. The density of *G. nagasakiense* cells was high when the residence time was long. We calculated the population dynamics of *G. nagasakiense* under the following assumptions: 1) the growth of this organism is influenced only by temperature and salinity, and the relationship between these factors follows Yamaguchi and Honjo's formula,; and 2) the washout of the cells from the inlet is due entirely to physical displacement by water exchange, and the water exchange rate is the reciprocal of the residence time obtained by the reservoir model. Since both in 1989 and 1990 *in situ* cell densities decreased abruptly in September, we selected the *in situ* cell density on the earliest observation day in September as the starting point for the calculations. We found that the seasonal changes of cell density calculated theoretically using these assumptions approximated those occurring *in situ*.

## 1. INTRODUCTION

The dinophyte *Gymnodinium nagasakiense* Takayama et Adachi is one of several species of flagellates causing noxious red tides in the coastal waters of western Japan (Matsuoka et al. 1989) and southern Korea (Kim 1989, Park 1991). The total damage caused by *G. nagasakiense* red tides over a 16-year period (1972–1987) in the Seto Inland Sea and Kumano-Nada areas, including Gokasho Bay, amounted to about 5.2 billion yen. Most of this damage was to fish culture operations. Mortalities of yellowtail, red sea bream, and pearl oysters were recorded for the above areas. There is an urgent need for elucidation of the causative mechanisms of these red tides to reduce the tremendous economic damage.

Recently, Yamaguchi and Honjo (1989) reported on the effects of temperature, salinity, and irradiance on the growth of *G. nagasakiense*. Furthermore, Honjo et al. (1990) described the annual cycle of motile cells of this organism and estimated *in situ* growth rates during the period of development of summer red tides in Gokasho Bay from 1984 to 1987. However, these growth rates, ranging from 0.32 to 0.47 divisions/day, were considerably lower than the maximum growth rate (1.0 divisions/day) estimated from *in vitro* studies (Iizuka 1979, Iizuka and Mine 1983). The discrepancy between *in situ* and *in vitro* growth rates must be attributed to loss processes such as washout and sedimentation, grazing, and pathogenic or physiological death. Of these loss processes affecting the abundance of phytoplankton, the physical displacement of cells by water exchange (washout) may play an important role in the sea.

In this paper, we investigated the seasonal changes in water exchange and annual cycles of the motile cells of *G. nagasakiense* from January 1989 to September 1990 in an inlet (Hazama-Ura) of Gokasho Bay in central Japan. We examined the effect of water exchange on the growth of this organism. Using a reservoir model, we analyzed the salinity budget and calculated the washout rate and residence time of the inlet. Then we compared the washout rate with theoretical growth rate calculated from Yamaguchi and Honjo's formula (1989). Finally, we calculated the theoretical changes in the *G. nagasakiense* population and compared them with changes occurring *in situ.*

## 2. ECOLOGICAL AND PHYSIOLOGICAL FEATURES OF *G. NAGASAKIENSE*

In the daytime, *G. nagasakiense* cells maintain themselves in the middle layer (5–10 m depth) when cell densities are low and in the upper layer (0–2 m depth) when cell densities are high (Honjo et al. 1990). They make diurnal vertical migrations at a speed of about 1.3 m/hr, and they can migrate about 8 m downward in 6 hours (Honjo et al. 1990). The mean depth of Hazama-Ura Inlet is 10.4 m and the maximum depth is 18 m. Therefore, during the night-time most *G. nagasakiense* cells pass through the bottom waters containing fairly high concentrations of ammonia, nitrate, and phosphate (Honjo et al. 1990). Cells can also reach the bottom mud that is extremely rich in nutrients and contains growth-promoting substances (Hirayama and Numaguchi 1972), although cells stay there only for a short time.

Yamaguchi and Honjo (1989) investigated the effects of temperature and salinity on the growth of *G. nagasakiense* and showed that this organism is a eurythermal and euryhaline phytoplankter. They characterized the growth rate of *G. nagasakiense* ($\mu$, divisions/day) by the formula

$$\mu=1.05753-0.3022T+0.01777T^2-0.00035T^3+0.00515TS-0.0001TS^2, \quad (1)$$

where T is the temperature and S is the salinity. The exponential growth rate (k, 1/day) is given by

$$k=\mu \ln 2=0.693\,\mu. \quad (2)$$

Here, ln represents the natural logarithm.

We collected water samples every week at five depths (0, 2, 5, 10, and 15 m) at Stn. A (Figure 1) and counted the number of motile cells of *G. nagasakiense* one day after

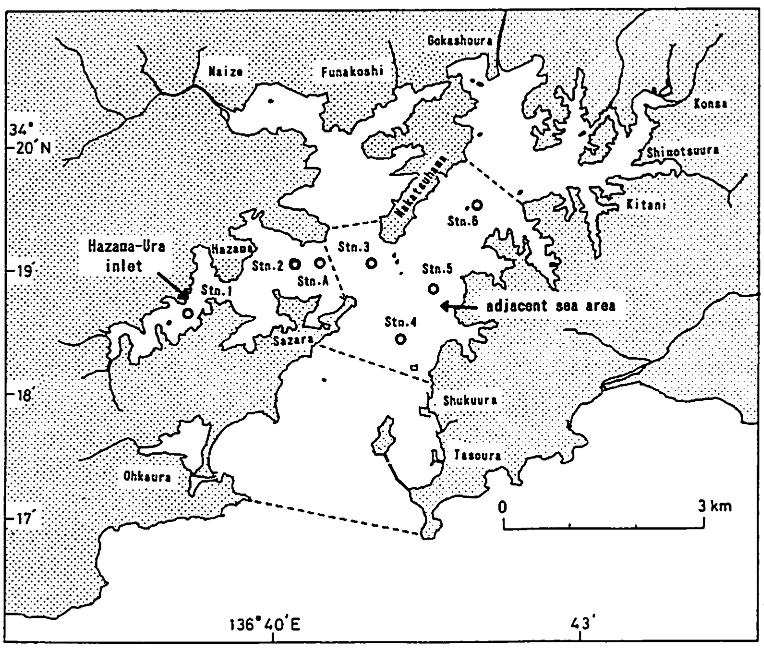


Figure 1. Sampling stations in Hazama-Ura Inlet and adjacent sea area in Gokasho Bay. The number of motile cells of *G. nagasakiense* was monitored at Stn. A. At Stations 1 to 6, the vertical distributions of temperature and salinity were observed.

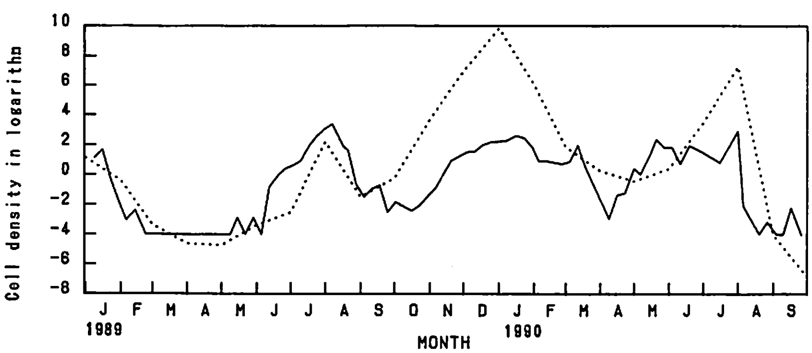


Figure 2. *In situ* changes in abundance of motile cells of *G. nagasakiense* (solid line) and theoretical changes calculated by the one-reservoir model (dotted line) from 1989 to 1990. *In situ* cell densities are expressed as $\log(n+10^{-4})$ and theoretical densities as $\log(n)$, where n equals the cell density (cells/ml).

sampling because the samples were transported from Gokasho Bay to the Nansei National Fisheries Research Institute in Hiroshima. When the cell densities were less than 10 cells/ml, we concentrated the plankton in the samples from the five depths (total 2.5 l) and then *G. nagasakiense* cells were counted.

Figure 2 shows the changes in the abundance of motile cells of *G. nagasakiense* in Hazama-Ura Inlet over the observed period. The population densities showed bimodal patterns with peaks in the summer and winter. Cells were not observed in the 2.5-l samples during the late winter to early spring in 1989.

## 3. SEASONAL CHANGES OF WATER EXCHANGE IN HAZAMA-URA INLET

### RESERVOIR MODEL

We considered water exchange between an inlet and an adjacent sea area using a one-reservoir model (Figure 3). The water in the inlet is assumed to be perfectly mixed. The budgets of water mass and salinity are as follows:

$$Q_{10}=Q_{01}+F_r \qquad (3)$$

and

$$V_1 dC_1/dt=C_0Q_{01}-C_1Q_{10}. \qquad (4)$$

Here, $C_1$ is the salinity in the inlet, $C_0$ the salinity in the adjacent sea area, $V_1$ the volume of the inlet, $F_r$ the fresh water inflow into the inlet, $Q_{01}$ the transfer coefficient, that is the flux of water from the adjacent sea area into the inlet, and $Q_{10}$ the transfer coefficient in the opposite direction. If the salinity $C_0$ and $C_1$ are observed at an interval dt, and water inflow $F_r$ is estimated from meteorological data, then we can estimate these transfer coefficients by

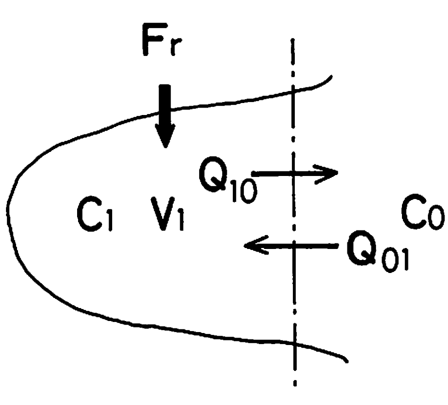


Figure 3. Schematic presentation of the one-reservoir model. Refer to the text for the meaning of the symbols.

$$Q_{10}=(V_1dC_1/dt+C_0F_r)/(C_0-C_1) \qquad (5)$$

and

$$Q_{01}=Q_{10}-F_r. \qquad (6)$$

The dimension of the transfer coefficient is volume per time, and

$$T=V/Q_{10} \qquad (7)$$

is called the residence time, which denotes the average time the fluid element spends in the inlet before being removed to the adjacent sea area. Further, the reciprocal of the residence time, 1/T, is the ratio of water flux from the inlet into the adjacent sea area to the volume of the inlet. In this paper we call it the water exchange rate or the washout rate.

### SEASONAL CHANGES OF WATER EXCHANGE IN HAZAMA-URA INLET

Using an STD, we measured temperature and salinity once a month from January 1989 to September 1990 at fixed stations and depths in Hazama-Ura Inlet and in the adjacent sea area (Figure 1).

$C_0$ and $C_1$ in Eq. (5) were estimated from the observed distributions of salinity by calculating the average weighted with the volume occupied by stations in each reservoir (Figure 4). Similarly, weighted average temperatures in the inlet and in the adjacent sea area were calculated (Figure 5). Mean salinities were high in the winter and low in the summer, and the difference in salinity between the inlet and the adjacent sea area was greater when the mean salinity was low. Mean temperatures ranged from 12°C to 26°C over the observed period, and the winter temperatures were higher in 1990 than in 1989.

Using meteorological data, we estimated the fresh water supply Fr in Eq. (5) by the following equations:

$$F_r=R+P+E, \qquad (8)$$

$$R=1000\,rfA, \qquad (9)$$

$$P=1000\,rB, \text{ and} \qquad (10)$$

$$E=5.417\,W\,(e_w-e_a)B. \qquad (11)$$

Here, R is the river discharge ($m^3$/hr), P the net precipitation on the bay surface ($m^3$/hr), E the fresh water loss by evaporation ($m^3$/hr), r precipitation (mm/hr), f run-off rate (0.64), A the area of the drainage basin ($km^2$), B the surface area of the bay ($km^2$), W wind speed (m/sec), $e_w$ the saturated vapor pressure (mb), and $e_a$ vapor pressure (mb).

Figure 6 shows the temporal variations in residence time estimated by Eqs. (5) and (7). The residence time ranged from 1.6 to 11.1 days. In both 1989 and 1990 it

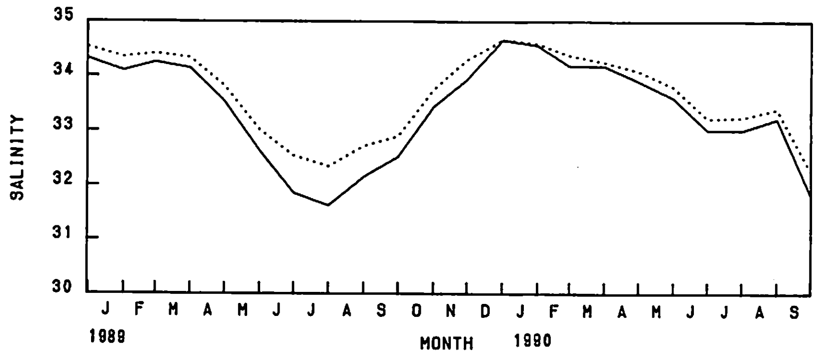


Figure 4. Monthly mean salinity in Hazama-Ura Inlet (solid line) and in the adjacent sea area (dotted line) from 1989 to 1990.

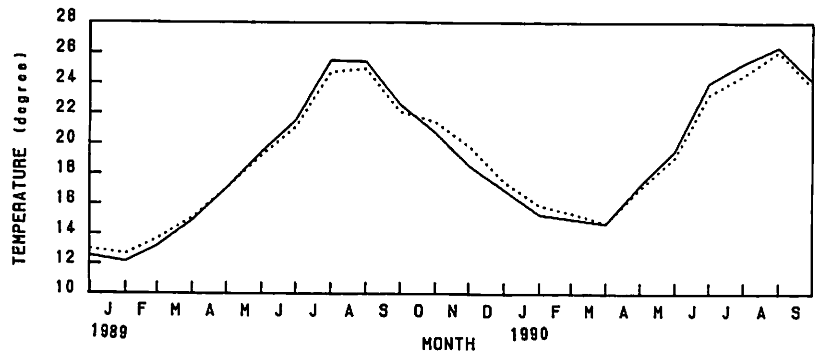


Figure 5. Monthly mean water temperature in Hazama-Ura Inlet (solid line) and in the adjacent sea area (dotted line) from 1989 to 1990.

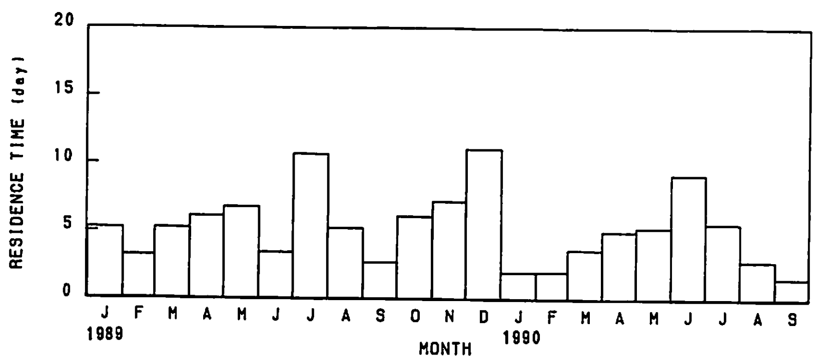


Figure 6. Monthly change in residence time estimated by the one-reservoir model from 1989 to 1990.

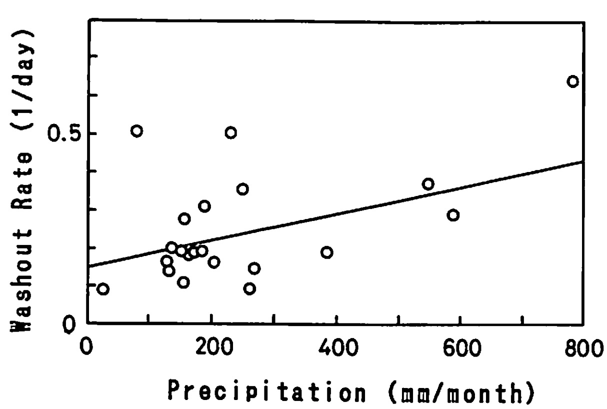


Figure 7. Relationship between precipitation (mm/month) and the water exchange rate, 1/T (1/day).

was low during September. Toda et al. (1990) analyzed the water exchange in Gokasho Bay and its branch inlets, including Hazama-Ura Inlet, and showed that the residence time of Hazama-Ura Inlet was much longer than those of the other inlets due to its smaller discharge. Abo et al.(1992) studied the fluctuations of current in the upper, middle, and lower layers at Stn. 2 (Figure 1) from May to July 1991. They showed that the currents were strongly affected by wind and fresh water inflow. The water exchange rate, 1/T (1/day), is plotted against precipitation (mm/month) in Figure 7. This figure demonstrates that the supply of fresh water is a major factor in controlling the water exchange in Hazama-Ura Inlet.

## 4. POPULATION DYNAMICS OF *G. NAGASAKIENSE*

We consider here the population dynamics of *G. nagasakiense*. As in the case of the salinity budget, we assume that the water in the inlet is perfectly mixed. The growth rate of *G. nagasakiense*, k, is assumed to be influenced only by temperature and salinity and is expressed by Eqs. (1) and (2). By substituting the density of *G. nagasakiense* cells for salinity in Eq. (4), and by adding the growth term, we get

$$V_I dp_I/dt = p_O Q_{OI} - p_I Q_{IO} + kV_I p_I. \quad (12)$$

Here, $p_I$ is the density of *G. nagasakiense* cells in Hazama-Ura Inlet, and $p_O$ is that in the adjacent sea area. We further assume that $p_O$ is zero. Dividing Eq. (12) by $V_I$ and using Eq. (7), we get

$$dp_I/dt = (k - 1/T)p_I. \quad (13)$$

If k and T are independent of time, the solution of Eq. (13), which applies the initial condition $p_I = p_I(0)$ at $t=0$, is

$$\log p_I(t) = \log p_I(0) + (k - 1/T)(\log e)\, t. \quad (14)$$

Here, log means the common logarithm. Eq. (14) shows that the logarithm of population density increases or decreases linearly with time at a slope of $(k-1/T)\log e$, and that, if we know the initial density $p_I(0)$, we can predict the population density $p_I(t)$.

Because our estimation of the water exchange rate (1/T) was obtained at monthly intervals, we assumed k and 1/T were constant for a month and applied Eq. (14) to calculate the population dynamics of *G. nagasakiense*. Figure 8 shows the monthly changes of k and 1/T. The growth rate calculated by Eqs. (1) and (2) using the mean salinity and mean temperature in Figures 4 and 5 showed a sinusoidal annual change ranging from 0.07 to 0.49/day, which corresponded to 0.10 to 0.71 divisions/day. The washout rate, 1/T, ranged from 0.09 to 0.65/day and was comparable to the growth rate, k. Using these parameters, we calculated the population dynamics of *G. nagasakiense*. The *in situ* population density on January 9, 1989, was used as the initial condition. Preliminary calculations over the observed period showed that the population density curve increased gradually with seasonal fluctuations and reached an excessive cell density ($10^{16}$ cells/ml) at the end of the calculations. Perhaps this occurred because the errors in estimating the parameters were accumulated over the calculated period. Both in 1989 and 1990, the *in situ* cell density decreased more abruptly in late August-early September than expected from Figure 8. Hence, we selected the *in situ* cell density on the earliest observation day in September as the starting and ending point for the calculations. The dotted line in Figure 2 shows the cell density calculated in this way as compared with *in situ* cell density. The seasonal changes in cell density calculated theoretically using these assumptions approximated those occurring *in situ*, suggesting that the washout by water exchange is one of the main factors regulating the growth of *G. nagasakiense in situ*.

## 5. CONCLUSIONS

We examined the effect of water exchange on the *in situ* growth of *G. nagasakiense* in Hazama-Ura Inlet. The washout rate was comparable to the growth rate. The seasonal changes in cell density calculated theoretically using a reservoir model approximated those occurring *in situ*. Hence, it is concluded that water exchange is one of the main factors regulating the growth of *G. nagasakiense* in this inlet.

These results are only a preliminary approximation because the model employed is simple and the intervals for estimating water exchange are long compared with the intervals for monitoring cell density. However, these results suggest strongly that the occurrence of this red tide is regulated by physical factors. The pycnocline was formed in the middle layer of the inlet during the summer. Furthermore, the layer inhabited by *G. nagasakiense* changed according to the cell densities. Considering these facts, more detailed interdisciplinary work on water exchange and biological events should be conducted in the future.

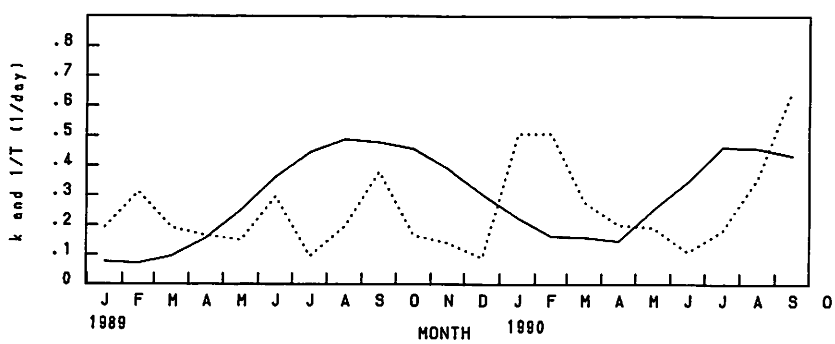


Figure 8. Monthly changes in estimated growth rate (solid line) and the water exchange rate, 1/T (dotted line).

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# WATER TREATMENT AND WASTEWATER GENERATION IN INTENSIVE RECIRCULATING FISH PRODUCTION SYSTEMS

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## ABSTRACT

The Aquaculture Research and Extension Program at North Carolina State University is evaluating components for use in water treatment in intensive recirculating fish production systems. Two different systems are currently under evaluation within the program. System #1 consists of an in-tank solids settling process with suspended solids removal being performed by an up-flow plastic bead filter. The effluent from the bead filter passes to and through a down-flow fluidized bed bead filter for ammonia-nitrogen nitrification. System #2 also employs in-tank settling and a bead filter; however, the primary nitrification occurs in a rotating biological contactor (also in series) prior to re-entry into the culture tank. Fine and dissolved solids in both systems are removed with counter-current (air-lift-driven) foam fractionation units. Wastewater is discharged from four points in System #1 and three points in System #2 at various times during daily operations. Waste volume and characteristics were monitored in each system, once a week for 4 weeks. The data generated in this study indicates that, by themselves, recirculating systems are not environmentally "friendly." Recirculating systems produce a high-strength, low-volume waste effluent that is more easily managed and treated than those from most conventional aquaculture production systems. Removal of particulate solids and treatment of dissolved nitrates and phosphorus is imperative before discharge to adjacent natural waterways.

## INTRODUCTION

Recirculating aquaculture systems have been the focus of scientific and commercial research and development for decades. Primarily, interest in these systems has grown out of limitations on water supplies, suitable land for traditional aquaculture ponds, and a growing concern for the environmental impact of effluents from traditional production systems. The Aquaculture Research and Extension Program at North Carolina State University has developed a facility to evaluate and demonstrate water reuse technology for use in tank based finfish production systems. The program is centered on a near commercial scale fish production demonstration system housed within a 200 $m^2$ (2,160 $ft^2$) metal clad barn. Referred to as the "North Carolina Fish Barn," the facility is currently configured to produce approximately 1,133 to 1,360 kilograms (kg) (2,500–3,000 lbs) per month of tilapia hybrids (*O. niloticaX O. aurea*). This paper describes the water treatment systems being evaluated, reviews the results of a preliminary study of the water quality maintained in the culture tanks and the characteristics of the wastewater generated by each system, and discusses their environmental impact and potential waste treatment options.

## WATER QUALITY MAINTENANCE

The economic viability of recirculating systems is largely dependent on maintaining non-stressful culture conditions for the aquatic crop. Critical water quality parameters controlling stress include the concentrations of dissolved oxygen, unionized ammonia-nitrogen, nitrite-nitrogen, pH, alkalinity and carbon dioxide. Producing fish in a cost effective manner requires that these water quality variables be controlled during periods of rapid fish growth. To provide for rapid growth, fish must be fed appropriately large quantities of high protein pelleted diets. Feeding rate, feed composition, fish metabolic rate and the quantity of wasted feed have a detrimental impact on the culture tank water quality. The by-products of fish metabolism include carbon dioxide, ammonia-nitrogen, and fecal solids. If uneaten feeds and metabolic by-products are left within the culture system, they will generate additional carbon dioxide and ammonia-nitrogen, reduce the oxygen content of the water and have a direct detrimental impact on the health of the cultured product. Recirculating systems must be designed and operated to effectively "remove" waste and metabolites from the system to maintain an optimum culture environment. Growth reductions and increased incidence of disease can result from stress due to poor water quality. The intensity of maintenance of environmental conditions within the culture tank is dependent upon the requirements of the species being cultured.

A key to successful recirculating production systems is the use of cost effective water treatment technologies. All recirculating production systems utilize processes to remove waste solids, oxidize ammonia and nitrite-nitrogen, and aerate and/or oxygenate the water (Figure 1). The following is a description of the water treatment processes being currently evaluated at the North Carolina Fish Barn.

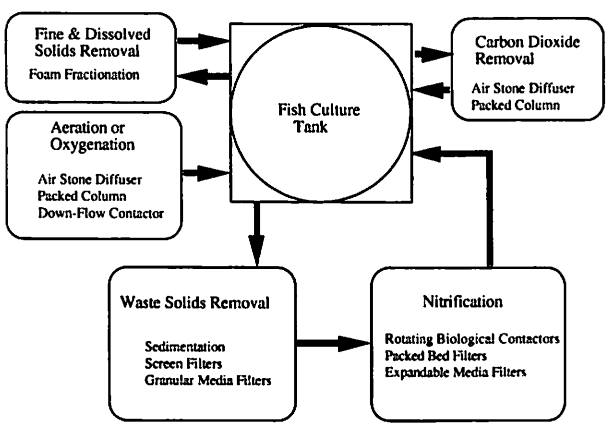


Figure 1. Required unit processes and typical components used in recirculating aquaculture production systems (after Losordo et al. 1992).

## SYSTEMS DESCRIPTION

The North Carolina Fish Barn is located on the Campus of North Carolina State University in Raleigh, NC. The finfish grow-out system consists of four 4.4 m (14.5 ft) diameter, 1.52 m (5 ft) deep fiberglass culture tanks (Hulls Unlimited-East, Inc., Deltaville Va.). The bottom of each tank slopes by 0.25 m (10″) to a center cone that is 0.96 m (38″) in diameter and an additional 0.61 m (24″) deep (Figure 2). The center cone has a 0.076 m (3″) inside diameter fitting leading to a waste drain. The tank's center cones are used for collecting and concentrating settleable waste solids.

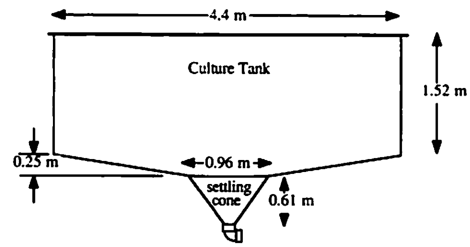


Figure 2. Side view and dimensions of the fish culture tank with in-tank settling cone.

Each tank is equipped with an individual suspended solids filter, biological filter, foam fractionator, and oxygenation system. The foam fractionators (Figure 3), used for fine and dissolved solids removal, are an air-lift driven counter current design (Aquatic EcoSystems, Inc. Apopka, FL, Model FMS-8) placed within each culture tank.

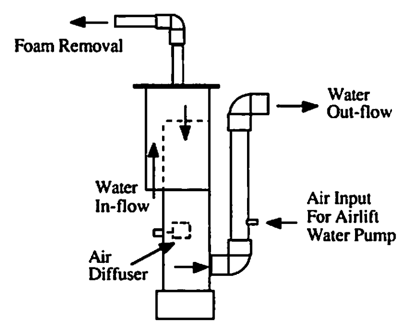


Figure 3. Foam fractionator used for fine and dissolved solids removal.

Oxygen is added to each tank in a side-stream through a down-flow bubble contactor oxygen saturator (Aquatic EcoSystems, Inc., Model OY-75) (Figure 4). The water is pumped by a 3/4 hp centrifugal pump at a rate of approximately 303 liter per minute (80 gpm).

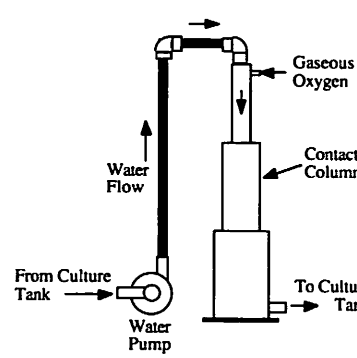


Figure 4. Down flow bubble contact oxygen saturator.

The suspended solids removal process is accomplished by low density floating plastic bead filters as described by Malone and Coffin (1992) that remove particulate solids from the water column and provide for some nitrification. The bead filters (Armant Aquaculture, Inc., Vachrie Louisiana, model PBF-10) each contain approximately 0.28 $m^3$ (10 $ft^3$) of 3 mm diameter plastic beads (Figure 5). The plastic beads have a specific surface area of 1,148 $m^2/m^3$ (350 $ft^2/ft^3$) providing the filter unit a total theoretical bead surface area of 321 $m^2$ (3,500 $ft^2$). Water from the mid-depth in each culture tank is pumped at approximately 379 L/min. (100 gpm) to the bead filter. As the water passed upward through the floating bead bed, suspended solids were removed and some nitrification occurs.

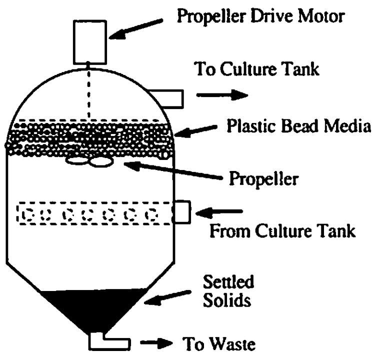


Figure 5. Low density plastic floating bead filter for suspended solids removal and nitrification (U.S. Patent #5126042).

The water treatment components of the two systems differ in the nitrification components that follow, in series, after the up-flow bead filters.

System #1

In System #1, the bead filter effluent flows to a down-flow fluidized bed bead filter for reduction of ammonia and nitrite-nitrogen by biological nitrification (Figure 6). The filter is a prototype unit developed by Waterline, Inc. of Prince Edward Island, Canada.

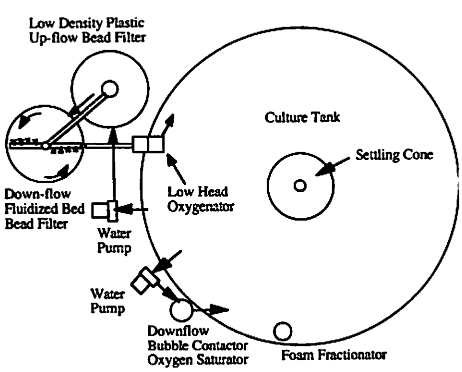


Figure 6. Fish culture system #1 with up-flow bead filter and down-flow fluidized bed bead filter.

Water is distributed at the top of the filter through a rotating perforated distribution pipe.

The filter (Figure 7) contains approximately 0.34 $m^3$ (12 $ft^3$) of flattened plastic beads (4 mm dia.$\times$2 mm thick) that have a specific surface area of approximately 1500 $m^2/m^3$ (450 $ft^2/ft^3$). The flow rate is just high enough (approximately 340 lpm) to create a downward velocity that slightly fluidizes the bed of low density plastic beads. The water, fine solids (not removed by the up-flow bead filter) and sloughed-off nitrifying bacterial solids move through the bead bed towards the bottom of the reactor. While the water velocity is great enough to fluidized the beads, the flow characteristics at the bottom of the reactor are quiescent enough to allow the solids to settle in a conical bottom. The clarified effluent exits the reactor from a standpipe, with vertical openings, above the conical bottom. The standpipe is fitted with an inverted cone to prevent beads from being entrained in the effluent stream.

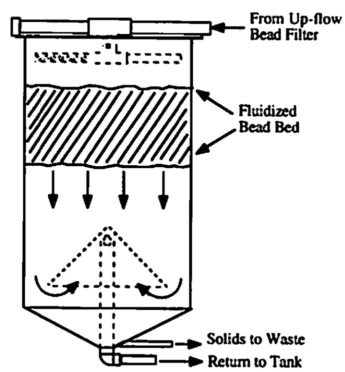


Figure 7. Down-flow fluidized bed bead filter.

The effluent from the fluidized bed bead filter flows through a low head oxygenator (Zeigler Bros., Inc, Gardners, PA, Product #923820) before returning to the culture tank. Oxygen is also injected into the flow-stream just prior to entering the up-flow bead filter.

System #2

In System #2 (Figure 8), the bead filter effluent flows to a rotating biological contactor (RBC) unit for reduction of ammonia and nitrite-nitrogen by biological nitrification. The RBC is a custom unit designed at North Carolina State University and fabricated by Hulls Unlimited-East, Inc., Deltaville, VA (Figure 9). The RBC has two contactor stages. Each stage is 112 cm (44″) in diameter and 91.4 cm (36″) long. The contactor stages are formed from bundles of extruded tubular plastic media similar to "hair curlers" (NSW Corp., Roanoke, VA.). The tubular media are 5.08 cm (2″) diameter tubes with concentric 2.54 cm (1″) tubes placed inside each larger tube. Each bundled media stage has approximately 209 $m^2$ (2,250 $ft^2$) of surface area providing a total surface area for the attachment of nitrifying bacteria of approximately 418 $m^2$ (4,500 $ft^2$). The RBC media stages are submerged in culture water TO approximately 40% of their diameter and rotate at 3 revolutions per minute (rpm).

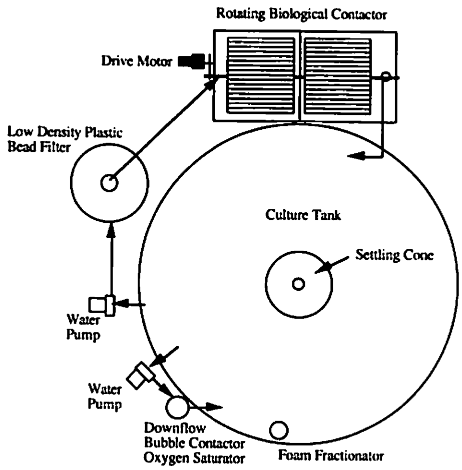


Figure 8. Fish culture system #2 with floating bead filter and rotating biological contactor.

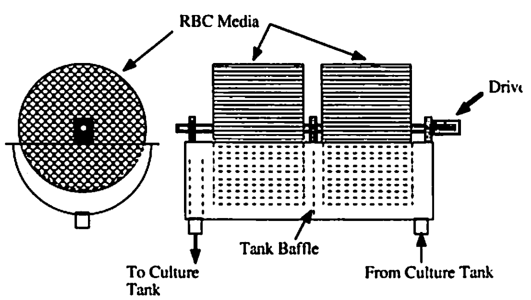


Figure 9. Rotating biological contactor used in the North Carolina Fish Barn.

## SYSTEM MAINTENANCE

Each system has a maintenance routine that has been developed to clean filter components and discharge waste from the system. The routines are identical for each system except for the additional step of removing waste solids from the bottom of the down-flow fluidized bed bead filter in System #1. The maintenance routine for both systems is as follows.

### Up-flow Bead Filter

The up-flow bead filters were designed to facilitate automation in their back-washing sequence. We have chosen to manually backwash the filters in the North Carolina facility to allow the operator to oversee the procedure. The up-flow bead filters are back-washed 3 times during an 8 hour working day (08:00, 12:00 and 16:30). The procedure starts by switching the water pumps off. If oxygen is being added to the influent stream of the filter, this too is discontinued. A propeller, mounted within the bead bed is activated by switching on the drive motor for 45 seconds. The propeller churns the beads and shears the excess biological floc and waste solids from the filter bed. Following completion of the bead agitation operation, a 5 minute settling period is allowed during which time the beads refloat and the waste solids settle to the conical bottom of the filter. The settled solids, in approximately 95 liters (25 gallons) of water, are drained to a wastewater discharge line.

### In-tank Settling Cones

Settleable solids are continuously deposited into the cone within each tank. Twice a day at 08:00 and 16:30 hours, a 7.62 cm diameter valve is opened for 30–60 seconds and the accumulated waste solids are discharged to a wastewater drain line. The total wastewater volume discharged during this operation is between 95–280 liters.

### Foam Fractionation Units

Both systems have an air-driven foam fractionation unit. These components create and discharge foam laden with fine and dissolved solids when the surface tension of the culture water is high enough. This process is ongoing almost continuously although the highest discharge rates occur during periods when no fish feed is being added to the culture tank. The foam from these units fall into a container where it condenses to liquid and is disposed of when the 114 liter container is full.

### Down-flow Bead Filter

System #1 has one additional waste stream. The solids that collect at the bottom of the down-flow fluidized bed filter (Figure 7) are drained to a wastewater line twice daily on the same schedule described above for wasting solids from the tank settling cones. A waste volume of 19 liters (5 gallons) per filter is discharged each time the solids are removed from the filters.

## MATERIALS AND METHODS

### SYSTEMS OPERATIONS

During the time that this preliminary study was conducted, only one culture tank with each filter system design was operational. Each culture tank was stocked with approximately 5,250 juvenile tilapia. The populations were a mixture of pure line tilapia (*O. nilotica*) and tilapia hybrids (*O. nilotica* × *O. aurea*). At the beginning of the study, the fish in Systems #1 and 2 had average weights of approximately 142 grams and 98 grams respectively. At the end of the study, the fish averaged approximately 218 grams and 201 grams respectively. Daily feed input rates (Purina #5133, 36% protein) were held as constant as possible for the 3 to 6 days prior to the sampling dates. Because the systems were being operated intensively to approximate conditions in commercial production, some abrupt feed rate changes were required when water quality problems arose.

### WATER AND WASTEWATER SAMPLING

The water quality in each culture tank and the wastewater from each discharge point were monitored on a weekly basis for 4 weeks. During the routine maintenance operations described above, the total waste flow from each operation was captured in a container. For each operation, the volume was measured and a sub-sample was taken and refrigerated at 4°C. For maintenance procedures that occurred twice daily, sub-sample of 500 ml were combined into a mixed "integrated" 1 liter sample. For the maintenance procedures that occurred 3 times daily the sub-samples were 333 ml. The mixed samples were refrigerated overnight and analyzed the following morning.

### WATER AND WASTEWATER ANALYSIS

Samples were analyzed for total solids (TS), volatile solids (VS), and suspended solids (SS) using methods as described in Standard Methods for the Examination of Water and Wastewater Analysis (American Public Health Association (APHA) 1989). Samples were analyzed by automated analysis for the following parameters: total ammoniacal nitrogen (TAN, $NH_3$–N+$NH_4$–N) by the salicylate-hypocholite method (Technicon 1974); total oxidized nitrogen ($NO_2$–N+$NO_3$–N) by the cadmium reduction method (APHA 1989); nitrite nitrogen ($NO_2$–N) by the colorometric method (APHA 1989); orthophosphate phosphorus ($PO_4$) by the automated ascorbic acid method (APHA 1989); total Kjeldahl nitrogen (TKN) and total phosphorus (TP) by persulfate digestion (APHA 1989) and subsequent automated analysis of the $NH_4$–N and $PO_4$ by methods stated previously; chloride (Cl) by the ferricyanide method (APHA 1989); and chemical oxygen demand (COD) by potassium dichromate-sulfuric acid digestion and colorimetric analysis (U.S. EPA 1979). Total organic carbon (TOC) was analyzed by the combustion-infrared method (APHA 1989). Analysis for sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu) and zinc (Zn) were by atomic emission or absorption spectrophotometry after wet digestion with nitric acid (U.S. EPA 1979). pH was determined using a Accumet Model 915 pH meter.

## RESULTS

Daily feed rates for the duration of the study are graphed in Figure 10. The volume of wastewater from the settling cones and up-flow bead filter back-washing routine can be found in Figure 11. The major water and wastewater characteristics for the study are graphed in Figures 12–23.

### CULTURE TANK WATER QUALITY

In general, water quality within both culture systems remained excellent during the study, with actively feeding fish and no mortalities. However, in System #1, the TAN concentration increased to undesirable levels for a short period during week three (Figure 12, sample date 10/26/92). Although the TAN concentration was relatively high, the concentration of un-ionized ammonia-nitrogen ($NH_3$) was extremely low due to a low pH. The TAN "spike" was due to reduced metabolic activity by the nitrifying organisms in the biological filters. This was most likely the result of the low pH ($<6.8$), a condition which has been shown to reduce the activity of nitrifying bacteria. The low pH was due to an increase in the $CO_2$ level within the culture system ($>75$ mg/l). The build up of carbon dioxide is a serious design problem in systems using submerged media biological filters. While it is most desirable to oxygenate, with pure oxygen, the flow-stream returning from the filters to the culture tank, $CO_2$ can build up within the system if some mechanism for degassing this flow-stream is not provided. This condition is not a problem in systems using non-submerged nitrifying filters such as the RBC in System #2. RBC's and non-flooded trickling nitrifying filters gain oxygen from the air and discharge $CO_2$ as the water moves over the filter media. The $CO_2$ concentration in System #2 never exceeded 25 mg/l, yielding a higher and more constant pH and TAN concentration (Figure 13, $<2.0$ mg/l).

The suspended solids concentration within both systems were extremely low (Figures 12 and 13). Although the concentration tended to increase with increased daily feed rate, the up-flow bead filters provided for excellent water clarity. As in most recirculating systems, utilizing low daily water exchange rates, the nitrate-nitrogen concentrations in both systems were very high (Figures 14 and 15). No adverse effects on the fish were noted. The chemical oxygen demand (COD) was also high. Most likely this is a reflection of a build-up of dissolved organic matter within the system's water. Malone (personal communication, R. F. Malone, Department of Civil Engineering, Louisiana

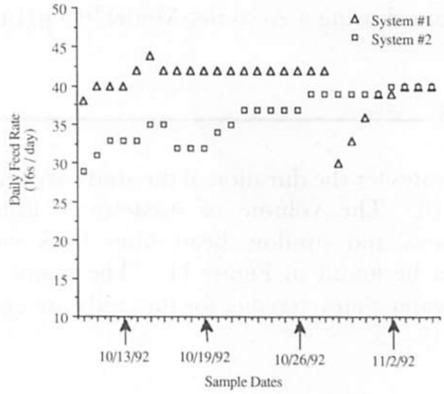


Figure 10. Daily feed rates for systems #1 and 2.

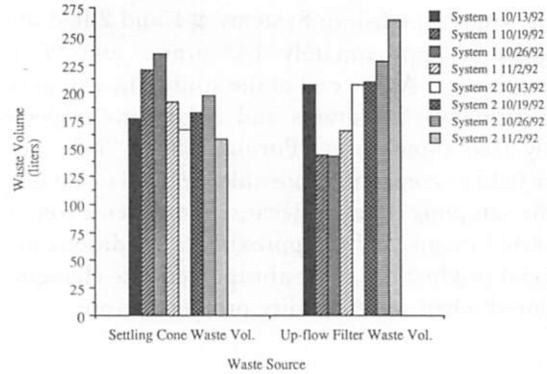


Figure 11. Systems #1 and 2 daily waste volumes.

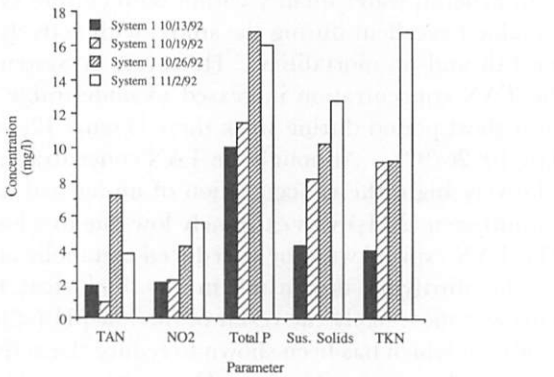


Figure 12. System #1 culture tank water quality analysis results.

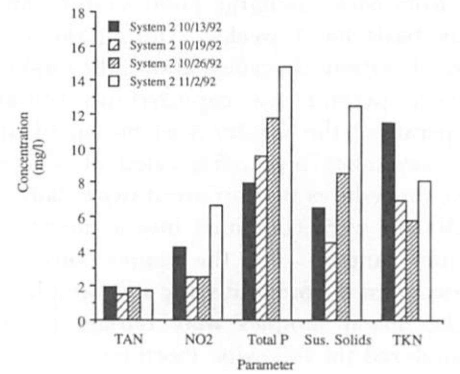


Figure 13. System #2 culture tank water quality analysis results.

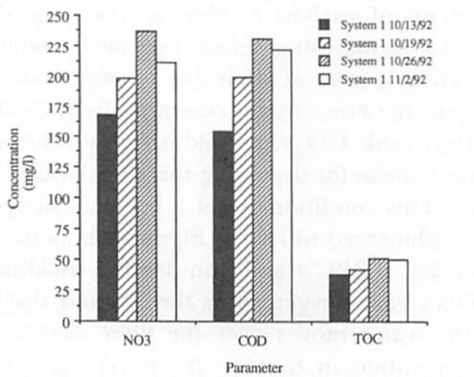


Figure 14. System #1 culture tank water quality analysis results continued.

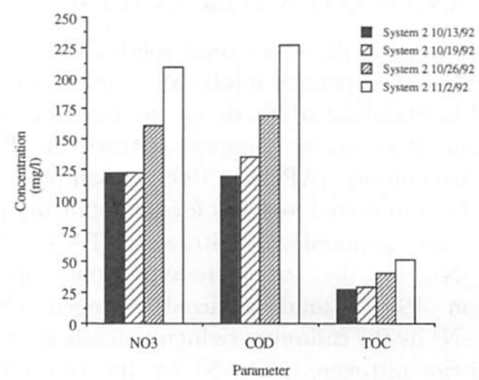


Figure 15. System #2 culture tank water quality analysis results continued.

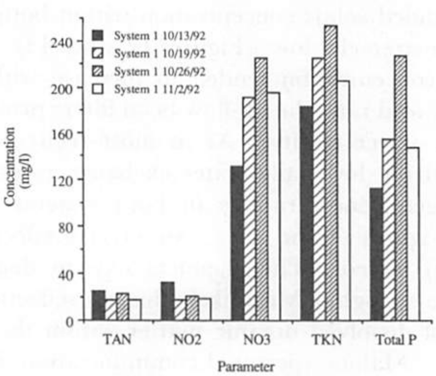


Figure 16. System #1 settling cone waste nitrogen and phosphorous analysis results.

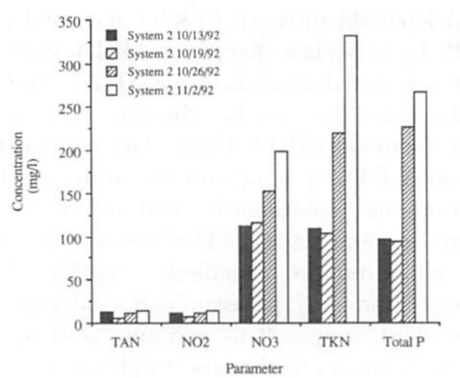


Figure 17. System #2 settling cone waste nitrogen and phosphorous analysis results.

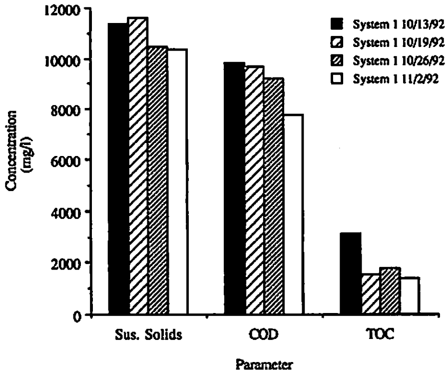


Figure 18. System #1 settling cone organic waste analysis results.

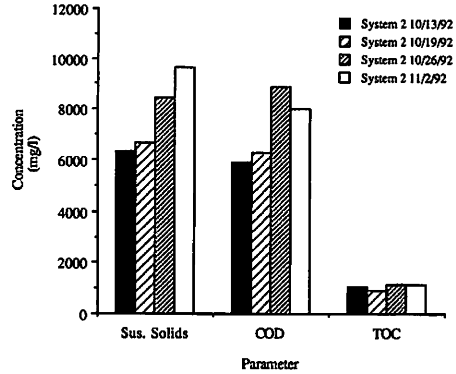


Figure 19. System #2 settling cone organic waste analysis results.

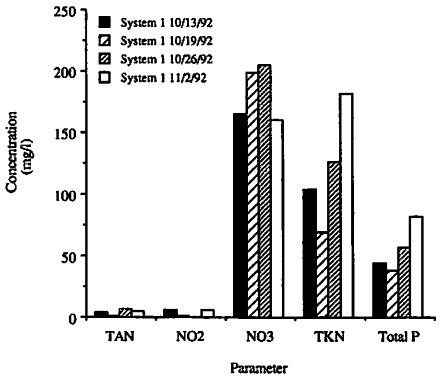


Figure 20. System #1 up-flow bead filter back-flushing waste nitrogen and phosphorus analysis results.

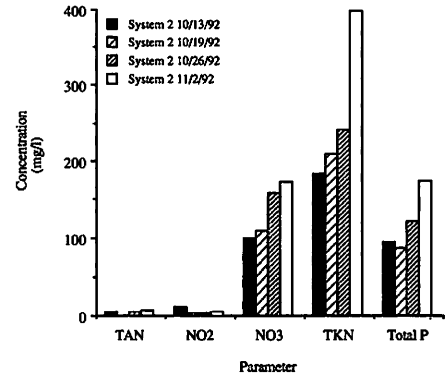


Figure 21. System #2 up-flow bead filter back-flushing waste nitrogen and phosphorus analysis results.

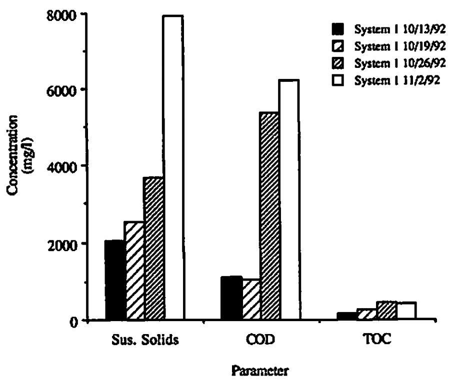


Figure 22. System #1 up-flow bead filter back-flushing organic waste analysis results.

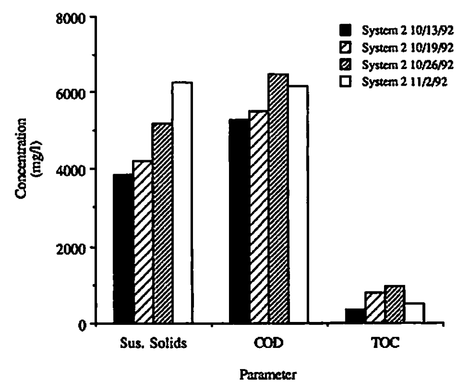


Figure 23. System #2 up-flow bead filter back-flushing organic waste analysis results.

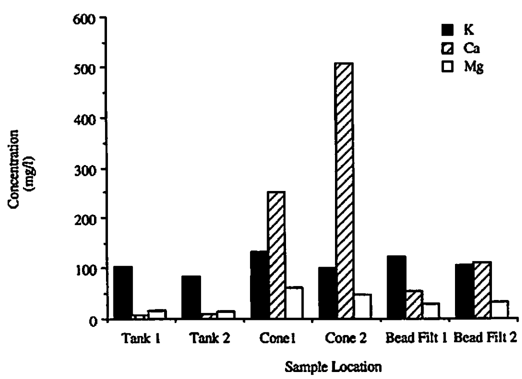


Figure 24. Mean concentrations of potassium, calcium, and magnesium in the culture tank water, settling cone wastes, and up-flow bead filter wastes.

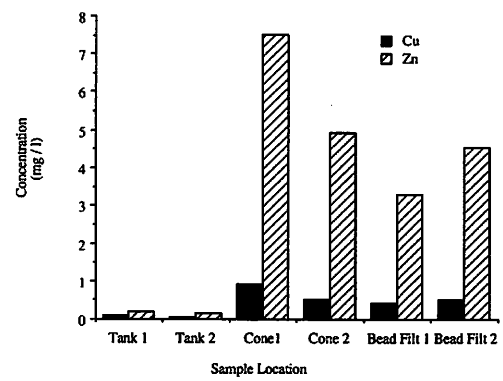


Figure 25. Mean concentrations of copper and zink in the culture tank water, settling cone wastes, and up-flow bead flter wastes.

State University, Baton Rouge, LA. 1992) suggests that these dissolved organics are not degraded by aerobic bacteria within the system and has found that these waters have extremely low Biochemical Oxygen Demands. Culture tank water was not routinely discharged to the waste line.

## SETTLING CONE WASTE CHARACTERISTICS

The settling cone waste was the highest strength and volume effluent stream from both systems. The high concentration of solids measured in the settling cone effluent and low suspended solids concentrations in the culture water is a good indication that the in-tank settleable solids removal system functions well. The concentrations of TAN and $NO_2$ (Figures 16 and 17) in this waste indicates that some degradation of organic solids and subsequent nitrification is occurring within the settling cones. Extremely high concentrations of TKN, suspended solids, COD, and TOC (Figures 18 and 19) indicate that the solids collected in the cones are organic in nature. The mean total solids concentration for this effluent source from both systems over the study period was 11,615 mg/l. Of the total solids measured, approximately 72% were determined to be volatile solids, confirming the organic nature of this waste. The concentration of total phosphorus in this waste was on average 12 to 15 times higher than that of the culture tank water. The mean daily volume of settling cone waste effluent from Systems #1 and 2 were 205 liters (standard deviation (sd=26) and 176 liters (sd=18) respectively.

## UP-FLOW BEAD FILTER WASTE CHARACTERISTICS

The waste from the up-flow bead filter back-flushing operation was second in strength and volume only to the settling cone effluent. Unlike the cone settling waste, the effluent from the bead filter did not have consistently higher concentrations of TAN, $NO_2$ or $NO_3$, suggesting that the solids trapped within the filter were not being degraded and oxidized to a significant degree. As with the settling cone waste, the bead filter effluent had extremely high concentrations of TKN, suspended solids, COD, and TOC (Figures 20, 21, 22 and 23) indicating that the solids were also organic in nature. The concentration of total phosphorus in this waste was on average 4 to 10 times higher than in the culture tank water. The mean daily volume of bead filter waste effluent from Systems #1 and 2 were 165 liters (sd=30) and 227 liters (sd=26) respectively.

## FOAM FRACTIONATOR WASTE CHARACTERISTICS

The foam fractionator effluent had elevated concentrations of suspended solids, TKN and COD with respect to the culture tank water. In general, the magnitude of these increases were 4.3 times for the suspended solids, and 2.4 times for the TKN and COD concentrations. These results are consistent with the intended function of the unit to concentrate fine and dissolved solids and organics. The mean daily volume of the effluent from the foam fractionators in Systems #1 and 2 were 47 liters (sd=22) and 33 liters (sd=27) respectively.

## DOWN-FLOW BEAD FILTER WASTE CHARACTERISTICS

The effluent waste characteristics from the down-flow fluidized bed bead filter on System #1 showed increased concentrations of TKN, COD and suspended solids. The most notable increase was in suspended solids, most likely a result of suspended solids migrating through the filter bed an the sloughing of nitrifying bacteria. The daily volume of this waste effluent was a constant 57 liters.

## OTHER NUTRIENT CHARACTERIZATION

The wastes in the settling cones and up-flow bead filter wastes for both systems showed elevated concentrations of calcium, magnesium, copper and zinc (Figures 24 and 25). Most notable were the high levels of calcium, magnesium and zinc. A logical conclusion is that these nutrients were being concentrated in the settleable and suspended solids waste from the uneaten feeds and fecal pellets within the culture tank.

# DISCUSSION

Water reuse in aquaculture has been viewed as a means to minimize the impact of aquaculture activities on the environment (Pillay 1992). From a water conservation viewpoint, this is a viable statement. However, on a per kg of production basis and from a waste impact viewpoint, recirculating systems produce no less waste than traditional aquaculture production systems. The data presented here clearly shows that, rather than the high-volume low-strength waste characteristic of many traditional aquaculture production systems, recirculating systems are capable of producing high-strength low-volume wastes. In this they have the advantage of a highly concentrated point source of waste that is more easily treated with conventional wastewater treatment technologies.

In the North Carolina Fish Barn systems, the waste streams from the settling cone and the up-flow bead filter back-washing process contain considerable pollutant loads that should not be discharged directly into receiving waters. The high levels of COD associated with the suspended solids could result in oxygen depletion in the environment. High levels of nitrogen and phosphorus could contribute to eutrophication. Particular concern should be given to the high nitrate levels. Concentrations of nitrate greatly exceed the 10 mg/L allowed in drinking water.

Treatment of the effluent from the types of systems described must address removal of suspended solids and nitrate. High levels of COD, TOC, and TP appear to be primarily associated with the suspended solids, so removal of the suspended solids will remove most of these pollutants. Alternatives to discharging directly into natural bodies of water or to municipal waste treatment plants, that take advantage of the high organic and nutrient content of these effluents, should be implemented.

One approach to treatment is to separate the suspended solids and land apply the clarified effluent. Several methods for solids separation might be considered. One possible method is sedimentation is a settling tank or pond. Potential problems with this method include the expense and expertise required to operate them, and denitrification causing settling problems. Dissolved air flotation would likely not be a suitable method because the solids are fairly dense and would not appear to lend themselves to flotation. The concentration of suspended solids may be too high for efficient operation of a rotary screen filter. Sand drying beds may offer a simple and inexpensive method of solids removal. Consider an operation of 13 tanks of similar design to those described in this paper. The system would produce approximately 45,500 kg (100,000) of fish per year, producing approximately 13,000 liters per day of effluent from the settling cones plus bead filter backwash. Removal of 60% moisture requires 10-15 days of drying (Metcalf and Eddy 1991). This could be accomplished with seven or eight beds, allowing two days of application to a bed followed by 12 to 14 days of drying. Sizing of sand drying beds is based on suspended solids loading rates. Suggested loadings for covered beds are 60 to 150 kg/$m^2$-yr (Metcalf and Eddy 1991). For the minimum sized operation with an average suspended solids waste load of 130 kg/day (10,000 mg/l × 13,000 liters/day), this translates to roughly 316 to 790 $m^2$ (3,400 to 8,500 $ft^2$) of sand beds. Taking the average of these estimates, 8 sand beds of 70 $m^2$ (750 $ft^2$) in surface area would be required. While this is a fairly large area to cover, the highly organic solids scraped from the surface could be marketed as fertilizer and soil conditioner.

The effluent from this process would still be very high in nitrates. Application to crop land may be a viable option for treatment. Area requirement will depend on the nutrient uptake rate, which depends on the type of crop and the number of crops that will be grown over a year. Suspended solids, COD, and TP will be relatively low in this effluent, thus the area required would likely be determined by nitrogen loading. Approximately 2.5 to 3.0 hectares (6 to 7.5 acres) will be required for an operation of the minimum size if two agricultural crops are grown per year (Metcalf and Eddy 1991; WPCF 1990; USEPA 1981). Problems include: as irrigation water, the effluent will be proportionally low in phosphorus and potassium; the sodium adsorption ratio will be close to the limit of acceptable levels (USEPA 1978), and the sodium and chloride concentrations in this water are fairly high and may exceed recommended levels for some crops. This procedure would require farm land and equipment and may not be suitable to all aquaculture operations.

Another option would be to land apply the whole wastewater from the settling cone and the bead filter backwash without removing the solids prior to application. This option would require more land area for application but would eliminate the need for solids separation. Area required for application again depends on the limiting factor, including available nitrogen, available phosphorus, BOD, and suspended solids. Land systems have a high capacity for assimilating BOD and suspended solids, and these factors do not appear to limit application of this wastewater. Phosphorus appears to be more restrictive than available nitrogen for the whole wastewater. Based on phosphorus loading, an area of about 4.0 to 5.5 hectares (10 to 14 acres) would be required for the minimum sized operation (Metcalf and Eddy 1991; WPCF 1990). Again, these requirements vary with crop species. Additional potassium may be required to balance the nitrogen and phosphorus added, and salt concentrations may be restrictive.

The basic characteristics of this wastewater that require attention are the suspended solids, along with associated COD and total phosphorus, and high dissolved nitrate. The suspended solids are relatively easily dealt with. Land application of high nitrate water is more of a problem, however, because of fears of groundwater contamination and the seasonality of nutrient uptake by crop plants. For these reasons, holding the effluent in a lagoon or wetland system that is managed for denitrification may be a desirable pretreatment to land application. Alternatively, a denitrification step may be included in the recirculating production systems design.

## CONCLUSIONS

From the data generated in this study, we can conclude that in-and-of-themselves, recirculating systems are not environmentally "friendly". Recirculating systems produce a high-strength, low-volume waste effluent that is more easily managed and treated than those from most conventional aquaculture production systems. Removal of particulate solids and treatment of dissolved nitrates and phosphorus is imperative before discharge to adjacent natural waterways. The highly organic solids, produced by recirculating systems, could used as a resource (fertilizer) or provide an additional source of income for aquafarmers if properly packaged and marketed.

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# MANAGING WATER QUALITY IN AQUACULTURE PONDS; THE TRADEOFF BETWEEN CARRYING CAPACITY AND ENVIRONMENTAL IMPACT

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## ABSTRACT

Ten different catfish production scenarios are examined and compared, for a specific 122 acre farm located in the foothills of the Blue Ridge Mountains of South Carolina. The various options range from lake cage culture of catfish, to typical pond culture, to high rate algal and catfish culture coupled with waste treatment and/or removal by filter feeding carp, to complete water reuse, as well as water flow-through systems. The best systems in terms of profit and reduced environmental impact are those that make maximum use of manipulated aquatic ecosystems for nitrogen removal from the culture water. In uncontrolled ponds, algal carbon fixation rates averaging 1.8 gm $C/m^2$/day will allow for a production of 5,500 lb/acre of catfish (with supplemental aeration) by removing toxic $NH_3$-nitrogen from the culture water, with little or no environmental impact. Pushing this system to the sustainable limits, by increasing algal productivities to 12 gm $C/m^2$/day and harvesting algal production with filter feeding fish, could increase yields to in excess of 30,000 lb/acre (again requiring supplemental oxygen). Such a system offers the potential of reducing environmental impact to public waters by employing engineered hyper-eutrophic aquatic ecosystems on private land, reducing the need for expensive, energy consuming waste treatment, by maximum utilization of solar driven algal photosynthesis.

## INTRODUCTION

The limit to aquaculture production is increasingly controlled by the availability of water and water discharge (i.e. environmental impact). A variety of culture and waste treatment options are available to the potential aquaculturists. This paper examines some of these options by comparing the production costs and environmental impact predicted at a specific site employing culture techniques ranging from typical low density stillwater pond culture of catfish to high density systems. The use of high rate algal oxidation ditches coupled with land application for waste treatment, as well as other options including lake cage culture and closed system culture are also examined.

## THE SITE

The proposed site is owned by the author and is located in the foothills of the Blue Ridge Mountains of South Carolina (Figure 1). This site is fairly typical of South Carolina Piedmont farms. This site consists of a total of 122 acres of which 20 acres is well suited for ponds; 15 acres is in permanent wetlands, with the remaining 87 acres consisting of forested hills and valleys with a total elevation difference of 200 feet maximum. A major stream flows through the center of this property (see Table 1) delivering a constant flow averaging 2000 gpm (2.88 MGD or 10.9 MLD). The stream vertical drop across the property is 30 ft, allow-

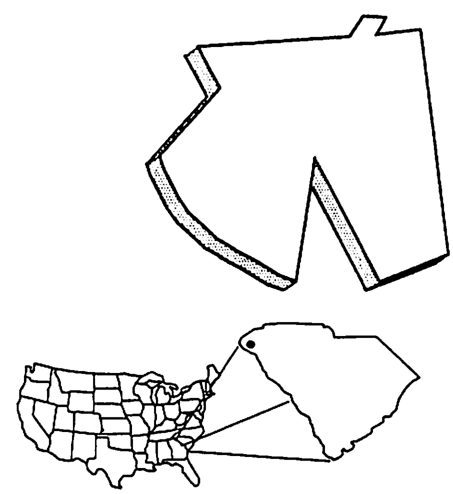

Figure 1. Aquaculture site location.

Table 1. Listing of proposed aquaculture site characteristics.

| SITE CHARACTERISTICS | |
|---|---|
| Total Area | 122 Acres (49.39 HA) |
| Potential Pond Area | 20 Acres (8.09 HA) |
| Wetland | 15 Acres (6.07 HA) |
| Forested | 87 Acres (35-22 HA) |
| Elevation Change in Land | 200 ft (60.9 m) |
| Stream Flow | 2,000 gpm (2.88 MGD, 10.9 MLD) |
| Stream Drop on Property | 30 ft (9.15 m) |
| Adjacent Lake Surface Area | 28.0 Acres (11.34 HA) |

ing gravity flow of the water to ponds in the low lying bottom fields. The property is adjacent to a Corp of Engineers-managed lake (Lake Hartwell) with 28 acres of open water directly adjacent to the property boundaries.

## PROPOSED AQUACULTURE OPTIONS

Ten different catfish culture options are considered on this property. These are summarized in Table 2. The limiting factor for each option is listed in Table 3. Rates and costs used in preparing the comparison of the various options are given in Table 4. The fish weight, percent feed per day, overall conversion, and length of growing season are taken from observations of typical catfish pond management reported in Tucker (1985). The fraction of nitrogen incorporated into fish flesh, excreted into the water, or deposited as solid waste were assumed to be similar to that reported for trout (Gunther et al. 1981). The feed nitrogen and phosphorus content, feed prices, oxygen, energy costs, fingerling, and catfish values are taken from Pomeroy et al. (1989). The cost of $FeCl_3$ were obtained by telephone quotation. Costs of waste treatment, specifically denitrification, was obtained from telephone conversations with consulting engineers. The value assigned to the carp was taken to be a minimum value, comparable to that obtained for fish to be processed into fish meal. Carbon fixation rates are values widely reported in the literature, furthermore, field trials at Clemson University (Drapcho and Brune 1989) have confirmed that algal productivities of 12 gm $C/m^2$/day can be sustained in slowly mixed outdoor cultures for most of the catfish growing season.

Table 2. Porposed aquaculture development options.

I. STREAM OR LAKE CULTURE
  A. Cage Culture in Lake
  B. Flow-Through Culture
II. POND CULTURE
  A. Still water Pond
  B. High Rate Pond
  C. High Rate Algal Pond
    1. Oxygen production limit
    2. Nitrogen fixation limit
      a. With irrigation
      b. With flocculation
      c. With biological algal harvest
      d. With water recycle and biological harvest
III. CLOSED SYSTEM CULTURE
  A. Nitrification for Nitrogen Control

## STILLWATER PRODUCTION

Drapcho and Brune (1989) and Brune et al. (1992) recently discussed the limits to the carrying capacity of

Table 3. Limiting factors and carrying capacities for the various options.

| | PROPOSED AQUACULTURE OPTIONS | | |
|---|---|---|---|
| | Type | Limitation | Carrying Capacity |
| 1. | Cage Culture in Lake | Eutrophication potential at 0.30 mg-N/liter<br>Reaeration limit | 8,142 lb/MGD (977 Kg/MLD)<br>940 lgs/acre (1,055/ha) |
| 2. | Flow-Through | Ammonia toxicity 2.0 mg-N/liter | 36,184 lb/MGD (4,342 Kg/MLD) |
| 3. | Stillwater Culture (no exchange, no aeration) | Surface reaeration | 1,5000 lbs/acre (1,684 Kg/ha) |
| 4. | High Rate Pond Culture (1.25 hp/acre night-time aeration) | Nitrogen toxicity | 5,500 lbs/acre (6,175 Kg/ha) |
| 5. | High Rate Algal Production for Oxygen Control (2 day cell detention time) | Night-time respiratory demand | 8,000 lbs/acre (8,976 Kg/ha) |
| 6–9. | High Rate Algal Production for Nitrogen Control (various options) | 6–12 gm Carbon/$m^2$/day maximum algal productivity | 15,356–40,885 lbs/acre (17,229–45,872 Kg/ha) |
| 10. | Closed Culture | Nitrogen disposal | $2 \times 10^6$ lbs/MGD used<br>32,152 lbs/MGD pumped (3,851 Kg/MLD) |

Table 4. Summary of input and cost data.

| SUMMARY OF INPUT AND COST DATA | |
|---|---|
| A. Weights, Rates, Compositions at Maximum Carrying Capacity | |
| 1. Fish wt. | 1.25 lbs |
| 2. Feed rate | 1.5% of body wt/day |
| 3. Solid waste production (as Nitrogen) | 20% |
| 4. Ammonia-N production | 60% |
| 5. Fish recovery (as Nitrogen) | 20% |
| 6. Oxygen uptake rate (overall night & day) | 0.00912 lb/lb wet wt |
| 7. $BOD_5$ production rate | 0.00622 lb/lb wet wt |
| 8. Feed Nitrogen content | 5.12% N |
| 9. Feed Phosphorus content | 0.512% N |
| 10. Growing season | 180 days |
| 11. Algal fixation rate | 6–12 gm $C/m^2/day$ |
| 12. Maximum tank density | 2.5 lb/gal |
| B. Process Costs | |
| 1. Oxygen | $0.09/lb |
| 2. Aeration | 2 lbs/hp-hr |
| 3. Energy | $0.08/Kw-hr |
| 4. Denitrification | $0.06/1000 gal |
| 5. $FeCl_3$ | $0.15/lb |
| 6. Feed | $0.15/lb |
| 7. Fingerling | $0.10/each |
| 8. Yearly average operating capacity defined as 66% of maximum carrying capacity | |
| 9. Catfish value | $0.70/lb |
| 10. Carp value | $0.12/lb |

catfish ponds. The minimum acceptable dissolved oxygen concentration, which occurs in the pre-dawn hours, limits biomass in each pond. Investigations have shown that at early morning dissolved oxygen concentrations of 3 mg/liter and at an average wind speed of 3 m/s(which is typical of the inland Southern United States), a theoretical carrying capacity of approximately 1,300 lb/acre is predicted. Field observations suggest that such ponds can safely carry 1,500 lb/acre, which implies that algal oxygen production in these ponds may be enhancing the carrying capacity. At this rate of production, the proposed site in question has the potential to produce 30,000 lb/year of catfish on 20 acres of ponds (Figure 2). At this production rate and at an expected conversion of 1.8/1 (lbs feed/lb fish produced) with 32% protein feed, 20% of excreted nitrogen in solid waste, 20% in fish flesh, and 60% losses as $NH_3$–N, the pond sediments will accumulate a maximum possible total of 2,211 lbs of nitrogen/year. Field experience has showed that significant portions of this nitrogen are lost from the aquaculture ecosystem through volatilization, denitrification, or mineralization and leakage to groundwater. However, in the worst case, at this level of production, sludge from the ponds, if applied to the surrounding land at an overall rate of 2,211 lbs per 87 acres, would result in a loading rate of 25 lb N/acre-yr. This level of aquaculture production would produce little or no environmental impact on the stream, lake, or ground water. Twenty acres of ponds will require $1.33 \times 10^6$ gallon/acre at 1.25 meter (4.1 ft)of depth. At a stream flow of 2.88 MGD, filling time will require 9.28 days at 100% diverted stream flow. Since the downstream section is relatively short (<1000 ft) and already subject to the influence of fluctuating lake levels, such short-term diversions of water from this stream for pond filling will likely have little impact on the stream ecology.

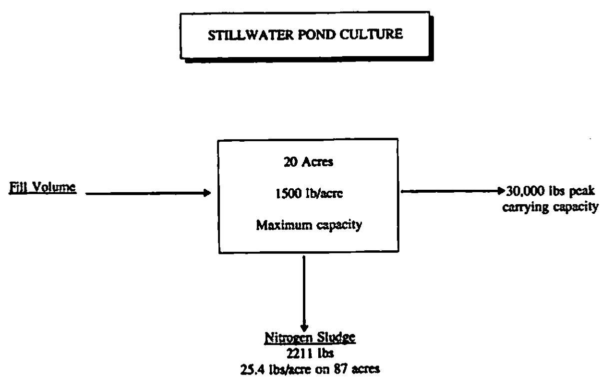


Figure 2. Flowchart for stillwater pond culture.

## HIGH RATE POND CULTURE

Current practice in pond aquaculture is to push carrying capacity to the limit to which the pond can safely assimilate nitrogen, using supplemental aeration during night-time hours to maintain acceptable early morning dissolved oxygen levels. This represents the limit at which algal photosynthesis in the unmixed (daytime hours) water column and bacteria nitrification can keep pace with the rate of ammonia released by the fish. Field experience suggests that this limit occurs around 5,500 lb/acre of catfish carrying capacity. Furthermore,field experience and theoretical predictions suggest that this level of oxygen demand will require 1.25 horse power/acre night-time aeration to avoid early morning oxygen stress. The fish production capacity

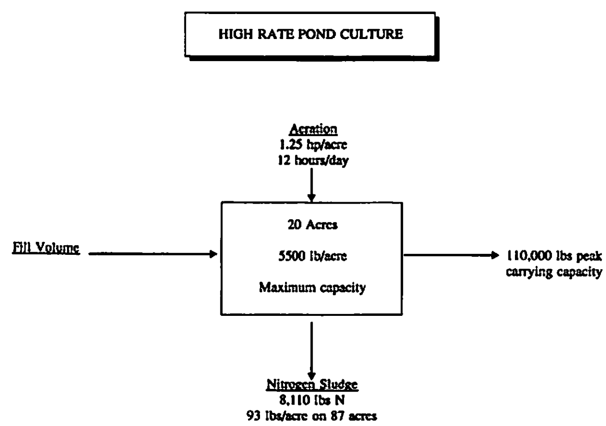


Figure 3. Flowchart for high rate pond culture.

at this proposed site of 110,000 lbs will require a nitrogen disposal capacity of 91.7 lbs N/acre-year (again, for the worst case, see Figure 3). This is still within limits of the expected nitrogen uptake capacity of the 87; acres of hardwood forest. Again, this scenario produces minimum environmental impact; however, it does increase the external energy requirement per unit fish produced to 0.24 Kw-hr/lb fish.

## CAGE CULTURE IN LAKE

Another possibility is to use the adjacent lake area as a site for cage culture of catfish. Discussion with the local Corp of Engineers representatives suggests that this is a possibility; however, there would likely be a substantial permitting process involved. There are two possible limits to producing fish in the lake, one being the surface reaeration potential of the lake, and the second being the eutrophication potential of the nitrogen and phosphorus released by the fish. An acceptable lower oxygen limit for the lake would likely be slightly more than that for the stillwater pond, since a minimum level of 3.0 mg/l dissolved oxygen would probably not be acceptable as the lower limit in public waters. At an allowable lower limit of 5 mg/l dissolved oxygen, carrying capacity would be reduced to 944 lb/acre. With 28 acres of lake area adjacent to the site in question, this suggests a total production of 26,432 lbs of fish. Nitrogen levels in the lake as a result of feed application will lead to an increased eutrophication in this area of the lake (Figure 4 and Figure 5). If no attempt is made to remove waste from the caged fish (and assuming an additional 33% flow volume to this lake from other streams on this arm of the lake), nitrogen concentrations will likely run at (26,432 lb) (1.8 lb/feed/lb fish) (32% protein) (16% nitrogen) (80% excreted) (66% loading factor) or 1,286 lbs ($5.8 \times 10^5$ gms) diluted into 3.8 MGD over a period of 6 months resulting in a concentration of 0.40 mg/l of total nitrogen. Surface water nitrogen concentrations in the region typically are in the range of 0.20 to 0.40 mg/liter. Most of the nitrogen loading in this region is due to agricultural activities. Therefore, this level of nitrogen loading will produce a

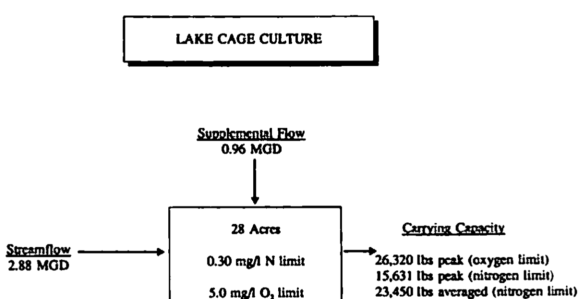


Figure 4. Flowchart for lake cage culture.

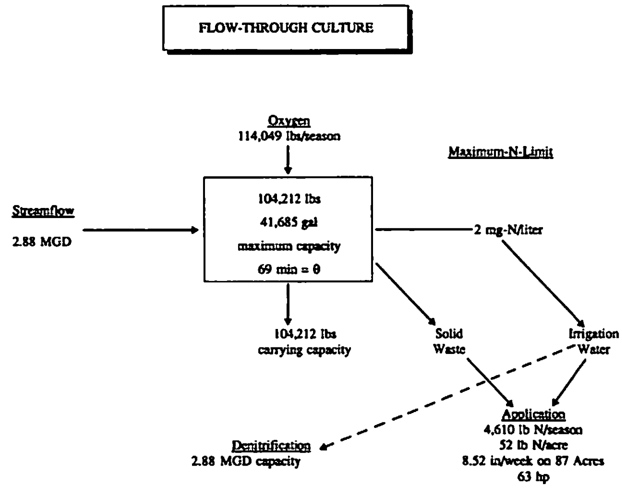


Figure 5. Flowchart for flow-through culture.

level of eutrophication similar to that seen in other agriculturally dominated areas of the lake.

## HIGH RATE ALGAL CULTURE

Another possibility is the application of new aquaculture production techniques recently discussed by Drapcho and Brune (1989). These techniques consist of the using of shallow, paddle-wheel-mixed algal growth ponds in conjunction with high density, raceway culture of catfish. This system may be operated as a photosynthetic oxygen supply technique (the approach discussed in Drapcho and Brune 1989) or it may be operated as a nitrogen control process.

### A) The Oxygen Limit

The carrying capacity of this system, utilizing algal photosynthesis and surface reaeration as the sole source of oxygen, can be expected to be 8,000 lb/acre (Drapcho and Brune 1989). Under these conditions, the bulk

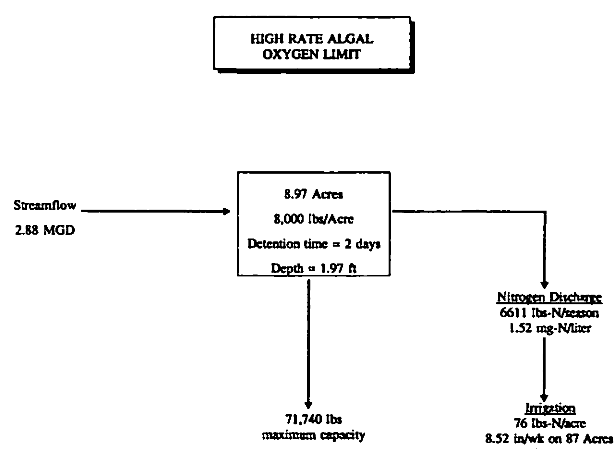


Figure 6. Flowchart for high rate algal oxygen limit.

pond is designed to operate at 60 cm depth (~2 ft) with a hydraulic detention time of 2 days. Because of the requirements for a 2-day hydraulic detention time to control the algal photosynthesis rate, this site will be limited by the available stream flow of 2.88 MGD. Therefore, total production will be limited to 71,740 lbs on 9 acres (Figure 6). The waste discharge must be disposed of since it will exceed the levels that the lake can assimilate. Therefore, it is assumed that the entire flow will be used as irrigation water on the 87 acres, resulting in a nitrogen loading of 76 lb-N/acre and a considerable pumping energy requirement of 63 hp.

B) The Nitrogen Limit

The system will operate at a similar hydraulic detention time of 2 days (with 60 cm of depth). Total carrying capacity is limited by disposal of nitrogen containing effluent (at the limit of both hydraulic capability of the soil, and the nitrogen loading limit). Furthermore, this system will be limited by algal production levels; field experience suggests that sustained yields of 12 gmC/m$^2$/day area may be possible. At typical algal C/N ratio of 5.67/1, this suggests a nitrogen assimilation rate of 2.11 gm N/m$^2$/day or maximum rate of 18.87 lbN/acre/day. This is equivalent to 368 lbs feed/acre-day or a maximum carrying capacity of 40,885 lb/acre, assuming that solid waste nitrogen is removed. Total nitrogen to be disposed of will average 27,038 lbs/season (Figure 7). Total acres is dependent on water flow available; at 100% of creek withdrawal, this amounts to 8.97 acres. Therefore, total carrying capacity (and production) will be 366,738 lbs/season with a nitrogen disposal requirement of 310 lbs N/acre. In addition to total use of creek flow, oxygen will need to be imported, either through energy consuming aeration

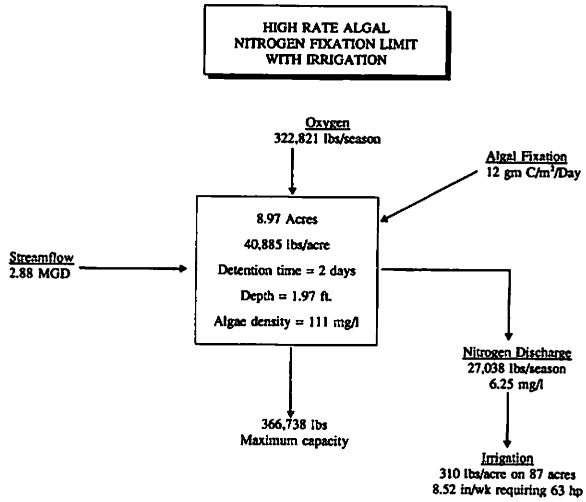


Figure 7. Flowchart for high rate algal, nitrogen fixation limit with irrigation.

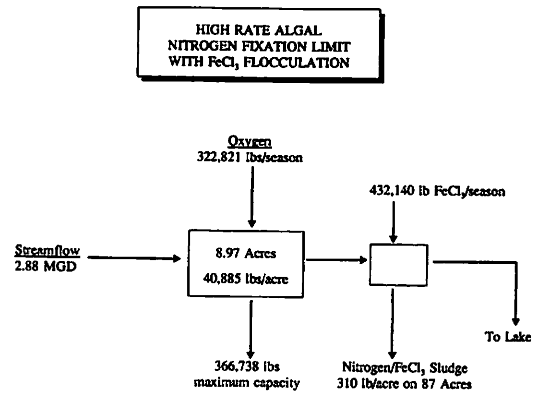


Figure 8. Flowchart for high rate algal, nitrogen fixation limit with $FeCl_3$ flocculation.

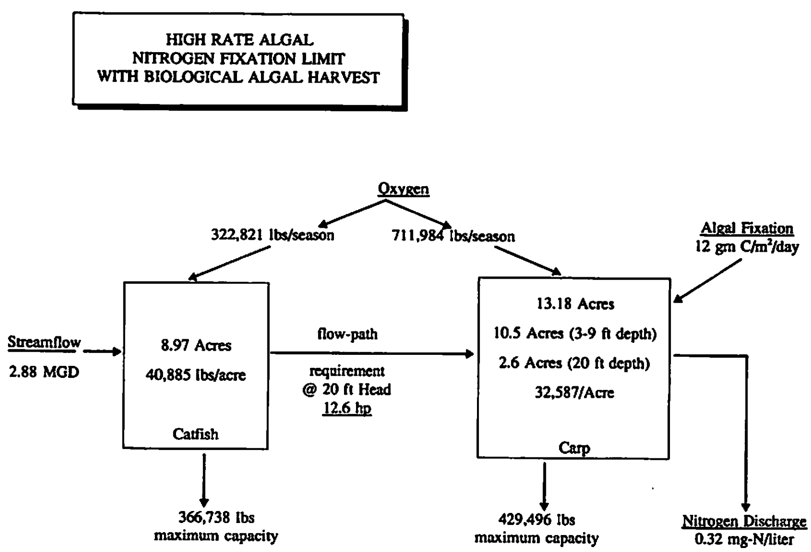


Figure 9. Flowchart for high rate algal, nitrogen fixation limit with biological algal harvest.

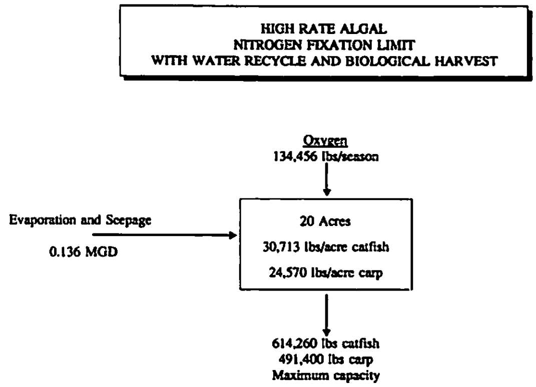


Figure 10. Flowchart for high rate algal, nitrogen fixation limit with water recycle and biological harvest.

devices or as pure oxygen for any carrying capacity in excess of 8,000 lbs/acre. This would result in an oxygen demand of an additional 322,821 lbs/season.

The need to dispose of 366,738 lbs of nitrogen/season will necessitate a large irrigation system capable of pumping 2.88 MGD across the hills (average height of 100 ft) and deliver the water at an average minimum pressure of 25 psi of head. Total energy requirement for pumping will be 63 hp. In addition to variable costs, there will be substantial capital costs for the irrigation system delivering an average daily application rate of 2.88 MGD or 1.21 inches per day on 87 acres. This water application rate is at the upper level of the weekly maximum application rate for this soil (5–10 in/week). At a maximum acceptance rate of 0.5 in/hr, 10 acre/day can be irrigated.

In addition to the high rate algal system using irrigation as the nitrogen disposal technique (Figure 7), three other versions of the system are presented. These are using flocculent ($FeCl_3$) to remove the algal-bound nitrogen from the water stream, returning the water to the lake (Figure 8), using a series cultures of algae and filter feeding carp in progressively deeper and smaller (area) cultures as a nitrogen removal technique (outlined in Figure 9), and finally, the reusing a closed cycle of culture water to grow catfish, algae, and carp in an in-line, high rate system with only evaporation and seepage make-up water requirements (Figure 10).

## CLOSED CULTURE WITH NITRIFICATION

For the basis of comparison, a flow chart is presented detailing the requirement of a 98% water recycle system, using bacterial nitrification as the ammonia control technique. This system is sized to limit total nitrogen disposal to a more desirable 200 lb/acre maximum on 87 acres. This results in a maximum carrying capacity of 236,002 lbs (Figure 11).

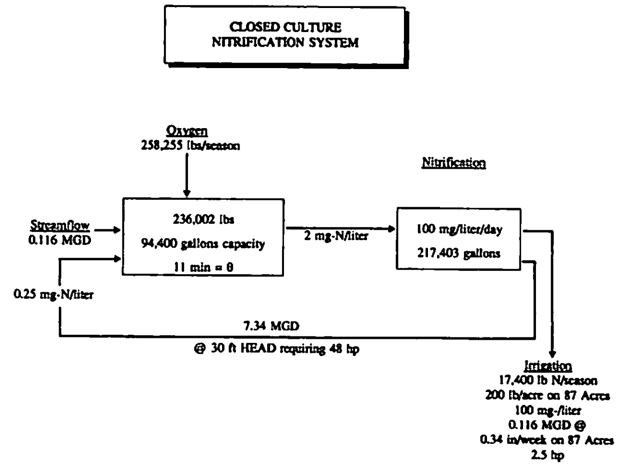


Figure 11. Flowchart for closed culture nitrification system.

## DISCUSSION

Detailed capital costs and complete variable costs for all of the 10 options are difficult to determine, particularly for the unproven and experimental techniques. Therefore, the approach taken was to calculate the major costs of each system including feed, fingerling, energy, oxygen, and chemical as specific waste treatment costs. In conventional catfish production, the major costs typically represent 40–62% of total costs; for the purpose of an approximate income potential of the 10 proposed options, a 62% multiplier is used to obta in the "adjusted net income" for the various culture options (summarized in Figure 12 and Table 5).

Of the five cases presented, with proven technology,

Table 5. Summary of total system production.

| TOTAL SYSTEM PRODUCTION | |
|---|---|
| System | Production |
| 1. Cage Culture<br>28 Acres | 26,320 lbs |
| 2. Flow-Through<br>2.88 MGD | 104,212 lbs |
| 3. Stillwater<br>20 Acres | 30.000 lbs |
| 4. High Rate Pond<br>20 Acres | 110,000 lbs |
| 5. High Rate Algal Oxygen Limit<br>9 Acres, 2.88 MGD | 71,740 lbs |
| 6. High Rate Algal Nitrogen/Irrigation<br>9 Acres, 2.88 MGD | 366,738 lbs |
| 7. High Rate Algal Nitrogen/$FeCl_3$<br>9 Acres, 2.88 MGD | 366,738 lbs |
| 8. High Rate Algal Nitrogen/Biological<br>9 Acres, 2.88 MGD | 796,234 lbs |
| 9. High Rate Algal Nitrogen/Recycle<br>9 Acres, 0.136 MGD | 1,105,660 lbs |
| 10. Closed Culture<br>0.116 MGD | 236,002 lbs |

| System | Income | MAJOR COSTS | | | | | Net[1] | Adjusted Net[2] | External Inputs (Non-feed) | Environmental Impact | Status of Technology |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Feed | Fingerling | Energy, Pumping, or Aeration | Denitrification or Chemicals | Oxygen | | | | | |
| Cage Culture | $18,424 | 7,106 | 2,632 | - 0 - | | - 0 - | $8,686 | $97/acre | none | Low level eutrophication | proven |
| Flow-Through | $72,948 | 28,136 | 10,421 | - 0 - | 52,560[3] DN | 10,264 | (28,433) | ($29/gpm) | oxygen, chemicals, energy | stream diversion | proven |
| | | | | 16,242 | - 0 - | | 7,885 | ($16/gpm) | | | |
| Stillwater Pond | $21,000 | 8,100 | 3,000 | - 0 - | - 0 - | - 0 - | 9,900 | $155/acre | none | 100% of land | proven |
| High Rate Pond | $77,000 | 29,700 | 11,000 | 3,222 | - 0 - | - 0 - | 33,078 | $308/acre | oxygen, energy | 100% of land | proven |
| High Rate Algal, Oxygen Limit | $50,218 | 19,369 | 7,174 | 16,242 | - 0 - | - 0 - | 7,433 | ($2,094/acre) | energy | stream diversion<br>45% of land | experimental |
| High Rate Algal, Nitrogen Limit/Irrigation | $256,716 | 99,018 | 36,673 | 16,242 | - 0 - | 29,053 | 75,730 | ($3,923/acre) | oxygen, energy | stream diversion<br>45% of land<br>Nitrogen to groundwater | experimental |
| | $128,358 | | | | | | (52,628) | ($18,233/acre) | | | |
| High Rate Algal, Nitrogen Limit/Flocculation | $256,716 | 99,018 | 36,673 | - 0 - | 64,828[3] | 29,053 | 27,144 | ($8,230/acre) | chemicals, oxygen, energy | stream diversion<br>45% of land<br>Iron loading of soil<br>Nitrogen to groundwater | experimental |
| | $128,358 | | | | | | (181,214) | ($22,540/acre) | | | |
| High Rate Algal, Nitrogen Limit/Biological | $308,256 | 99,018 | 79,623 | 3,248 | - 0 - | 93,132 | 33,235 | ($6,109/acre) | oxygen, energy | stream diversion<br>low level Eutrophication<br>100% of land | experimental |
| | $154,128 | | | | | | (120,893) | ($13,067/acre) | | | |
| High Rate Algal, Nitrogen Limit/Recycle | $488,950 | 165,849 | 110,566 | - 0 - | - 0 - | 12,101 | 200,434 | $1,180/acre | oxygen | 100% of land | unknown |
| | $244,475 | | | | | | (44,041) | ($11,043/acre) | | | |
| Closed Culture, Nitrification | $165,201 | 63,720 | 23,600 | 17,280 | - 0 - | 23,245 | 37,356 | ($8/gpm) | oxygen, energy | Nitrogen to groundwater | proven |

[1] Not including "other" variable costs such as insurance, taxes, repairs, labor, interest or capital.
[2] Assuming major variable costs represent 62% of total costs.
[3] Includes other variable costs and capital costs.

Figure 12. Summary of costs and net income for culture options.

the best in terms of minimum environmental impact and income produced is the high rate pond producing at 5,500 lb/acre. At this level of fish production, algal production in the pond at an average rate of 1.8 gm C/$m^2$/day is effectively removing the potentially toxic $NH_3$ from the water column and sending it to the pond sediments. There it either undergoes denitrification, degradation and leaching, or accumulation to be removed at the end of the growing season for spreading on the adjacent land. This option is successful because it is using the pond ecosystem as the treatment and nitrogen concentration mechanism. It is no surprise that this option has become the most common industry practice. The other four proven technologies all present environmental problems (i.e., 100% diversion of stream, or eutrophication of the lake, or both) or they require expensive inputs such as pumping or effluent treatment for nitrogen removal.

Of the five remaining options, the most promising technique is unfortunately the one that is currently the least understood. The case of high rate algal culture with water reuse to control nitrogen is based on the co-culture of catfish and a filter feeding organism such as silver carp. This system is accomplishing what the conventional high rate pond system is doing. However, it is pushed to the sustained photosynthetic limit by design of water mixing and high rate algal cell removal by controlling the algae cell removal rate with high densities of carp. This system has the greatest potential to reduce environmental impact, since all potentially polluting discharges are converted to a useful product. Further, it shows the greatest net profit because expensive waste treatment processing or irrigation need is eliminated. Furthermore, oxygen requirements are reduced since this system fully utilizes the oxygen production of the algal crop (see detailed discussion in Drapcho and Brune 1989).

In effect, the best system to reduce environmental impact to public waters and maximize profit is one in which a hyper-eutrophic system is engineered within the confines of the private property. If properly managed, this system has lowest cost because it is taking advantage of natural biological processes pushed to their limits of efficiency. The major stumbling blocks in implementing this technique are questions related to the filtering rate of herbivorous fish such as silver carp. A major gap exists in knowledge concerning the rate of algae and zooplankton uptake by such fish, particularly as a function of algae cell concentration. Furthermore, although sustained algal productivities of 12 gm C/$m^2$/day have been widely reported, it is not clear if these rates can be sustained in continuously recycled water. Also, it is not clear if off-flavor of catfish flesh can be avoided in such systems. An additional stumbling block is the need for permits to culture the various carps required for such systems. Unfortunately, regulations against the culture of these exotic species may slow the development of the most "environmental friendly" types of aquaculture.

## ACKNOWLEDGMENTS

I want to thank Scott Davis, Caye Drapcho, Tom Schwedler, John Collier, and Jack Whetstone for useful suggestions and culture data. The South Carolina Sea Grant Consortium provided partial support for the presentation of this paper at the Joint US-Japan Aquaculture meeting, Kyoto Japan, November 26–27, 1992.

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# ENERGY BUDGET FOR A YELLOWTAIL, *SERIOLA QUINQUERADIATA* IN PEN CULTURE*

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## ABSTRACT

It is desirable that the use of feeds in fish culture, which exert negative effects on environment, is practiced by adopting a utilization system which meets the environmental capacity of coastal fish farms. For the purpose, it is essential to find facts in terms of basic energy budget for yellowtail culture which includes metabolic wastes, feces, and growth that are associated with pen feeding operation.

This paper elucidated an energy budget for yellowtail culture process including remaining feed, feed supplied, feed intake, respiration metabolism, excretion, and body growth from fry to harvest. The fish were studied in a water current system of a culture tank, the following results were obtained.

1) The remaining feed was shown as sum of solid remaining feed (*SRF*) and liquid remaining feed (*LRF*). There is a relationship of linear regression between *LRF*, *SRF* (mg dry/*l*) and *COD* (mg $O_2/l$), respectively.

$$LRF=1.54 \cdot COD \qquad SRF=4.65 \cdot COD$$

2) The average caloric equivalents in kcal/g dry adopted for feed, solid remaining feed larger than 165 $\mu m$, liquid remaining feed smaller than 165 $\mu m$, and feces were 5.68±0.26, 5.01±0.31, 4.67±0.13, and 2.68±0.30, respectively.

3) The average excretion of ammonia nitrogen on feeding days was 191±184 mg N/ind./day and twice as much as that of non-feeding days 85±98 mg N/ind./day during the experimental period.

4) Daily heat gain per individual as *SDA* (kcal/ind./day) is a function of fish weight (*W*, *g*) and water temperature (*T*, °C), and is expressed in the following equation:

$$SDA=0.044 \cdot 1.037^{(T-20)} \cdot W^{0.73}$$

5) The minimum daily heat loss per individual (H, kcal/ind./day) of metabolism required for maintaining normal metabolism is a function of body weight (W, g) and water temperature (T, °C), and is obtained by the following equation:

$$H=0.074 \cdot 1.044^{(T-20)} \cdot W^{0.88}$$

6) The rate of body weight accumulation of yellowtail is 30% at 4 to 13 g, 22% at 26 to 796 g, and around 10% at 945 to 2,809 g, respectively. Assimilation efficiency of feed taken in was 97 to 98% in calories. Accumulated energy, respiration metabolism, and excretion energy by metabolites were –63 to 29%, 33 to 150%, and 12 to 37% of energy consumed, respectively. These results of biological production shows that the allocation pattern of metabolism varied markedly by growth phase of cultured yellowtail, and that assimilation efficiency and growth efficiency were higher in the early stages of growth.

## INTRODUCTION

The yellowtail, *Seriola quinqueradiata* Temminck & Schlegel, is a migratory fish of the Temperate Zone that belongs to the yellowtail tribe of the horse mackerel family. Its spawning season is believed to begin in January to February and end in August to September (Matubara and Ochiai 1965). The fry hatch in the Kuroshio region south of Kyushu island, grow in floating seaweed, and separate into the Kuroshio and Tsushima warm currents. As they head northward, they grow up to juvenile stage and young stage. During the young stage, schools break up, and individual fish move to coastal areas. In the growth process, they grow to 3 to 7 cm long in the late phase of the juvenile

* This work was submitted in partial fulfillment of the requirements for the degree of Doctor at Hokkaido University.

stage. Yellowtail in the late juvenile stage are called Mojako. They are caught and supplied as fry for yellowtail culture in the regions southwest and east of Kyushu, Shikoku coast, and Kinki coast from April to July.

Yellowtail culture was initiated in the form of enclosure fish farms in Adoike, Kagawa prefecture around 1930. Modern feeding culture systems were rapidly developed about 1960. Around that time, pen culture offish, which made culture farms easy to secure, was developed, and migratory fish such as sardine and mackerel, which were low in cost and available in large mass, were converted to feed for fish culture. Production volume of cultured yellowtail reached 62,000 tons in 1971, which was more than the largest catch, 55,000 tons, of non-cultured yellowtail in the past years. Cultured production reached 156,000 tons in1983, but stagnated thereafter because of overproduction, aging of culture farms, and frequent occurrence of fish diseases. Nevertheless, yellowtail culture remains to play a primary role in fish cultures of Japan. Its production was 161,000 tons or 13% of total yield of surface cultured fish in 1991, and occupies 60% of the total surface area of feeding fish culture. The total culture area is 2,803 ha, and the number of business entities involved is 2,425, of which 99% have adopted pen culture (Statistic and Information Department of MAFF 1991). Pelletized feed, prepared by blending ground frozen fish, dry feed, and nutrients, is believed to have less contaminating effects on coastal fish farms than fresh fish in that it leaves smaller amounts of organic pollutants such as thaw water, remaining feed, and feed loss, when pen culture of fish is adopted. Therefore, pelletized feed of proper size depending on the growth phase of cultured fish, is supplied by belt conveyers or compression ejectors. But, the culture of fish in pens, makes leaching of soluble components and sedimentation of remaining feed and feces down to the sea bottom inevitable. The organic load of the feed on the environment led to expanded self-pollution, formation of low oxygen water masses, arrested growth of yellowtail, yield reduction due to fish diseases, and even mass mortality. Some fish farms were exhausted and abandoned. In this regard, a problem is lack of quantitative investigation into a series of mass balances associated with feeding; for example, how self polluting thaw water from feed, remaining feed, and feces are related to the consumption of dissolved oxygen in water.

It is desirable that the use of feeds in fish culture, which exert negative effects on environment, is practiced by adopting a utilization system which meets the environmental capacity of coastal fish farms. For the purpose, it is essential to find facts in terms of basic energy budget for yellowtail culture which includes metabolic wastes, feces, and growth that are associated with pen feeding operation.

The past physiological and ecological findings and knowledge of yellowtail culture technology do not necessarily provide enough information for developing an energy budget. Yellowtail culture is not understood in terms of production ecology centered around existins feeding regimes (Mitani 1960; Harada 1965; Fujita 1969; Minamizawa and Sakai 1969; Hagino 1977; Hata and Katayama 1977; Kitamori 1977; Kubota 1977; Kusuda 1977, 1990; Tanaka 1977; Sakamoto 1986; Hata 1990; Hirata and Kadowaki 1990; Tamai 1990).

This paper discusses an energy budget for yellowtail culture including, remaining feed, feed supplied, feed intake, respiration metabolism, excretion, and body growth from fry to harvest.

## METHODS

Described are common methods and procedures for obtaining an energy budget for feed supplied to individual yellowtail; procedure for measuring heat gain, heat loss, and body growth concomitant with the quantities of remaining feed, feces, metabolic excretion, and food intake; and, the experimental conditions of culture and the structure of culture tank.

For the purpose of obtaining energy flow at the level of individual fish, the minimum heat loss of metabolism required for maintaining normal metabolism corresponding to the amounts of feed supplied, remaining feed, feed intake, excretion, and growth during feeding and swimming activities at each growth phase in water current is obtained by the following procedure.

The fish used for the experiment are mojakos, caught near the Koshikijima, Kagoshima prefecture, transported to Azuma-cho, and reared to marketable size in surface pen culture. Sample fish are transported alive from surface pens to land tanks in about 30 minutes, and then acculimated for 1 to 21 days. Using a body weight of 4 g (age 0, 138 individuals) and a body weight of 2,809 g (age 1, one individual) as controls, samples were taken monthly while the experimental group grew 4 g to 1,312 g for the first 12 months, and every two months during the period when growth went from 1,465 g to 2,808 g; that is, from the 13th month until the 18th month. Sample fish were weighed at the beginning and at the completion of the experiment. They were anesthetized with MS222 ($1/5\times10^3$ to $1/10\times10^3$), wiped with a paper towel to eliminate errors resulting from surface-adhered moisture, and put into PVC bags for protection from injure.

The same feeds in quality and shape as used in commercial surface pen culture were supplied depending on growth phrase. The fish were fed a mixture of frozen sand lance 70% and frozen krill 30%, for individuals of the age 0 during the stocking period in June. Moist pellets (Kitabayashi 1988) consisting of frozen sardine 50 to 90% and formulated feed for Hamachi, young yellowtail, (crude protein 55%, crude fat 5%, crude fiber 4%, crude ash 20%,carbohydrate 10%, and moisture 6%) 10 to 50% were fed thereafter until the age one. The frozen feed was kept at 0 to 3°C prior to feed supply. For the age one individuals, moist pellets of 100% frozen mackerel with proper nutrient addition were supplied from December to January, and pellets consisting of 100% sardine, with proper nutritional fortification, were used from the thinning period in February until the harvesting period in December (Table 1).

The experiment on yellowtail tank culture was carried out under natural in-house conditions at the Fisheries Research Laboratory, Faculty of Fisheries, Kagoshima University, from July 14th, 1986, to December 31th, 1987. Sea water for culture was pumped up into a 22 $m^3$ settling tank at 8 to 12 $m^3/h$, through a sand filter tank installed on 5 to 8 m deep sea bottom 200 m off the laboratory, as shown in Figure 1. It then passed through a 5 $m^3$ aeration tank and a 7 $m^3$ reservoir tank, and fell about 3 m into a 1 $m^3$ closed rearing tank. The

Table 1. Summary of the experimental conditions and materials.

| No. of Exp. | Date | Experimental priod | | | Water temperature | | | Water exchange (% volume per hour) |
|---|---|---|---|---|---|---|---|---|
| | | Rearing $t$ (day) | Feeding $t_1$ (day) | Non-feeding $t_2$ (day) | Min. (°C) | Max. (°C) | Mean (°C) | |
| 1 | June 14–July 3 | 19 | 16 | 3 | 21.1 | 23.2 | 22.2 | 100 |
| 2 | July 7–24 | 17 | 14 | 3 | 25.1 | 26.3 | 25.7 | 100 |
| 3 | Aug. 22–Sep. 9 | 18 | 15 | 3 | 26.4 | 27.2 | 26.8 | 100 |
| 4 | Sep. 19–Oct. 4 | 15 | 12 | 3 | 24.8 | 25.3 | 25.1 | 121 |
| 5 | Oct. 14–27 | 13 | 10 | 3 | 20.3 | 21.5 | 20.9 | 121 |
| 6 | Nov. 22–Dec. 2 | 10 | 8 | 2 | 16.9 | 19.1 | 18.0 | 100 |
| 7 | Dec. 16–22 | 6 | 3 | 3 | 15.4 | 16.4 | 15.9 | 94 |
| 8 | Jan. 28–Feb. 3 | 6 | 3 | 3 | 12.3 | 13.2 | 12.8 | 90 |
| 9 | Mar. 12–16 | 4 | 1 | 3 | 11.2 | 13.5 | 12.4 | 87 |
| 10 | Apr. 1–4 | 3 | 1 | 2 | 12.8 | 13.9 | 13.4 | 83 |
| 11 | Apr. 22–May 2 | 10 | 7 | 3 | 16.3 | 17.6 | 17.0 | 79 |
| 12 | May 15–30 | 15 | 13 | 2 | 18.6 | 21.7 | 20.2 | 75 |
| 13 | June 17–July 7 | 20 | 17 | 3 | 21.4 | 23.2 | 22.3 | 100 |
| 14 | Aug. 7–21 | 14 | 11 | 3 | 25.6 | 27.1 | 26.4 | 100 |
| 15 | Oct. 8–19 | 11 | 8 | 3 | 22.8 | 24.2 | 23.5 | 102 |
| 16 | Dec. 24–31 | 7 | 4 | 3 | 15.3 | 16.3 | 15.8 | 102 |

(Continued)

| No. of Exp. | Fish | | | | | | | | Feed | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of fish (indi.) | Body length | | Body weight | | | Dry-wet weight ratio | Type | Shape | Amount of supplied (g dry) |
| | | Initial (cm) | Final (cm) | Initial (g wet) | Final (g wet) | Mean (g wet) | | | | |
| 1 | 138 | 6.5 | 9.7 | 4 | 13 | 8 | 0.247 | sand lance 70% and krill 30% | minced | 1052 |
| 2 | 40 | 11.9 | 15.3 | 26 | 51 | 39 | 0.277 | sardine 50% and *1) A.D. 50% | *2) M.P. | 1107 |
| 3 | 13 | 19.4 | 22.7 | 115 | 179 | 147 | 0.321 | sardine 70% and A.D. 30% | M.P. | 1233 |
| 4 | 9 | 28.6 | 29.5 | 348 | 399 | 374 | 0.349 | sardine 90% and A.D. 10% | M.P. | 1145 |
| 5 | 4 | 37.0 | 36.9 | 780 | 813 | 796 | 0.361 | sardine 90% and A.D. 10% | M.P. | 641 |
| 6 | 4 | 38.8 | 38.4 | 945 | 971 | 958 | 0.344 | sardine 90% and A.D. 10% | M.P. | 506 |
| 7 | 3 | 38.2 | 38.2 | 1004 | 1008 | 1006 | 0.392 | mackerel 100% | *3) F.P. | 89.1 |
| 8 | 3 | 41.0 | 39.8 | 1108 | 1101 | 1105 | 0.373 | mackerel 100% | F.P. | 53.5 |
| 9 | 3 | 42.5 | 41.6 | 1294 | 1290 | 1292 | 0.402 | sardine 100% | F.P. | 17.1 |
| 10 | 3 | 43.4 | 42.9 | 1328 | 1323 | 1326 | 0.412 | sardine 100% | F.P. | 18.4 |
| 11 | 3 | 42.9 | 40.0 | 1136 | 1106 | 1121 | 0.365 | sardine 100% | F.P. | 171 |
| 12 | 3 | 39.2 | 40.8 | 1005 | 1033 | 1019 | 0.366 | sardine 100% | F.P. | 440 |
| 13 | 3 | 42.4 | 44.8 | 1227 | 1312 | 1270 | 0.308 | sardine 100% | F.P. | 909 |
| 14 | 2 | 47.7 | 48.8 | 1465 | 1517 | 1491 | 0.313 | sardine 100% | F.P. | 540 |
| 15 | 1 | 49.8 | 51.1 | 1725 | 1775 | 1750 | 0.318 | sardine 100% | F.P. | 234 |
| 16 | 1 | 42.4 | 55.9 | 2798 | 2809 | 2804 | 0.443 | sardine 100% | F.P. | 121 |

*1) A.D.: artificial diet, *2) M.P.: moist pellet, *3) F.P.: frozen pellet.

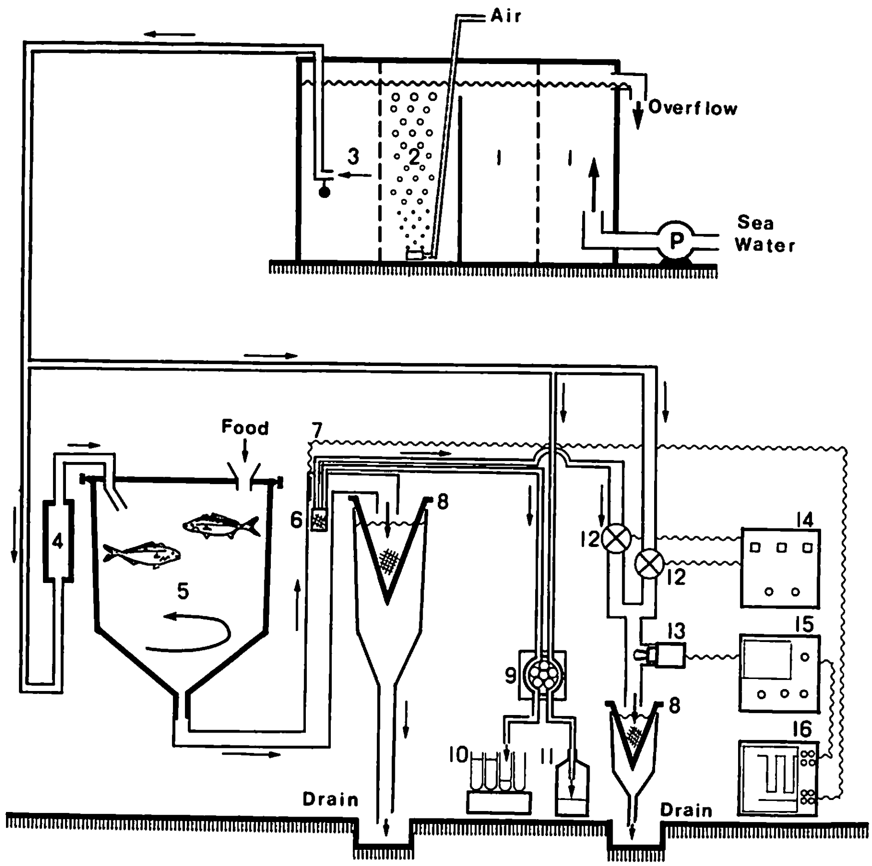


Figure 1. A diagram of the experimental arrangements used to measure the respiratory parameters of yellowtail with a flow system. Arrows express the flowing of sea water. 1: settling tank, 2: aeration tank, 3: reservoir tank, 4: flow meter, 5: closed rearing tank, 6: nets (165 $\mu m$ and 957 $\mu m$ mesh size), 7: thermosensor, 8: feces and solid remained feed collector net (165 $\mu m$), 9: peristaltic pump, 10: outlet water sampling bottles, 11: inlet water sampling bottle, 12: electro magnetic valves, 13: polarographic oxygen sensor, 14: control panel, 15: dissolved oxygen meter, 16: recorder.

aeration tank was recived about 55 *l*/min of compressed air in order to maintain over 80% *DO* saturation of the water running into the closed rearing tank. The settling tank overflowed continually to keep constant water influx into the closed rearing tank. Flow velocity inside the closed rearing tank was 8 cm/s by the wall and 5 cm/s at the center. The closed rearing tank, of 1,000 *l* capacity had a cone-shaped top with a 27° inclination from the basal plane over a cylinde rmade of black panlight (120 cm in diameter × 120 cm deep). The top of the tank was closed with a white styrofoam lid covered with a PVC sheet to exclude about 98% of natural light so that the experiment was conducted under dim light. A small opening was provided in the lid for supplying feed and making observations, but the opening was usually closed with a small cover (10 cm rectangle). Feed was supplied to satiation once every morning between 9 and 10 o'clock.

A test comprised a fish group of an age (A), and a control (B) was provided to a test. A taming period was provided for test fish to learn to come to the surface for feeding. The experiment began the day when the above feeding behavior was confirmed. They were fed for 17 days continually, after which they were subjected to fasting for 2 to 3 days. Control (B) was to correct for the consumption and generation of oxygen intest (A). It was performed in a tank of the same size as (A), and given the same water exchanger using a flow meter for adjustment.

A dissolved oxygen (*DO*) meter, a polarographic oxygen sensor *YSI*-58 based on the single oxygen electrode method (Kadowaki *et al.* 1980), was chosen to measure *DO* in order to avoid errors resulting from electrodes placed in water that contains a large amount of organic substances. Water level differentials between tank water surface and electrode membrane surface was adjusted to control water flow to the *DO* electrode membrane at more than 30 cm/s. *DO* consumption by yellowtail was measured by a flow water method: *DO* (a) of the inlet water of the test, *DO* (b) of the outlet water, and *DO* (c) of the outlet water of the control were measured alternately for 10 minutes each using triangle electromagnetic valves and a control panel space. The results were recorded by a *YEW*-3057 recorder, and *DO* consumption by cultured fish was assumed to be (a)−(b)−(c). Water exchange ratios ofthe test (A) and the control (B) varied depending on temperature and fish size, but remained within a range of 75 to 121% of the tank water. However, constant amounts of inlet water was maintained using a digital flow integrator for experiments divided by the month. The temperature of tank water was measured continually with a *YEW* thermosensor.

The remaining feed and feces were collected by filtering sea water continually from an outlet at the center of the rearing tank bottom through polyethylene nets (165 $\mu m$ mesh size, 40 cm opening diameter, and 80 cm long). The mesh size of 165 $\mu m$ was chosen, because the particle size distribution of suspended materials resulting from feed supply had a mode around 30 $\mu m$ and a range of 10 to 80 $\mu m$ (Kadowaki *et al.* 1978). The remaining feed, over 165 $\mu$m, was collected in a settling tank once a day 2 to 3 hours after feeding defecation. Feces were collected twice a day, 2 to 8 hours after feeding and secondly before feeding on the following day. The remaining feed and feces were collected by siphon collection and filtered with filter paper #2. Inlet and outlet water were collected with a peristaltic pump every hour for 2 to 3 days in row. *COD* of the sample water and samples was analyzed at 100°C by an alkaline potassium permanganate method using a *COD* meter, *HC*-307, Central Kagaku. Ammonia nitrogen of sample water was analyzed by an indophenol method (Liddicoat *et al.* 1975) using a water autoanalyzer, Chem-Lab Co. All the individual fish were dissected on the last day of the experiment. Body component parts were separated into muscle, skin, head bone, gill, liver, gonad, and other internal organs. The energy content of each part was measured. The other internal organs comprises heart, stomach, intestine, appendix pylorica, gall bladder, spleen, kidney, air bladder, and blood. Calorie values of body component parts, feed, and feces were measured with a digital calorimeter, *YM* Nenken, after they were dried at constant temperature of 60°C for 72 hours and ground.

## RESULTS AND DISCUSSION

In order to understand production ecology it is essential to understand metabolism and growth associated with body maintenance of individual yellowtail, and food consumption in terms of function. This research elucidated the energy budget of the culture process from stocking to harvesting considering both food cunsumed and remaining feed. The quantities of various production elements of yellowtail are as following:

*Feed intake (I) = Feed supplied (S) − Remaining feed (R)*
*Assimilation (A) = Feed intake (I) − Feces (F)*
*Assimilation (A) = Growth (G) + Heat loss (H) + Specific Dynamic Action (SDA) + Non-fecal excretion (U)*

The flow is shown in a diagram of Figure 2. The energy budget was obtained by clarifying each of the items.

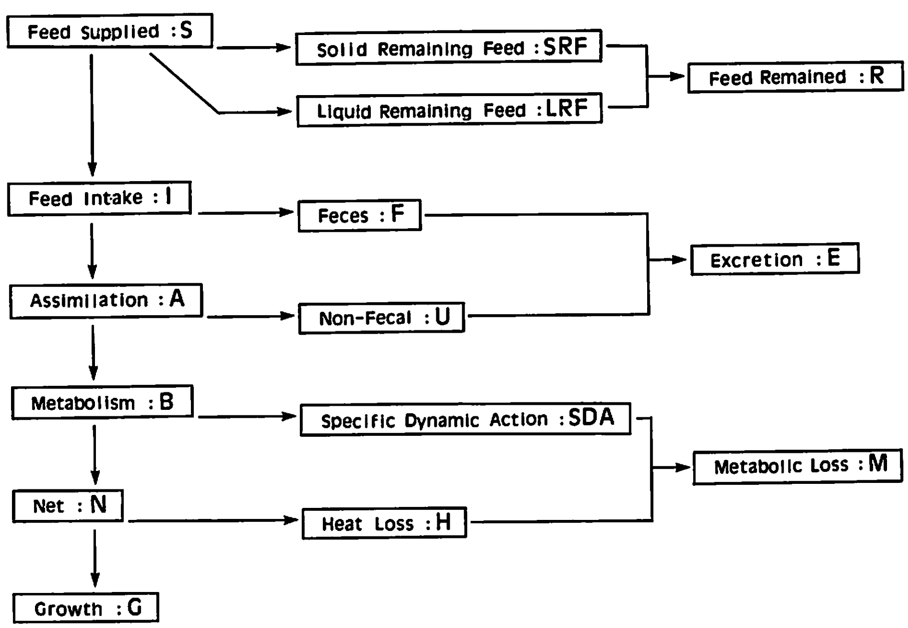


Figure 2. Diagram showing the energy budget of yellowtail *Seriola quinqueradiata* cultured (based on Brett and Groves, 1979).

Table 2. Summary of body weight, daily feed efficiency, feed supplied, feed remained, feed intake, feces, and assimilation of yellowtail cultured. *SRF*: solid remaining feed, *LRF*: liquid remaining feed. Data are expressed in g dry/ind/day.

| Date | Body weight (g dry/ind.) | | Feed efficiency (%) | Feed supplied (*S*) | Feed remained | | | Feed intake (*I*) | Feces (*F*) | Assimilation (*A*)=*I*−*F* |
|---|---|---|---|---|---|---|---|---|---|---|
| | Initial | Final | | | >165 μm (*SRF*) | <165 μm (*LRF*) | Total (*R*) | | | |
| June 14–July 3 | 1.0 | 3.2 | 23.0 | 0.48 | 0.03 | 0.05 | 0.09 | 0.39 | 0.03 | 0.36 |
| July 7–24 | 6.4 | 12.6 | 20.8 | 1.98 | 0.13 | 0.27 | 0.40 | 1.58 | 0.07 | 1.51 |
| Aug. 22–Sep. 9 | 28.4 | 44.2 | 17.4 | 6.33 | 0.46 | 0.89 | 1.35 | 4.97 | 0.23 | 4.74 |
| Sep. 19–Oct. 4 | 86.0 | 98.5 | 11.5 | 10.6 | 0.96 | 1.64 | 2.60 | 8.01 | 0.35 | 7.66 |
| Oct. 14–27 | 192 | 200 | 8.1 | 16.0 | 2.29 | 2.82 | 5.11 | 10.9 | 0.57 | 10.3 |
| Nov. 22–Dec. 2 | 233 | 239 | 6.1 | 14.0 | 2.08 | 3.00 | 5.08 | 8.99 | 0.47 | 8.52 |
| Dec. 16–22 | 247 | 248 | 4.1 | 9.90 | 1.94 | 2.78 | 4.73 | 5.17 | 0.36 | 4.81 |
| Jan. 28–Feb. 3 | 273 | 271 | 2.2 | 5.94 | 1.99 | 1.56 | 3.54 | 2.40 | 0.21 | 2.19 |
| Mar. 12–16 | 319 | 318 | 1.8 | 5.70 | 2.10 | 1.70 | 3.81 | 1.89 | 0.18 | 1.72 |
| Apr. 1–4 | 327 | 326 | 1.9 | 6.13 | 1.71 | 1.94 | 3.64 | 2.49 | 0.21 | 2.27 |
| Apr. 22–May 2 | 280 | 273 | 3.0 | 8.18 | 1.43 | 2.76 | 4.19 | 3.99 | 0.25 | 3.74 |
| May 15–30 | 248 | 255 | 4.5 | 11.3 | 1.46 | 2.56 | 4.02 | 7.28 | 0.40 | 6.88 |
| June 17–July 7 | 303 | 323 | 5.7 | 17.8 | 2.07 | 3.31 | 5.38 | 12.46 | 0.63 | 11.8 |
| Aug. 7–21 | 361 | 374 | 6.7 | 24.5 | 3.66 | 3.20 | 6.86 | 17.68 | 1.01 | 16.6 |
| Oct. 8–19 | 425 | 438 | 6.8 | 29.2 | 4.45 | 5.03 | 9.48 | 19.79 | 1.10 | 18.6 |
| Dec. 24–31 | 690 | 693 | 4.4 | 30.3 | 8.53 | 8.54 | 17.0 | 13.29 | 0.81 | 12.4 |

## a. FOOD ASSIMILATION

***Feed supplied:*** Feed was supplied to the age 0 individuals twice a day during stocking period, and to the age 1 individuals once a day until harvested. Feed efficiency (Table 2, column 4) was obtained through observations when feed was provided to satiation after 10 to 30 minutes. Monthly averages of daily feed efficiency expressed in dry weight were converted to calorie values, and shown in column 5 of Table 2. Daily feed efficiency was 27% during the stocking period (June), decreased to 13 to 19% during rearing period of the age 0 fish (July to August), and reached 5 to 8% during growout period (September to October). It went down to 2 to 4% per individual from November to December, and further kept decreasing to 1 to 2% during thinning period from January to April. It then went up during the age 1 rearing period (May to July), and reached a level of 5% during growout period (August to October). It was 2% during the harvesting period (December).

The feed efficiency in wet weight during yellowtail culture is 43% during the stocking period (June), 13 to 28% for the age 0 rearing period (July to August), 2 to 5% in the age 0 fish during the growout period (September to December), and under 1% during the thinning period (January to March), up to 2 to 5% in the age 1 rearing period (April to November), and down to 2% (Matui 1981) for the age 1 fish during the harvesting period (December). In this experiment, the daily feed efficiency in stocking period (June) was 20% lower than the feed efficiency above, and closer to the rate of feed intake. The difference is thought to come from the feeding methods: random feeding by a feeding machine versus sprinkling by hand with observation. Daily feeding efficiency obtained in this experiment is not believed to be way off that of general culture process. The remaining feed is the sum of feed dispersed by the feeding action of yellowtail and the food lost through the gills by their feeding action. It usually is close to daily feed efficiency, and is not exceptional. The level of unused feed in January to March was about the same as that of October to December and April to May. Temperatures lower than 14°C elicited searching behavior for feed, but the fish did not to take it in.

Daily feed supply was summarized in column 2 of Table 4, as calorie values were obtained as shown in Table 3; that is, daily feed supply perreared yellowtail was 2.7 kcal during the stocking period (June). Daily feed supply went up during the age 0 rearing period (July to September), and reached 80 to 90 kcal during the growout period (October to November). It started decreasing in December, and further kept going down under 40 kcal during the thinning period (January to March). It then increased during the age 1 rearing period (April to August), and reached a level of 170 kcal from the growout period to the harvesting period (October to December).

***Remaining feed:*** Solid remaining feed (*SRF*) larger than 165 μm and liquid remaining feed (*LRF*) were separately collected (Kadowaki 1989). *SRF* was collected with polyethylene nets of 165 μm mesh for 1 to 3 hours immediately after feed supply, dried, and weighed (Table 2, column 6).

*LRF* in dry weight (Table 2, column 7) was estimated from *COD*, because *LRF* (mg dry/*l*) of sample water filtrate through 165 μm polyethylene nets is correlated with the *COD* (mg $O_2/l$) by linear regression.

Table 3. Caloric values of feed, remained feed, feces, and each body component of yellowtail cultured. Data are expressed in kcal/g dry weight.

| Date | Feed | Feed remained | | Feces | Body component parts | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | SRF | LRF | | Muscle & skin | Head & bone | Gill | Liver | Gonad | Other |
| June 14–July 3 | 5.68 | 4.98 | 4.84 | 1.84 | 4.91 | 4.54 | 4.48 | 5.78 | — | 5.54 |
| July 7–24 | 5.56 | 4.36 | 4.61 | 2.98 | 5.56 | 4.99 | 4.95 | 6.17 | — | 5.93 |
| Aug. 22–Sep. 9 | 5.52 | 5.05 | 4.61 | 2.85 | 5.50 | 5.11 | 4.90 | 5.71 | — | 6.39 |
| Sep. 19–Oct. 4 | 5.41 | 5.12 | 4.61 | 2.70 | 5.96 | 5.23 | 4.98 | 6.42 | — | 6.88 |
| Oct. 14–27 | 5.56 | 4.93 | 4.61 | 2.84 | 6.14 | 5.50 | 5.07 | 7.01 | 5.17 | 7.31 |
| Nov. 22–Dec. 2 | 5.76 | 4.97 | 4.61 | 2.61 | 6.25 | 5.59 | 4.99 | 6.68 | 5.31 | 7.34 |
| Dec. 16–22 | 6.03 | 4.88 | 4.98 | 2.90 | 6.27 | 5.61 | 4.86 | 6.64 | 5.27 | 7.25 |
| Jan. 28–Feb. 3 | 6.12 | 4.84 | 4.98 | 2.72 | 6.50 | 5.72 | 5.37 | 7.28 | 5.07 | 7.59 |
| Mar. 12–16 | 5.62 | 5.62 | 4.61 | 2.73 | 6.89 | 5.80 | 5.09 | 7.63 | 4.85 | 7.77 |
| Apr. 1–4 | 5.23 | 4.76 | 4.61 | 2.23 | 6.38 | 5.76 | 5.18 | 7.00 | 4.78 | 7.55 |
| Apr. 22–May 2 | 5.17 | 4.47 | 4.61 | 2.37 | 5.14 | 5.84 | 4.62 | 6.66 | 4.81 | 6.66 |
| May 15–30 | 5.87 | 5.45 | 4.61 | 2.51 | 6.04 | 5.72 | 5.06 | 6.51 | 5.25 | 6.77 |
| June 17–July 7 | 5.71 | 5.00 | 4.61 | 2.88 | 5.83 | 5.54 | 4.34 | 5.82 | 4.70 | 6.73 |
| Aug. 7–21 | 5.87 | 5.21 | 4.61 | 2.84 | 5.96 | 5.70 | 4.62 | 6.13 | 5.59 | 6.54 |
| Oct. 8–19 | 5.98 | 5.32 | 4.61 | 2.97 | 6.25 | 5.45 | 4.58 | 6.60 | 4.87 | 7.06 |
| Dec. 24–31 | 5.77 | 5.18 | 4.61 | 1.91 | 6.76 | 5.64 | 4.63 | 6.34 | 5.35 | 6.79 |
| Mean | 5.68 | 5.01 | 4.67 | 2.68 | 6.08 | 5.48 | 4.86 | 6.52 | 5.08 | 6.88 |
| S.D. | 0.26 | 0.31 | 0.13 | 0.30 | 0.47 | 0.34 | 0.27 | 0.52 | 0.27 | 0.58 |

Table 4. Daily amount of feed supplied, feed remained, feed intake, feces, assimilation and assimilation efficiency of yellowtail cultured. Data are expressed in kcal/ind./day. SRF: solid remaining feed, LRF: liquid remaining feed.

| Date | Feed supplied ($S$) | Feed remained | | | Feed intake | Feces | Assimilation | Assimilation efficiency |
|---|---|---|---|---|---|---|---|---|
| | | $>165\,\mu m$ ($SRF$) | $<165\,\mu m$ ($LRF$) | Total ($R$) | ($I$)$=S-R$ | ($F$) | ($A$)$=I-F$ | (%) |
| June 14–July 3 | 2.71 | 0.16 | 0.26 | 0.42 | 2.29 | 0.05 | 2.23 | 97.7 |
| July 7–24 | 10.9 | 0.56 | 1.24 | 1.80 | 9.19 | 0.20 | 8.99 | 97.8 |
| Aug. 22–Sep. 9 | 34.9 | 2.35 | 4.10 | 6.45 | 28.4 | 0.64 | 27.8 | 97.7 |
| Sep. 19–Oct. 4 | 57.3 | 4.89 | 7.58 | 12.4 | 44.9 | 0.94 | 43.9 | 97.9 |
| Oct. 14–27 | 89.1 | 11.3 | 12.9 | 24.3 | 64.8 | 1.61 | 63.2 | 97.5 |
| Nov. 22–Dec. 2 | 81.1 | 10.3 | 13.8 | 24.2 | 56.9 | 1.22 | 55.6 | 97.9 |
| Dec. 16–22 | 59.6 | 9.48 | 13.8 | 23.3 | 36.2 | 1.03 | 35.2 | 97.2 |
| Jan. 28–Feb. 3 | 36.3 | 9.62 | 7.76 | 17.3 | 18.9 | 0.58 | 18.3 | 97.0 |
| Mar. 12–16 | 32.0 | 11.8 | 7.86 | 19.6 | 12.3 | 0.48 | 11.8 | 96.1 |
| Apr. 1–4 | 32.0 | 8.13 | 8.92 | 17.0 | 15.0 | 0.48 | 14.5 | 96.8 |
| Apr. 22–May 2 | 42.2 | 6.40 | 12.7 | 19.1 | 23.1 | 0.58 | 22.5 | 97.5 |
| May 15–30 | 66.2 | 7.94 | 11.8 | 19.7 | 46.5 | 1.00 | 45.5 | 97.9 |
| June 17–July 7 | 101 | 10.3 | 15.2 | 25.5 | 76.3 | 1.83 | 74.4 | 97.6 |
| Aug. 7–21 | 143 | 19.0 | 14.7 | 33.8 | 110 | 2.87 | 107 | 97.4 |
| Oct. 8–19 | 174 | 23.6 | 23.1 | 46.8 | 128 | 3.27 | 124 | 97.4 |
| Dec. 24–31 | 175 | 44.1 | 39.3 | 83.5 | 91.6 | 2.34 | 89.2 | 97.4 |
| Mean | 71.2 | 11.2 | 12.2 | 23.4 | 47.8 | 1.19 | 8.61 | 97.4 |
| S.D. | 52.0 | 10.3 | 8.95 | 19.0 | 36.4 | 0.92 | 35.5 | 0.5 |

$$LRF=1.54 \cdot COD \quad (r=0.970, t=24.23, p<0.001) \qquad (1)$$

There is a relationship of linear regression between $SRF$ (mg dry/$l$) and $COD$ (mg $O_2/l$), as shown in the following equation:

$$SRF=4.65 \cdot COD \quad (r=0.963, t=20.34, p<0.001) \qquad (2)$$

Remaining feed was shown as sum of $SRF$ and $LRF$ (Table 2, column 8).

When the slope of the regression line between $SRF$ and $COD$ was compared with that between $LRF$ and $COD$ obtained by equation (*1*), $DO$ consumption of $SRF$ was about one third of $LRF$. As a significant difference exists between them, it is necessary to calculate $DO$ consumptions of $SRF$ and $LRF$ separately, when

*DO* consumption of remaining feed is estimated.

Daily remaining feed per individual expressed as monthly average in calorie units was summarized in column 5 of Table 4. It was 0.4 kcal during the stocking period (June), and stayed at a level of 20 to 24 kcal from July of the age 0 to May of the age 1. It then kept increasing from June to August and was up to 47 kcal in October. It quickly reached a level of 84 kcal during the harvesting period (December).

***Feed intake:*** Feed intake was calculated by subtracting remaining feed from feed supplied, and shown as daily calorie value per individual in column 6 of Table 4. Feed intake was 2.3 kcal in the stocking period (June), increased in the age 0 rearing period (July to September), and reached a level of 60 kcal in October and November. It began to decrease in December, and kept going down to 10 to 20 kcal during the thinning period (January to March), then increased in the age 1 rearing period (April to August), and reached 130 kcal in the growout period (October),and decreased to 90 kcal in the harvesting period (December). Thus, feed intake by yellowtail continued during the culture period. When seasonal temperature variation of rearing tank water, as shown in Figure 3, was compared with seasonal variation of daily feed intake, daily feed intake of the thinning period (January to March) was one quarter and one eighth, respectively, of the rearing and growout periods (August to November) of the age 0 and 1. This suggests that the daily feed intake during the thinning period was suppressed by water temperature lower than 14°C that persisted from January to March. It was also pointed out that reared yellowtail of the ages 0 and 1 lost rather than gained weight under water temperature lower than 14°C.

***Feces:*** The daily amount of feces per reared yellowtail was summarized in column 7 of Table 4. It was 0.05 kcal during the stocking period (June),increased during the age 0 rearing period, and reached a level of more than 1 kcal in October to December. It sharply went down under 0.6 kcal during the thinning period (January to April) and up in the age 1 rearing period (May to July), and reached 3 kcal in August to October


Figure 3. Average water temperature in aquaria. Broken lines show the range of temperature.

and 2 kcal in the harvesting period (December).

Significant differences were found in *COD* per dry weight of feces depending on growth phase. The relationship between feces ($F_0$, mg dry/$l$)and *COD* (mg $O_2$/$l$) of age 0 fish (8 to 958 g wet) and that between feces ($F_1$) of age 1 fish (1006 to 2804 g wet) and *COD* are expressed in the following equations:

$$F_0=5.26\cdot COD \quad (r=0.947, t=12.51, p<0.001) \qquad (3)$$

$$F_1=10.3\cdot COD \quad (r=0.984, t=19.13, p<0.001) \qquad (4)$$

*DO* consumption of age 0 fish feces is about twice as high as that of age 1 fish, as shown by the slopes of equations (3) and (4). The significant difference necessitates separate calculations for the age 0 fish and age 1 fish in estimating *DO* consumption of feces.

***Assimilation:*** Feed assimilation was obtained by subtracting feces from feed intake, and shown in column 8 of Table 4. Daily assimilation per reared yellowtail showed a tendency similar to feed intake. It was 2.2 kcal in the stocking period, increased in the age 0 rearing period (July to September), and reached a level of 60 kcal in October and November. It then began to decrease in December, sharply went down to about 10 to 20 kcal in the thinning period of January to March, increased during the age 1 rearing period (April to August), kept increasing to reach a level of 125 kcal in the fatting period (October), and decreased to 90 kcal in the harvesting period (December). Average assimilation efficiency was around 97±0.5% throughout the experimental period, as shown in the far right column of Table 4.

## b. FOOD CONVERSION

Food taken in by animals is digested, and absorbed as nutrients by digestive organs. Materials that are not digested or absorbed are excreted externally as non-digested substances. Assimilated nutrients areconverted to metabolites such as urine or mucous secretion, heat gain originating from food intake, or heat loss in activities and maintenance of the body. What remains is used for body constituents as growth. Sufficient food is taken in to ensure growth. Growth, therefore, dependson how energy from food taken in and assimilated is allocated through conversion to each body component (Fuji and Hashizume 1974; Fuji 1980).

There are two methods for obtaining heat generation by metabolism of aquatic animals: indirectly by conversion of measured oxygen consumption to calorie values, and directly by conversion of energy consumed. Heat loss ($H$) expressed as the sum of metabolism for maintenance and activities was obtained by the direct method.

Table 5. Daily concentrations of ammonia values as non-fecal of yellowtail cultured on feeding and non-feeding days.

| Cultured period (days) | $NH_4$-N in feeding day | | (a) | $NH_4$-N in non-feeding day | | (b) | Ammonia-excretion $X=(a \cdot t_1+b \cdot t_2)/t$ |
|---|---|---|---|---|---|---|---|
| | (mg N/day) | (mg N/ind./day) | (kcal/ind./day) | (mg N/day) | (mg N/ind./day) | (kcal/ind./day) | (kcal/ind./day) |
| 19 (June–July) | 1445 | 10 | 0.79 | 101 | 1 | 0.01 | 0.66 |
| 17 (July) | 1394 | 35 | 3.02 | 312 | 8 | 0.14 | 2.51 |
| 18 (Aug–Sep) | 1267 | 97 | 9.07 | 379 | 29 | 0.52 | 7.65 |
| 15 (Sep–Oct) | 1734 | 193 | 13.0 | 632 | 70 | 1.25 | 10.6 |
| 13 (Oct) | 1493 | 373 | 15.1 | 523 | 131 | 2.33 | 12.1 |
| 10 (Nov–Dec) | 809 | 202 | 12.5 | 310 | 77 | 0.92 | 11.4 |
| 6 (Dec) | 574 | 191 | 3.41 | 237 | 79 | 1.41 | 2.41 |
| 6 (Jan–Feb) | 204 | 68 | 1.21 | 117 | 39 | 0.70 | 0.95 |
| 4 (Mar) | 260 | 87 | 0.51 | 118 | 39 | 0.70 | 0.66 |
| 3 (Apr) | 366 | 122 | 0.72 | 227 | 76 | 0.90 | 0.84 |
| 10 (Apr–May) | 163 | 54 | 2.38 | 78 | 26 | 0.46 | 1.80 |
| 15 (May) | 218 | 73 | 5.99 | 99 | 33 | 0.39 | 5.24 |
| 20 (June–July) | 298 | 99 | 11.7 | 101 | 34 | 0.60 | 10.0 |
| 14 (Aug) | 516 | 258 | 24.3 | 118 | 59 | 1.05 | 19.3 |
| 11 (Oct) | 724 | 724 | 27.1 | 368 | 368 | 6.56 | 21.5 |
| 7 (Dec) | 475 | 475 | 12.2 | 285 | 285 | 5.08 | 9.18 |
| Mean | 746 | 191 | 8.95 | 250 | 85 | 1.44 | 7.32 |
| S.D. | 523 | 184 | 8.06 | 160 | 98 | 1.76 | 6.44 |
| Min | 163 | 10 | 0.51 | 78 | 1 | 0.01 | 0.66 |
| Max | 1734 | 724 | 27.1 | 632 | 368 | 6.56 | 21.5 |

Heat gain coming from specific dynamic action (*SDA*) and feed intake, was obtained indirectly by estimating the difference between oxygen consumption of feeding days and that of non-feeding days, and was calculated by dividing by the oxygen calorie equivalent (Brett and Groves 1979) of 3.24 kcal/g $O_2$. Oxygen consumption necessary for reared fish to maintain normal metabolism is obtained as metabolic loss (*M*): sum of heat loss and heat gain of specific dynamic action.

Metabolic excretion, heat loss and *SDA* measured in calorie values per day per individual were shown in Table 5, Table 6, and Table 7, respectively. Body growth was obtained as energy value per day per individual by converting to calorie value of a whole yellowtail using calorie equivalent of each body component; the product of dry weight change (columns 2, 3 of Table 2) and the number of fish (column 2, bottom rows of Table 1) was divided by the number of experiment days. In general, energy taken in is expressed as a function of body weight and water temperature by the following basic equation (Inoue 1969; Elliott 1976):

$$Q=\alpha_{(T)} \cdot W^b=\alpha_{(20)} \cdot Q_J^{(T-20)} \cdot W^b \qquad (5)$$

In the above equation, $Q$ represents energy (kcal/ind./day); $W$, body weight (g); $T$, water temperature (°C); $\alpha_{(T)}$, energy level at water temperature ; $\alpha_{(20)}$, energy level at 20°C; $Q_J$, temperature coefficient; and b, body weight exponent.

***Metabolic excretion of nitrogen:*** Nitrogen taken in from feed by the fish goes through metabolic processes, and is converted to body constituents for growth, metabolites, and urine. Energy not utilized in the deamination steps of metabolic process is excreted as urine and mucous secretion into water of rearing tank. The excretion consists mostly of ammonia, and partly the trimethylamine oxides (Wood 1958). In this study, therefore, energy in metabolic excretion was calculated by converting excreted ammonia nitrogen to caloric value. Ammonia nitrogen of the culture water was measured at the inlet and outlet of the rearing tank every hour 1 to 3 days in a row on feeding days and non-feedings days. The difference obtained was multiplied by the ammonia nitrogen calorie equivalent (Brett and Groves 1979) of 5.94 kcal/g N to calculate energy in metabolic excretion. Ammonia nitrogen excretion varied between feeding days and non-feeding days (Figure 4). Average excretion of ammonia nitrogen on feeding days was 191±184 mg N/ind./day and twice as much as that of non-feeding days, 85±98 mg N/ind./day, during the experimental period. Daily metabolic excretion per individual was 0.71 kcal in the stocking period (June), and increased to 17.5 kcal during the age 0 rearing period (July to September). It began to decrease in November, and went down under 1.9 kcal during the thinning period (January to March) characterized by inactive feed intake. It increased during the age 1 rearing period (April to July), reached 25.4 to 33.7 kcal in the growout period (August to October), and was 17.3 kcal in the harvesting period (December)

Table 6. Estimated urea and nitrogen excretion culculated by the difference of heat loss and indirect calorimetory oxygen consumption in feeding day.

| Cultured period (days) | Heat loss H=I−F−U −SDA−G | Urea excreted Y=H−c | Non-fecal U=X+Y | X/U |
|---|---|---|---|---|
| | (kcal/ind./day) | (kcal/ind./day) | (kcal/ind./day) | (%, kcal) |
| 19 (June–July) | 0.53 | 0.05 | 0.71 | 93.0 |
| 17 (July) | 2.80 | 0.65 | 3.16 | 79.5 |
| 18 (Aug–Sep) | 9.44 | 1.97 | 9.62 | 79.5 |
| 15 (Sep–Oct) | 18.8 | 3.60 | 14.2 | 74.7 |
| 13 (Oct) | 34.1 | 5.28 | 17.4 | 69.7 |
| 10 (Nov–Dec) | 30.6 | 1.99 | 13.4 | 85.2 |
| 6 (Dec) | 27.0 | 2.41 | 4.82 | 50.0 |
| 6 (Jan–Feb) | 22.0 | 0.94 | 1.90 | 50.2 |
| 4 (Mar) | 21.8 | 0.58 | 1.24 | 53.1 |
| 3 (Apr) | 24.8 | 0.81 | 1.65 | 50.9 |
| 10 (Apr–May) | 27.8 | 1.05 | 2.85 | 63.1 |
| 15 (May) | 29.3 | 1.14 | 6.38 | 82.2 |
| 20 (June–July) | 43.9 | 2.27 | 12.3 | 81.6 |
| 14 (Aug) | 60.6 | 6.05 | 25.4 | 76.2 |
| 11 (Oct) | 70.3 | 12.1 | 33.6 | 63.9 |
| 7 (Dec) | 59.0 | 8.16 | 17.3 | 53.0 |
| Mean | 30.2 | 3.07 | 10.3 | 69.1 |
| S.D. | 19.2 | 3.21 | 9.28 | 13.9 |
| Min | 0.53 | 0.05 | 0.71 | 50.1 |
| Max | 70.3 | 12.1 | 33.6 | 93.0 |

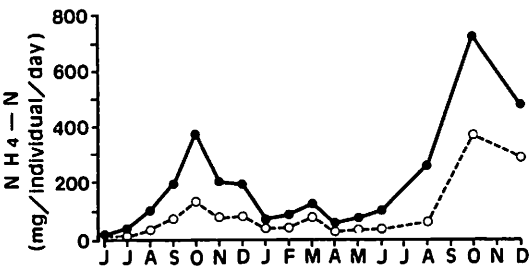


Figure 4. Average daily ammonia excretion by yellowtail cultured on feeding and non-feeding days. ●—●: feeding days, ○—○: non-feeding days.

Table 7. Specific dynamic action of yellowtail estimated by the difference of oxygen consumptions between feeding and non-feeding days.

| Cultured period (days) | Metabolism | | | | Specific dynamic action SDA=c−d | |
|---|---|---|---|---|---|---|
| | Feeding day (c) | | Non-feeding day (d) | | | |
| | (mg/ind./h) | (kcal/ind./day) | (mg/ind./h) | (kcal/ind./day) | (mg/ind./h) | (kcal/ind./day) |
| 19 (June–July) | 6 | 0.48 | 3 | 0.25 | 3 | 0.23 |
| 17 (July) | 28 | 2.15 | 18 | 1.37 | 10 | 0.78 |
| 18 (Aug–Sep) | 96 | 7.46 | 62 | 4.81 | 34 | 2.65 |
| 15 (Sep–Oct) | 196 | 15.2 | 143 | 11.1 | 53 | 4.13 |
| 13 (Oct) | 371 | 28.8 | 272 | 21.1 | 100 | 7.74 |
| 10 (Nov–Dec) | 368 | 28.6 | 293 | 22.8 | 75 | 5.81 |
| 6 (Dec) | 317 | 24.6 | 292 | 22.6 | 25 | 1.96 |
| 6 (Jan–Feb) | 271 | 21.0 | 261 | 20.3 | 10 | 0.77 |
| 4 (Mar) | 274 | 21.3 | 265 | 20.6 | 9 | 0.70 |
| 3 (Apr) | 309 | 24.0 | 298 | 23.2 | 11 | 0.82 |
| 10 (Apr–May) | 345 | 26.8 | 327 | 25.4 | 18 | 1.37 |
| 15 (May) | 363 | 28.2 | 317 | 24.6 | 46 | 3.57 |
| 20 (June–July) | 536 | 41.6 | 444 | 34.5 | 91 | 7.11 |
| 14 (Aug) | 702 | 54.6 | 540 | 41.9 | 163 | 12.6 |
| 11 (Oct) | 748 | 58.1 | 519 | 40.3 | 229 | 17.8 |
| 7 (Dec) | 654 | 50.8 | 511 | 39.7 | 143 | 11.1 |
| Mean | 349 | 27.1 | 285 | 22.1 | 64 | 4.95 |
| S.D. | 214 | 16.6 | 162 | 12.6 | 64 | 4.99 |
| Min | 6 | 0.48 | 3 | 0.25 | 3 | 0.23 |
| Max | 748 | 58.1 | 540 | 41.9 | 229 | 17.8 |

(Table 6, far right column). Ammonia excretion was 15.1 kcal/ind/day during September to November, which was a tenfold increase over January to April. This suggests enhanced metabolism for urine and mucous secretion correlated to the temperature of the rearing tank water above 18°C. Excretion of urea nitrogen such as urea and low molecular proteins was estimated by dividing the difference between heat loss and respiratory metabolism by urea nitrogen calorie equivalent of 5.51 kcal (Brett and Groves 1979). The heat loss was obtained directly by energy conversion, and the respiratory metabolism was obtained indirectly by calorimetric measurement of oxygen consumption. Total metabolic excretion of nitrogen ($U$) was calculated as the sum of ammonia and urea nitrogen excretion (Table 6, column 6). The ratio of ammonia nitrogen excretion to total nitrogen excretion was 70 to 93% from June to December of the age 0, decreased to a level of about 50%during the period of low water temperature from December to April of the age 1, and went up to 63 to 82% from May to October, as the water temperature went up, suggesting increasing ammonia nitrogen excretion (Table 6, far right column).

***Specific dynamic action (SDA):*** It is known that apparent oxygen consumption by reared yellowtail varies from feeding days to non-feeding days (Kadowaki *et al.* 1981). The energy increase required for digestion, absorption and catabolism of food material concomitant with feed intake is specific dynamic action (*SDA*). Results obtained through indirect calorimetry of measured difference between oxygen consumptions on feeding days and non-feeding days are given in the far right column of Table 7. Daily heat gain per individual as *SDA* (kcal/ind./day) is a function of fish weight ($W$, g) and water temperature ($T$, °C), and expressed in the following equation:

$$SDA = 0.044 \cdot 1.037^{(T-20)} \cdot W^{0.73} \qquad (6)$$

The equation is applicable to yellowtail of the ages 0 and 1 in a range ofwater temperature 15 to 27°C.

***Heat loss:*** Heat loss equals the sum of standard metabolism and active metabolism, and is estimated by the following equation for allocation of energy intake:

$$Heat\ loss\ (H) = S - R - F - U - SDA - G$$

Figure 5 shows the relationship between body weight and heat loss of yellowtail per unit time. There was no significant difference between slopes at different temperatures (f=1.322, $p<0.05$). Therefore, daily heat loss per individual ($H$, kcal/ind./day) is a function of body weight ($W$, g) and water temperature ($T$, °C) for all the months under consideration, andis obtained by the following equation:

$$H = 0.074 \cdot 1.044^{(T-20)} \cdot W^{0.88} \qquad (7)$$

for yellowtail of ages 0 and 1 in a water temperature range of 15 to 27°C.

***Growth:*** Growth was obtained as the difference in each body component,not as difference in body weight. The reason was to clarify that energy allocation varied

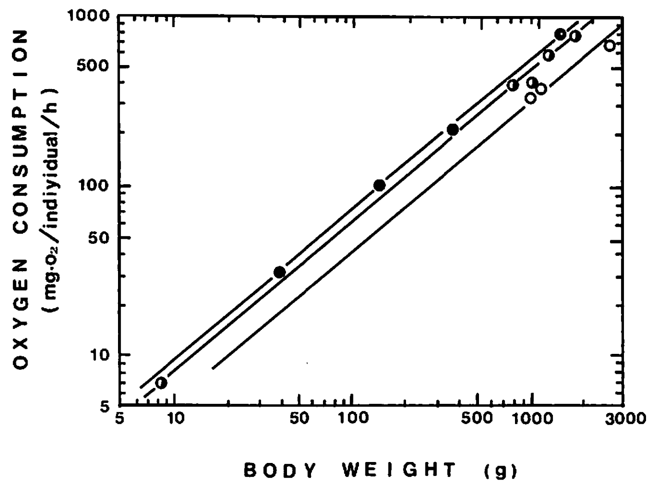


Figure 5. The relationship between body weight and oxygen consumption of yellowtail on feeding days at different temperature. ●: 24.8 to 27.2°C, ○: 18.6 to 24.2°C, ○: 15.3 to 17.6°C.

by growth phase, as growth rate and calorie value are different depending on body component; therefore, individual fish were dissected into skin, muscle, head bone, gill, liver, gonad, and other internal organs. Their dry weights (Table 8) were measured, multiplied by the calorie equivalent of each (Table 3), and summed for the calorie value of a whole fish, as shown in the following equations:

*Calorie of a whole fish*
*=∑ (calorie value of body component)*
*Calorie value of body component=Dry weight of body component · Calorie equivalent of body component*

*Calorie equivalents of body components throughout the rearing*

Table 8. Composition of body component part of yellowtail at the end of experiment. Data are expressed in g dry weight per individual.

| Date | Body component parts | | | | | | Whole body |
|---|---|---|---|---|---|---|---|
| | Muscle & skin | Head & bone | Gill | Liver | Gonad | Others | |
| July 3 | 1.6 | 0.8 | 0.1 | 0.1 | — | 0.6 | 3.2 |
| July 24 | 8.2 | 3.9 | 0.4 | 0.2 | — | 1.4 | 14.1 |
| Sep. 9 | 36.4 | 14.3 | 1.9 | 0.9 | — | 4.1 | 57.5 |
| Oct. 4 | 80.6 | 40.7 | 4.3 | 3.1 | — | 10.5 | 139 |
| Oct. 27 | 178 | 78.1 | 7.8 | 3.9 | 0.4 | 25.3 | 293 |
| Dec. 2 | 197 | 84.0 | 7.1 | 10.1 | 0.2 | 35.3 | 334 |
| Dec. 22 | 256 | 80.2 | 7.2 | 12.4 | 0.6 | 38.5 | 395 |
| Feb. 3 | 255 | 90.3 | 14.8 | 10.5 | 0.4 | 40.1 | 411 |
| Mar. 16 | 336 | 103 | 10.1 | 13.6 | 0.4 | 54.9 | 518 |
| Apr. 4 | 352 | 112 | 12.2 | 9.2 | 0.5 | 57.6 | 544 |
| May 2 | 252 | 90.9 | 9.0 | 5.5 | 0.4 | 45.5 | 403 |
| May 30 | 228 | 93.6 | 10.2 | 3.7 | 0.5 | 41.1 | 377 |
| July 7 | 235 | 123 | 13.2 | 4.5 | 0.8 | 26.6 | 403 |
| Aug. 21 | 268 | 138 | 22.0 | 6.2 | 1.1 | 39.5 | 475 |
| Oct. 19 | 311 | 165 | 29.7 | 10.6 | 2.1 | 44.6 | 563 |
| Dec. 31 | 816 | 244 | 37.7 | 11.6 | 3.1 | 131 | 1244 |

*process were as follows: skin and muscle, 6.08±0.47 kcal/g dry; head bone, 5.48±0.34 kcal/g dry; gill, 4.86±0.27 kcal/g dry; other internal organs, 6.88±0.58 kcal/g dry; liver, 6.52±0.52 kcal/g dry; and gonad, 5.08±0.27 kcal/g dry (Table 3). There was no significant monthly difference in the calorie values among head bone, gill, gonad, feed, remaining feed, and feces. Calorie values of skin and muscle and those of liver and other internal organs tended to be low during the stocking period (June) and the rearing period (July to August), and high during the thinning period (January to March). This suggests that fat in yellowtail decreased as water temperature went up, and decreased as water temperature went down. It indicates that enhanced metabolism caused by high water temperature consumed body fat in summer, and that fat accumulation concomitant with reduced metabolism took place in skin, muscle, liever, and other internal organs in winter (Shimizu et al.* 1973).

## c. ENERGY BUDGET

Allocation pattern of supplied energy was clarified by the month through supply, intake, assimilation, excretion, metabolism, and growth. Energy allocation of supplied feed was summarized in Table 9, and that of energy taken in was summarized in Table 10.

Average calaorie equivalents in kcal/g dry adopted for feed, solid remaining feed larger than 165 *μm*, liquid remaining feed smaller than 165 *μm*, and feces were 5.68±0.26, 5.01±0.31, 4.67±0.13, and 2.68±0.30, respectively.

Figure 6 shows the daily allocation of supplied energy per individual in the flow sequence of the rearing process. The results were summarized for each growth period: (I). Out of the 2.71 kcal of feed supplied to an individual of age 0 stocking period, 0.42 kcal is unused, 2.29 kcal is taken in, and 98% of it is assimilated. Thirty seven percent and 33% of assimilated energy is lost by excretion metabolism and respiratory metabolism, respectively. The remaining 30% or 0.67 kcal is accumulated in the body; (II). Out of the 48.1 kcal of feed supplied to an individual of the age 0 growout period, 11.3 kcal is unused, 36.9 kcal is taken in, and 98% of it is assimilated. Twenty nine percent and 49% of assimilated energy is lost by excretion metabolism and respiration metabolism, respectively. The remaining 22% or 6.6 kcal is accumulated in the body; (III). Out of the 70.4 kcal of feed supplied to an individual of the age 0 rearing period, 23.8 kcal is unused, 46.6 kcal is taken in, and 98% of it is assimilated. Eighteen percent and 72% of assimilated energy is lost by excretion metabolism and respiration metabolism, respectively. The remaining 10% or 4.7 kcal is accumulated in the body; (IV). Out of the 35.7 kcal of feed supplied to an individual of the age 1 thinning period, 18.3 kcal is unused, 17.4 kcal is taken in, and 97% of it is assimilated. Twelve percent and 150% of assimilated energy is lost by excretion metabolism and respiration metabolism, respectively. There is a net loss of 63% or 9.9 kcal causing a negative growth in weight; (V). Out of the 104.1 kcal of feed supplied to an individual of the age 1 rearing period, 26.4 kcal is

Table 9. Feed energy budget of yellowtail cultured. Data are expressed as kcal/ind./day.

| Cultured period (days) | Feed Supplied (S) | Feed remained | | | Feed intake (I) | Feces (F) | Non-fecal (U) | Excretion (E)=F+U | Specific dynamic action (SDA) | Heat loss (H)= I−F−U −SDA−G | Metabolic loss (M)= SDA+H | Growth (G) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | >165 *μm* (SRF) | <165 *μm* (LRF) | Total (R) | | | | | | | | |
| 19 (June–July) | 2.71 | 0.16 | 0.26 | 0.42 | 2.29 | 0.05 | 0.80 | 0.86 | 0.23 | 0.53 | 0.76 | 0.67 |
| 17 (July) | 10.9 | 0.56 | 1.24 | 1.80 | 9.19 | 0.20 | 2.75 | 2.95 | 0.78 | 2.80 | 3.58 | 2.66 |
| 18 (Aug–Sep) | 34.9 | 2.35 | 4.10 | 6.45 | 28.4 | 0.64 | 8.08 | 8.72 | 2.65 | 9.44 | 12.0 | 7.65 |
| 15 (Sep–Oct) | 57.3 | 4.89 | 7.58 | 12.4 | 44.9 | 0.94 | 12.3 | 13.3 | 4.13 | 18.8 | 22.9 | 8.63 |
| 13 (Oct) | 89.1 | 11.3 | 12.9 | 24.3 | 64.8 | 1.61 | 13.9 | 15.5 | 7.74 | 34.1 | 41.8 | 7.37 |
| 10 (Nov–Dec) | 81.1 | 10.3 | 13.8 | 24.2 | 56.9 | 1.22 | 13.2 | 14.4 | 5.81 | 30.6 | 36.4 | 6.05 |
| 6 (Dec) | 59.6 | 9.48 | 13.8 | 23.3 | 36.2 | 1.03 | 2.88 | 3.91 | 1.96 | 27.0 | 29.0 | 3.35 |
| 6 (Jan–Feb) | 36.3 | 9.62 | 7.76 | 17.3 | 18.9 | 0.58 | 1.22 | 1.80 | 0.77 | 22.0 | 22.7 | −5.62 |
| 4 (Mar) | 32.0 | 11.8 | 7.86 | 19.6 | 12.3 | 0.48 | 0.91 | 1.39 | 0.70 | 21.8 | 22.5 | −11.6 |
| 3 (Apr) | 32.0 | 8.13 | 8.92 | 17.0 | 15.0 | 0.48 | 1.17 | 1.64 | 0.82 | 24.8 | 25.6 | −12.3 |
| 10 (Apr–May) | 42.2 | 6.40 | 12.7 | 19.1 | 23.1 | 0.58 | 3.49 | 4.07 | 1.37 | 27.8 | 29.2 | −10.2 |
| 15 (May) | 66.2 | 7.94 | 11.8 | 19.7 | 46.5 | 1.00 | 7.82 | 8.82 | 3.57 | 29.3 | 32.9 | 4.76 |
| 20 (June–July) | 101 | 10.3 | 15.2 | 25.5 | 76.3 | 1.83 | 14.6 | 16.4 | 7.11 | 43.9 | 51.0 | 8.83 |
| 14 (Aug) | 143 | 19.0 | 14.7 | 33.8 | 110 | 2.87 | 25.3 | 28.1 | 12.6 | 60.6 | 73.3 | 8.69 |
| 11 (Oct) | 174 | 23.6 | 23.1 | 46.8 | 128 | 3.27 | 24.6 | 27.9 | 17.8 | 70.3 | 88.1 | 11.9 |
| 7 (Dec) | 175 | 44.1 | 39.3 | 83.5 | 91 | 2.34 | 11.3 | 13.6 | 11.1 | 59.0 | 70.1 | 7.85 |
| Mean | 71.2 | 11.2 | 12.2 | 23.4 | 47.8 | 1.19 | 9.04 | 10.2 | 4.95 | 30.2 | 35.1 | 2.42 |
| S.D. | 52.0 | 10.3 | 8.95 | 19.0 | 36.4 | 0.92 | 7.77 | 8.61 | 4.99 | 19.2 | 23.8 | 7.71 |
| Min | 2.71 | 0.16 | 0.26 | 0.42 | 2.29 | 0.05 | 0.80 | 0.86 | 0.23 | 0.53 | 0.76 | −12.3 |
| Max | 175 | 44.1 | 39.3 | 83.5 | 128 | 3.27 | 25.3 | 28.1 | 17.8 | 70.3 | 88.1 | 11.9 |

Table 10. Precentage of feed energy budget of yellowtail cultured.

| Cultured period (days) | Feed Supplied (S) | Feed remained >165 μm (SRF) | <165 μm (LRF) | Total (R) | Feed intake (I) | Feces (F) | Non-fecal (U) | Excretion (E)=F+U | Specific dynamic action (SDA) | Heat loss (H)= I−F−U −SDA−G | Metabolic loss (M)= SDA+H | Growth (G) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19 (June–July) | 118.3 | 7.2 | 11.2 | 18.3 | 100.0 | 2.3 | 35.1 | 37.4 | 10.0 | 23.2 | 33.1 | 29.4 |
| 17 (July) | 119.6 | 6.1 | 13.5 | 19.6 | 100.0 | 2.2 | 29.9 | 32.1 | 8.5 | 30.4 | 39.0 | 28.9 |
| 18 (Aug–Sep) | 122.7 | 8.2 | 14.4 | 22.7 | 100.0 | 2.3 | 28.4 | 30.6 | 9.3 | 33.2 | 42.5 | 26.9 |
| 15 (Sep–Oct) | 127.8 | 10.9 | 16.9 | 27.8 | 100.0 | 2.1 | 27.5 | 29.6 | 9.2 | 42.0 | 51.2 | 19.2 |
| 13 (Oct) | 137.5 | 17.4 | 20.0 | 37.5 | 100.0 | 2.5 | 21.5 | 24.0 | 11.9 | 52.7 | 64.6 | 11.4 |
| 10 (Nov–Dec) | 142.5 | 18.2 | 24.3 | 42.5 | 100.0 | 2.1 | 23.3 | 25.4 | 10.2 | 53.8 | 64.0 | 10.6 |
| 6 (Dec) | 164.3 | 26.1 | 38.2 | 64.3 | 100.0 | 2.8 | 7.9 | 10.8 | 5.4 | 74.6 | 80.0 | 9.2 |
| 6 (Jan–Feb) | 191.6 | 50.7 | 40.9 | 91.6 | 100.0 | 3.0 | 6.5 | 9.5 | 4.1 | 116.1 | 120.2 | −29.7 |
| 4 (Mar) | 259.3 | 95.7 | 63.6 | 159.3 | 100.0 | 3.9 | 7.3 | 11.2 | 5.7 | 177.2 | 182.8 | −94.1 |
| 3 (Apr) | 213.7 | 54.2 | 59.5 | 113.7 | 100.0 | 3.2 | 7.8 | 11.0 | 5.5 | 165.6 | 171.1 | −82.0 |
| 10 (Apr–May) | 182.7 | 27.7 | 55.0 | 82.7 | 100.0 | 2.5 | 15.1 | 17.6 | 5.9 | 120.6 | 126.5 | −44.1 |
| 15 (May) | 142.5 | 17.1 | 25.4 | 42.5 | 100.0 | 2.1 | 16.8 | 19.0 | 7.7 | 63.1 | 70.8 | 10.2 |
| 20 (June–July) | 133.5 | 13.6 | 20.0 | 33.5 | 100.0 | 2.4 | 19.2 | 21.6 | 9.3 | 57.6 | 66.8 | 11.6 |
| 14 (Aug) | 130.7 | 17.3 | 13.4 | 30.7 | 100.0 | 2.6 | 23.0 | 25.6 | 11.5 | 55.1 | 66.5 | 7.9 |
| 11 (Oct) | 136.6 | 18.5 | 18.1 | 36.6 | 100.0 | 2.6 | 19.3 | 21.8 | 13.9 | 54.9 | 68.9 | 9.3 |
| 7 (Dec) | 191.2 | 48.2 | 43.0 | 91.2 | 100.0 | 2.6 | 12.3 | 14.9 | 12.1 | 64.9 | 76.5 | 8.6 |
| Mean | 157.2 | 27.3 | 29.8 | 57.2 | 100.0 | 2.6 | 18.8 | 21.4 | 8.8 | 74.0 | 82.8 | −4.2 |
| S.D. | 38.3 | 23.1 | 17.1 | 38.8 | 0.0 | 0.5 | 8.6 | 8.3 | 2.8 | 44.9 | 43.1 | 36.8 |
| Min | 118.3 | 6.1 | 11.2 | 18.3 | 100.0 | 2.1 | 6.5 | 9.5 | 4.1 | 23.2 | 33.1 | −94.1 |
| Max | 259.3 | 95.7 | 63.6 | 159.3 | 100.0 | 3.9 | 35.1 | 37.4 | 13.9 | 177.2 | 182.8 | 29.4 |

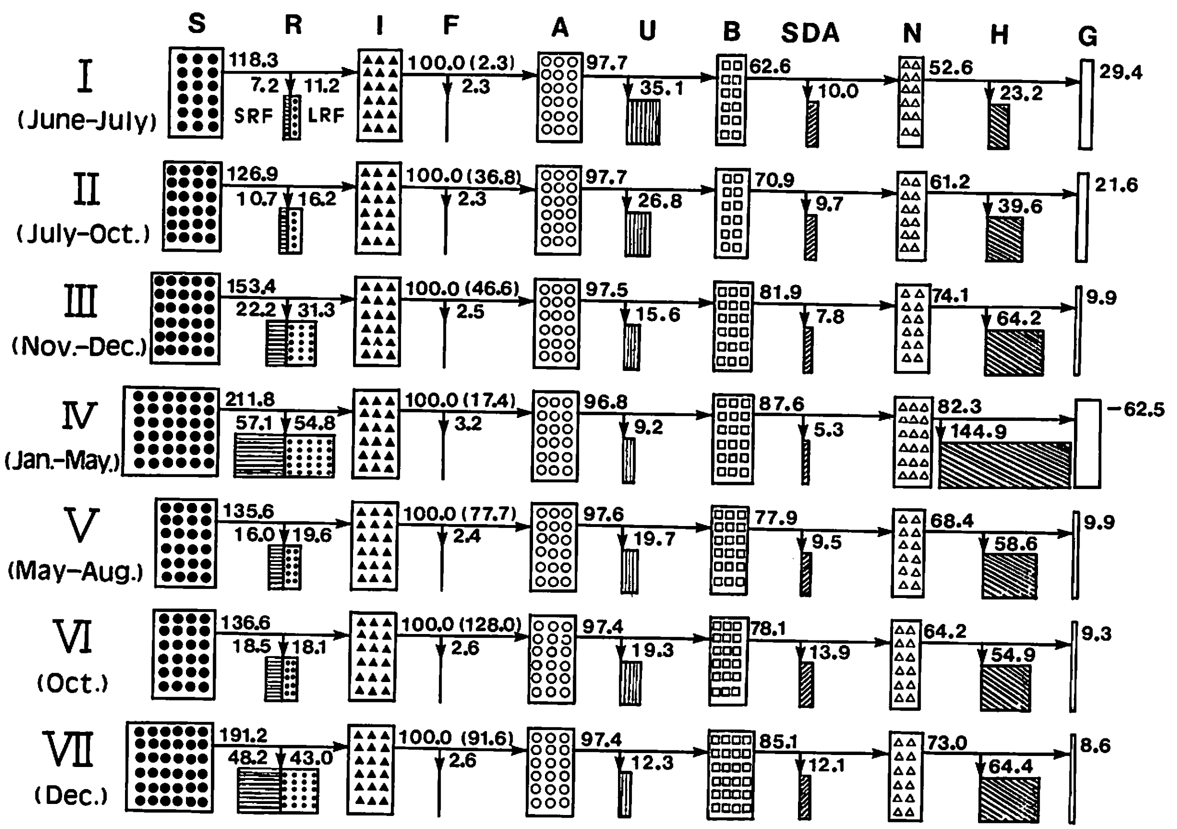


Figure 6. Flowing chart of culture process showing the rate of energy budget of yellowtail cultured. The number in each parenthesis is shown as the amount of food intake as kcal/ind./day. *S*: feed supplied, *R*: feed remaining, *I*: feed intake, *F*: feces, *A*: assimilation, *U*: non-fecal, *B*: metabolism, *SDA*: specific dynamic action, *N*: net, *H*: heat loss, *G*: growth.

unused, 77.7 kcal is taken in, and 98% of it is assimilated. Twenty two percent and 68% of assimilated energy is lost by excretion metabolism and respiration metabolism, respectively. The remaining 10% or 7.4 kcal is accumulated in the body; (VI). Out of the 174.9 kcal of feed supplied to an individual of the age 1 growout period, 46.9 kcal is unused, 128.0 kcal is taken in, and 97% of it is assimilated. Twenty two percent and 69% of assimilated energy is lost by excretion metabolism and respiration metabolism, respectively. The remaining 9% or 11.9 kcal is accumulated in the body; (VII). Out of 175.2 kcal of feed supplied to an individual of the age 1 harvesting period, 83.5 kcal is unused, 91.6 kcal is taken in, and 97% of it is assimilated. Fifteen percent and 77% of assimilated energy is lost by excretion metabolism and respiration metabolism, respectively. The remaining 9% or 7.9 kcal is accumulated in the body.

A review of energy allocation through each growth phase shows the following: the assimilation efficiency of feed taken in was 97 to 98%, and the remaining portion is excreted externally as feces. The assimilated energy is accumulated, lost by respiration metabolism, or excreted as metabolites such as urea. Accumulated energy, respiration metabolism, and excretion energy by metabolites were −63 to 29%, 33 to 150%, and 12 to 37% of energy taken in, respectively. These results of biological production shows that the allocation pattern of metabolism varied markedly by growth phase of reared yellowtail and that assimilation efficiency and growth efficiency were higher in the early stages of growth.

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# EVALUATION OF WATER QUALITY BY OBSERVATION OF DISSOLVED OXYGEN CONTENT IN MARICULTURE FARMS

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## ABSTRACT

Evaluation of water quality by observation of DO (dissolved oxygen) content was conducted for 38 fish farms in Azuma Town, Kagoshima Prefecture, in order to study the process of water deterioration in mariculture farms. The observation of DO was done by monitoring the horizontal and vertical DO distributions. The DO reduction rates were then calculated for each farm. Relationships between DO reduction rates and fish mortality were examined. The farms were then classified by a "standard score" system that was based on DO reduction rates. It was concluded that DO observation for the farms provides one method of scientific diagnosis for the assessment of maricultural water quality and can be easily measured by the farmers themselves.

## INTRODUCTION

Mariculture of the yellowtail, *Seriola quinqueradiata,* was initiated at Adoike Farm, Kagawa Prefecture, in 1927. The techniques have been developing rapidly in Shikoku and Kyushu Islands since the 1960's. However, water pollution due to excess nutrients from the farms has become a serious problem (Hirata 1989; Hirata and Kadowaki 1990). The blooming of red tide organisms in fish farms is a typical example. This has become a serious problem in shrimp culture (Danakusumah and Hirata 1991; Millamena et al. 1991; Visscher and Duerr 1991). Sustainable development of mariculture within ecosystems should be studied (Folke and Kautsky 1989, 1992).

Inoue and Tanaka (1973) proposed that the difference in dissolved oxygen (DO) in and out of a fish farm should be studied as a part of mariculture management and regarded as a necessary procedure to understand the mechanics of the whole fish farm environment. Because the method of Inoue and Tanaka (1973) used the Winkler method for DO level determination, their data was limited. Succeeding studies by Hirata et al. (1976, 1978) measured DO levels with an electronic DO meter from a cruising ship. This technique could gather large amounts of data in a short time and was applied to the mariculture farms. The reason why DO could be used as a tool for mariculture management, aside from the various farm environmental factors, is that the change of DO is a biological index (Kadowaki 1989; Kadowaki et al. 1989).

In order to inspect the water quality in the farms, some aspects of DO content in the yellowtail pen culture farms were observed in experiments.

## HORIZONTAL DO DISTRIBUTION

Horizontal DO distributions were observed in all the fish farms around Azuma Town, Kagoshima Prefecture, during the period of study in 1984 and 1987.

The method of measuring DO is shown in Figure 1. The oxygen electrode of the DO meter (YSI 57 and YSI 58 were used) was lowered from the boat to 2 to 3 m water depth, and the oxygen volume was continuously recorded at a cruising speed of 2 kt. The difference in the oxygen volume could be determined easily between various places such as the fish culture area and the non-culture area.

Changes in DO between the waters of the upper stream and down stream directions of the cages were observed. These changes are shown graphically in

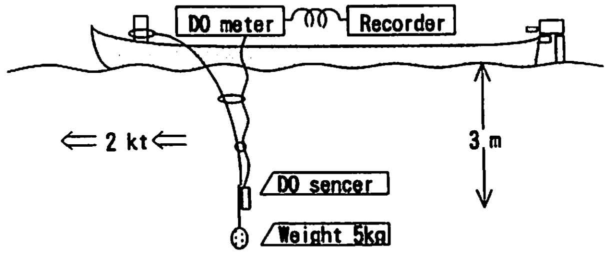


Figure 1. Schematic diagram of cruising observation of horizontal distribution of dissolved oxygen in the fish farm.

Figures 2-A and 2-B. The oxygen consumption of a fish cage was then determined to be the difference between the upper and lower stream lines as shown in Figure 2-C.

The relationship between the oxygen reduction rate and actual fish mortality is illustrated in Figure 3. In general, fish mortality of 0.085%/day is considered as the "economical lethal value" for maintaining profitable mariculture (Hirata and Kadowaki 1991). Therefore, oxygen reduction rates should not exceed 10% (as shown in the dotted area in Figure 3) to maintain economic profitability of the fish farm.

Horizontal DO distributions were variable by area and season. The seasonal variation in DO distribution of a fish farm (Farm No. 22) is shown in Figure 4-A. The observations were made on March 10, June 6, September 4, and December 12, 1983. The DO distribution did not only vary by season but also by area. The DO distribution of four other different farms is

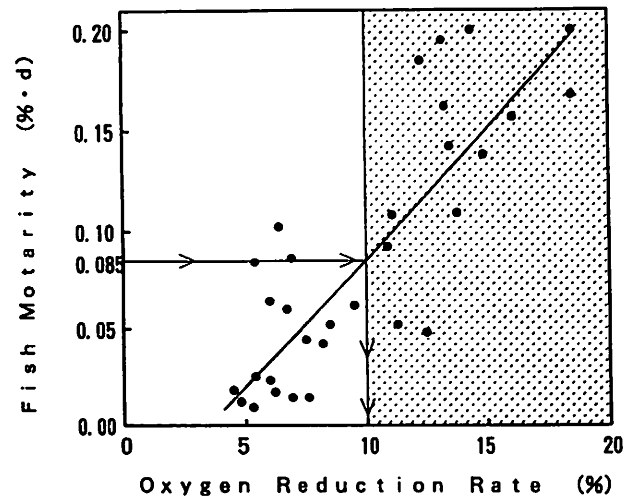


Figure 3. Relaltion between oxygen reduction rate and fish mortality. Fish mortality 0.085%/day is "economic lethal value".

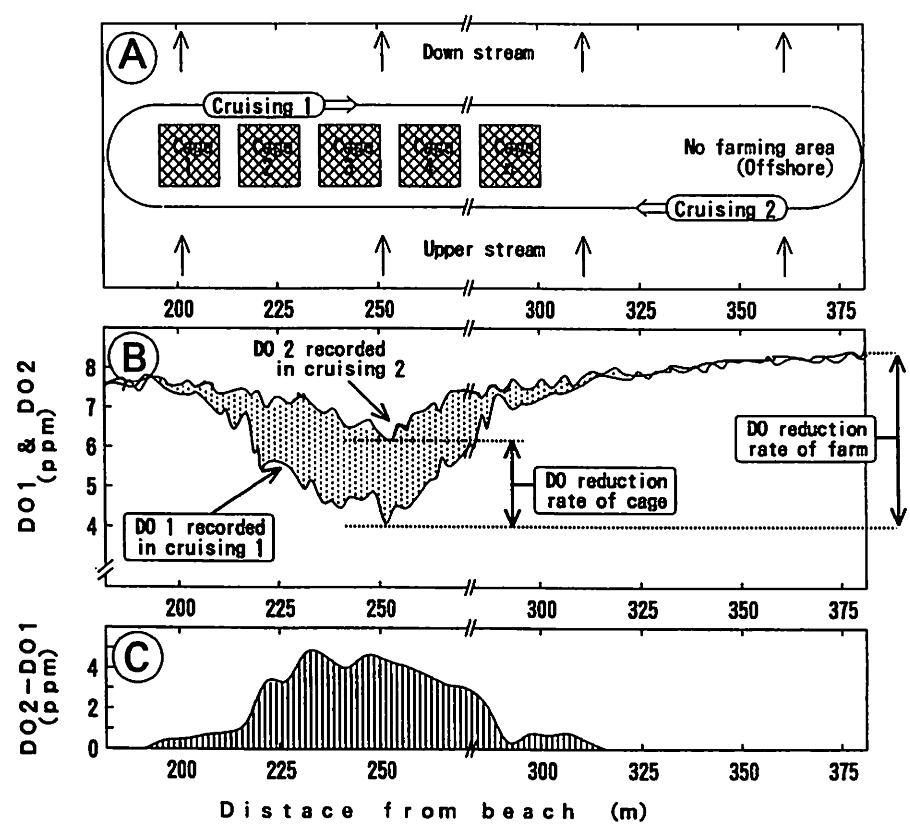


Figure 2. Observation dissolved oxygen (DO) by cruising in the fish farm.
Ⓐ Cruising course 1 at down stream and course 2 at upper stream.
Ⓑ DO 1 DO 2 recorded in cruising 1 and cruising 2, respectively.
Ⓒ Difference of DO 2 and DO 1 around the fish cages.

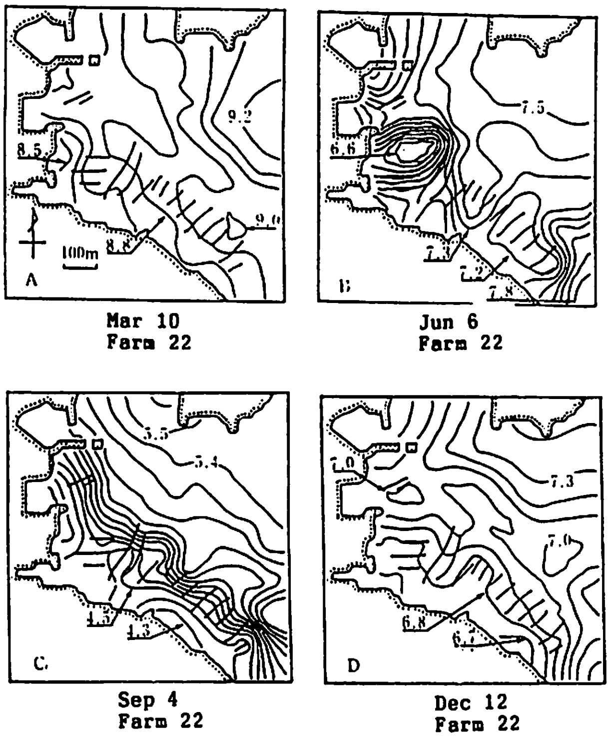


Figure 4-A. Horizontal DO distribution in different seasons at the same farm.

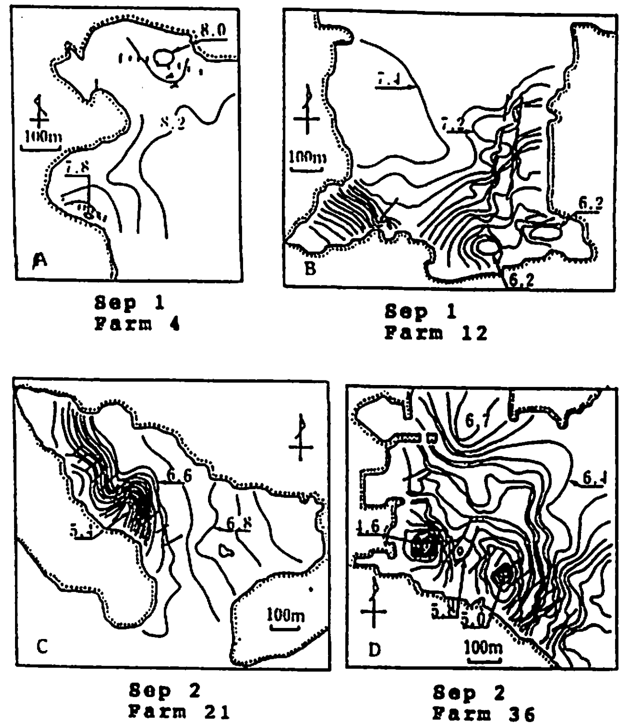


Figure 4-B. Horizontal DO distribution in different farms during the same season.

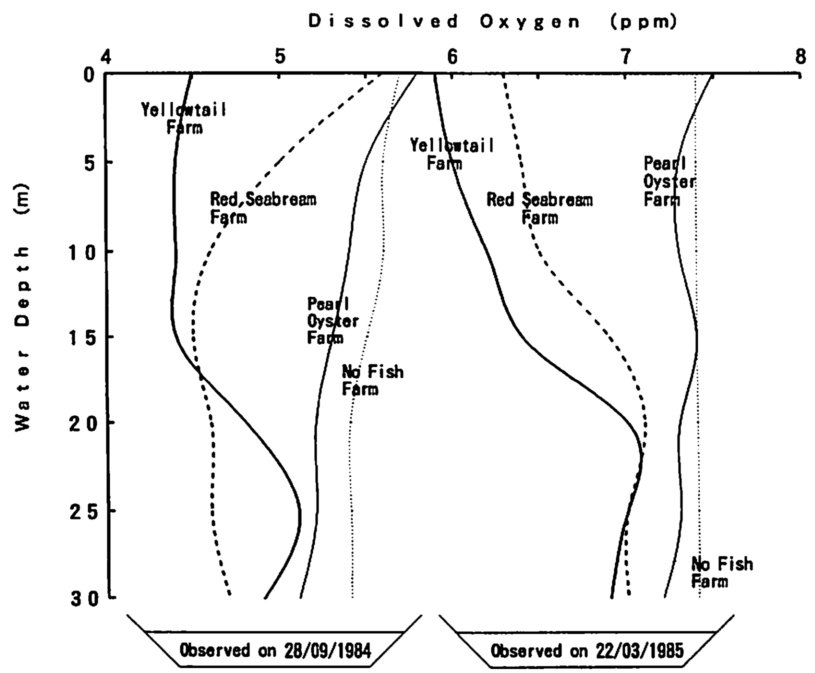


Figure 5. Vertical distribution of dissolved oxygen in the Shitaba Fish Farms, Ehime Pref.

shown in Figure 4-B. All of the observations were made during the first week of September 1978. The DO distributions in Farms A and B were simpler than those of Farms C and D. This means that mariculture activity in Farms C and D was higher than Farms A and B.

## VERTICAL DO DISTRIBUTION

Vertical DO distribution of the waters in the mariculture farms (Shitaba Farms) around the Uwa Sea, Ehime Prefecture, were observed, by the same method as described above, in September 1984 and March 1985.

The results are presented in Figure 5.

The DO values varied from 4.4 to 5.8 ppm in September 1984 and from 5.9 to 7.5 ppm in March 1985. The DO levels in the pearl oyster farm were much higher than those in the yellowtail farm, while the DO levels in the red sea bream farms were intermediate.

In general, DO levels of the surface water were higher than those of the deeper waters. However, surface DO levels in the red sea bream and yellowtail farms were lower than those of deep waters. These results are the opposite of what could be commonly observed under natural sea conditions wherein surface waters usually have higher DO levels than deeper waters. Lower DO values observed in the surface waters indicated oxygen consumption by the cultured fish in these areas.

## EVALUATION OF THE WATER ENVIRONMENT BY DO REDUCTION RATES

The DO reduction rates were calculated by the formula below:

$$\text{DO reduction rate } (\%) = [100(A-B)/B],$$

where A is DO level in the farm, and B is the DO level outside the farm.

"Standard Score" (SS) of the environment of the 38 farms around Azuma Town were calculated using the formula below:

$$SS = [10(a-b)/s] + 50,$$

where a is the average value of the DO reduction rates of the 38 farms, and b is the DO reduction rate of each farm.

"Standard Scores" are commonly adopted by the middle and high schools in Japan. Highest SS was 64, indicating a DO reduction rate of zero; lowest SS was 24 with a DO reduction rate of 38%. Group A farms obtained the SS ranging from 55–64 points and had DO reduction rates of less than 10%. Group B farms obtained intermediate SS ranging from 44–54 points and had DO reduction rates of between 10–19%. Group C farms obtained the lowest SS ranging from 24 to 41 and had DO reduction rates of over 21% (Table 1).

Table 1. Standard score (SS) of water environment determined by DO reduction rates in fish farm.

| Order | Farm number | Rate of DO reduction (%) | Standard score (*1) | Rank (*2) |
|---|---|---|---|---|
| 1 | 36 | 0 | 64 | A |
| 2 | 19 | 0 | 64 | A |
| 3 | 3 | 1 | 63 | A |
| 4 | 5 | 2 | 62 | A |
| 5 | 4 | 2 | 62 | A |
| 6 | 33 | 3 | 61 | A |
| 7 | 38 | 4 | 60 | A |
| 8 | 6 | 6 | 58 | A |
| 9 | 7 | 6 | 58 | A |
| 10 | 20 | 7 | 57 | A |
| 11 | 26 | 7 | 57 | A |
| 12 | 35 | 8 | 56 | A |
| 13 | 24 | 8 | 56 | A |
| 14 | 18 | 9 | 55 | A |
| 15 | 28 | 10 | 54 | B |
| 16 | 12 | 10 | 54 | B |
| 17 | 25 | 11 | 53 | B |
| 18 | 14 | 11 | 53 | B |
| 19 | 15 | 14 | 50 | B |
| 20 | 27 | 14 | 50 | B |
| 21 | 32 | 14 | 50 | B |
| 22 | 31 | 15 | 49 | B |
| 23 | 37 | 15 | 49 | B |
| 24 | 29 | 16 | 47 | B |
| 25 | 34 | 16 | 47 | B |
| 26 | 13 | 16 | 47 | B |
| 27 | 11 | 17 | 46 | B |
| 28 | 1 | 17 | 46 | B |
| 29 | 16 | 17 | 46 | B |
| 30 | 17 | 18 | 45 | B |
| 31 | 21 | 19 | 44 | B |
| 32 | 2 | 22 | 41 | C |
| 33 | 9 | 22 | 41 | C |
| 34 | 8 | 23 | 40 | C |
| 35 | 30 | 28 | 35 | C |
| 36 | 22 | 34 | 28 | C |
| 37 | 23 | 36 | 26 | C |
| 38 | 10 | 38 | 24 | C |

*1) $\{10(a-b)/s\}+50$
a: each DO reduction rate in individual farm
b: average DO reduction rate in all the farms
s: standard deviation

*2) Rank A: below 10% of DO reduction rate
Rank B: between 11 and 20% of the rate
Rank C: over 21% of the rate

## ACKNOWLEDGMENTS

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# THE ROLE OF BACTERIA IN MASS CULTURE OF THE ROTIFER *BRACHIONUS PLICATILIS*

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## ABSTRACT

The rotifer *Brachionus plicatilis* is a food organism widely used for rearing the larvae of fishes and crustaceans. The rotifer is found to need vitamin $B_{12}$ for its growth when it is cultured under bacteria-free condition. In traditional culture of the rotifer, the output of the $B_{12}$ in the rotifer culture tank is 2–3 times more than the input of $B_{12}$. Accordingly, bacteria are found to be very important as a vitamin $B_{12}$ supplier. The rotifer can grow rapidly when some bacterial strains are provided as $10^{7-10}$ CFU/m*l*. When a bacterial strain, TP4, is added to rotifer cultures, the rotifer densities increase to 4,417–5,540/m*l* in beakers and to 1,017–1,254/m*l* in tanks. Some freshwater *Chlorella* strains, which are cultured on a large scale, are found to absorb $B_{12}$. When the $B_{12}$-enriched *Chlorella* is used as food for culturing the rotifer, the growth improves remarkably.

## INTRODUCTION

The rotifer *Brachionus plicatilis* is a small zooplankton that lives in brackish and coastal waters. There are two variations called large (L) and small (S). Techniques for rotifer culture are classified into two types —batch culture and semicontinuous culture. The former is when the whole culture in the tank is harvested at once and a part of it is inoculated into next culture. The latter, which is also called thinning culture, is when the rotifer density is kept constant by periodic elimination for harvest. The advocation of the rotifer as a food source for rearing the larvae of fishes and crustaceans makes the mass culture of the rotifer a successful seedling production. However, unexpected sudden death or suppressed growth of the rotifer sometimes occurs in mass culture in outdoor ponds. The $B_{12}$ deficiency or the unstable growth of $B_{12}$-producing bacteria is one of the problems in culturing the rotifer. In this study, the functions of $B_{12}$ for the stable culture of the rotifer are reviewed.

## VITAMIN $B_{12}$ REQUIREMENT OF THE ROTIFER

*Brachionus plicatilis* was first reported to require vitamin $B_{12}$ by Droop and Scott (1978). To examine the uptake of the vitamin by the rotifer, Scott (1981) used the bacteria-free cultures of the algae *Brachiomonas submarina* var. *pulsifera* Droop and *Dunaliella* SMBA Strain 246 to investigate the mode of the uptake of the vitamin. The rotifer was found to have a definite vitamin $B_{12}$ requirement. The rate of uptake by the rotifer has been measured to be 0.1 pg/animal/day by adding $^{57}Co$ labeled $B_{12}$. Meanwhile, Hirayama and Funamoto (1983) also found the vitamin requirement for the rotifer when baker's yeast *Saccharomyces cerevisiae* was given as food for the culture in test tubes under bacteria-free conditions. First laid eggs or just hatched neonates were transferred into the tubes (ten per tube) for several days (batch culture) or (one or two per tube) for life time (individual culture) experiments. The study indicated that the yeast without any supplement is deficient in the nutritive quality for the population growth of the rotifer (Table 1). The supply of the vitamin in the culture water showed a considerable effect both on population growth indices and on hatching of laid eggs.

For estimating $B_{12}$ demand of the rotifer, the sterilized animals were cultured for 7 days with both $B_{12}$-free *Nannochloropsis oculata* and a fixed quantity of $B_{12}$ (Yu et al. 1990a). Without $B_{12}$, the rotifer did not increase even in the food suspension of *N. oculata*. Using a dosage from 50 to 1,000 pg/tube, the initial 10 individuals increased to 48–431/tube for S strain and to 30–240/tube for L strain, respectively. $B_{12}$ demand of the

Table 1. Rotifer growth after receiving vitamin $B_{12}$ (Hirayama and Satuito 1991).

| Culture (period) | Index | Basic medium* | Basic medium plus $B_{12}$ (1.4 $\mu$g/m*l*) |
|---|---|---|---|
| Individual (lifetime) | r | 0.23 | 0.39 |
| | Ro | 1.93 | 3.20 |
| Batch** (3 days) | Live | 19.0 | 24.5 |
| | Dead | 6.5 | 4.0 |
| | Egg | 9.0 | 15.5 |
| | Total | 34.5 | 44.0 |
| Batch** (6 days) | Live | 22.0 | 35.5 |
| | Dead | 5.5 | 10.0 |
| | Egg | 5.5 | 9.5 |
| | Total | 33.0 | 54.5 |

*: The basic medium contains a 200 $\mu$g/m*l* of baker's yeast. **: Mean values of duplicated experiments. r: The intrinsic rate of population increase. Ro: Net reproduction rate.

Table 2. Balance of vitamin $B_{12}$ during batch culture.

| Input | ($\mu$g) | Output | ($\mu$g) |
|---|---|---|---|
| Rotifer inoculated | 2,486 | Rotifer harvested | 1,639 |
| Particle suspended | 359 | Particle suspended | 1,255 |
| Water | 217 | Water | 2,152 |
| $\omega$-yeast | 42 | | |
| Total | 3,104 | Total | 5,046 |

Table 3. Balance of vitamin $B_{12}$ during semicontinuous culture.

| Input | ($\mu$g) | Output | ($\mu$g) |
|---|---|---|---|
| Rotifer inoculated | 13,960 | Rotifer harvested | 36,676 |
| Particle suspended | 5,300 | Particle suspended | 12,836 |
| Water | 1,200 | Water | 7,300 |
| *N. oculata* | 4,833 | | |
| $\omega$-yeast | 3 | | |
| Total | 25,296 | Total | 56,812 |

rotifer calculated through dividing the $B_{12}$ dosage by the rotifer increment was 0.88–1.04 (mean 1.0) pg/rotifer for the Thai S strain and 1.32–1.67 (mean 1.5) pg/rotifer for the Nagasaki L strain.

## VITAMIN $B_{12}$ CONTENTS

Although $B_{12}$ is essential for rotifer growth, baker's yeast contains little vitamin $B_{12}$. Meanwhile, the rotifer culture is successful when the yeast plus *N. oculata* or only the yeast is used as foods with the traditional culture method. Imada (1984) evaluated $B_{12}$ contents in both the rotifer and its food from a mass culturing site and found out that the $B_{12}$ levels in foods were much lower than that in the rotifer. The yeast and *N. oculata* contained 6.6 and 42–89 $\mu$g/kg in their cells, respectively. Yu et al. (1989) also evaluated the $B_{12}$ contents concerning mass culture of the rotifer: *N. oculata* with culture medium, 16.1 pg/m*l*; baker's yeast, 0.12 $\mu$g/kg; $\omega$-yeast (the yeast enriched with squid liver oil), 0.48 $\mu$g/kg; tap water, 0.88 pg/m*l*; and seawater, 11.0 pg/m*l*. Those values could not support the high $B_{12}$ contents of the rotifer (6,222–11,231 $\mu$g/kg) even after considering the amount of ingestion.

## FUNCTION OF VITAMIN $B_{12}$-PRODUCING BACTERIA

From the numerical values stated above, the total input ($B_{12}$ in the water introduced, feed, and rotifer inoculum) and the total output ($B_{12}$ in harvested rotifer and culture) during batch culture were calculated (Table 2). They were estimated as 3,104 $\mu$g and 5,046 $\mu$g in a 11 $m^3$ pond, respectively. However, $B_{12}$ contained in the rotifer became less with the lapse of time because of mortality and bad growth. As to semicontinuous culture in a 150 $m^3$ pond, the input was estimated as 25,296 $\mu$g and the output as 56,812 $\mu$g (Table 3). The calculations for both cultures show that the total output of $B_{12}$ was 1.6–2.2 times higher than the total input (Yu et al. 1989). Yu et al. (1989) observed the changes in density of $B_{12}$-producing bacteria during semicontinuous culture, in which the total bacterial density increased from $10^{6.2}$ to $10^{8.2}$ CFU/m*l*, and the $B_{12}$-producing bacteria increased from $10^{5.9}$ to $10^{7.3}$ CFU/m*l*. During the experiment, 100 strains of bacteria were isolated, and 35 of them were found to have $B_{12}$ productivity. Those $B_{12}$-producing bacteria were composed of *Pseudomonas* (65.7%), *Moraxella* (11.4%), *Vibrio* (8.6%), *Bacillus* (8.6%), and others (5.7%). Yu et al. (1988) investigated vitamin productivity on 6 strains of $B_{12}$-producing bacteria and found that $B_{12}$ in the culture

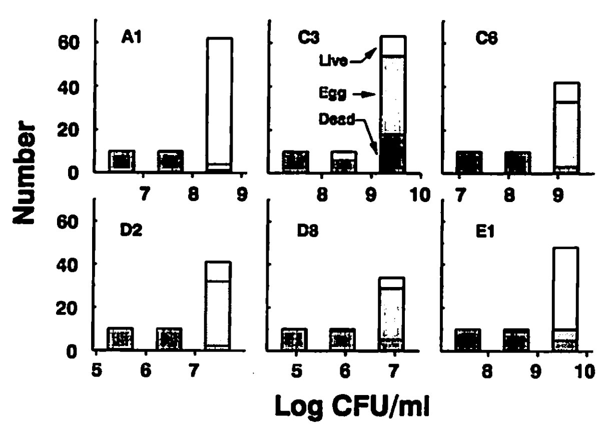


Figure 1. Number of the rotifer after 7 days of batch culture (25°C) fed with $B_{12}$-producing bacterial strains of A1, C3, C6, D2, D8, and E1. Initial number was 10.

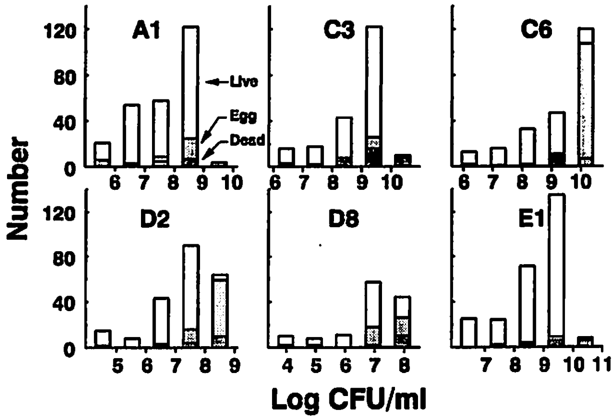


Figure 2. Number of the rotifer after 7 days of batch culture provided with baker's yeast(250 $\mu$g/m$l$) and supplemented with $B_{12}$-producing bacteria. The culture conditions and the symbols are the same as in Figure 1. Initial number was 10. The final number in the culture without any bacteria addition was 24.

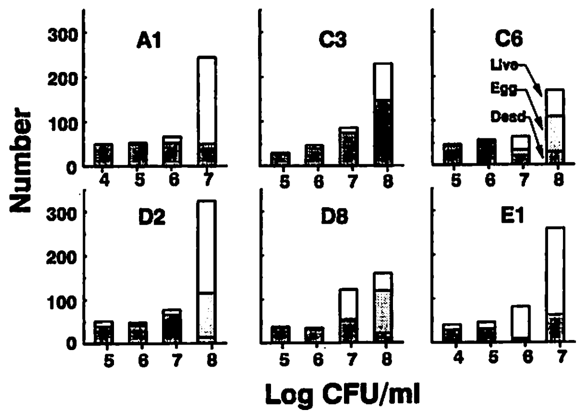


Figure 3. Number of rotifers after 7 days of batch culture provided with *N. oculata* suspension ($5\times10^6$ cells/m$l$) and supplemented with $B_{12}$-producing bacteria. The culture conditions and the symbols are same as in Figure 1. Initial number was 10. The final number in a culture without any bacteria addition was 33.

media reached 1.18–16.50 ng/m$l$ within 8 days. Moreover, $B_{12}$ was proved to be stored inside cells from the fact that dissolved $B_{12}$ in the culture media had accounted for only 0.7–1.9%. When those bacteria were added as $10^7$–$10^{11}$ CFU/m$l$ into the culture, the rotifer growth was remarkably improved (Figsure 1–3).

To select an excellent bacterial strain, 34 of $B_{12}$-producing strains were tested on their nutritive complement. When the strain TP4 was propagated and added into mass culture together with baker's yeast, the rotifer increased from 124–139/m$l$ to 4,417–5,540/m$l$ in 9 days in 2 $l$ beakers (Figure 4). In 500 $l$ tanks, the rotifer increased from 242–288 to 1,017–1,254/m$l$ in 6 days (Figure 5).

Studies show that $B_{12}$-producing bacteria play an important role as a nutritive complement particularly in the traditional culture containing baker's yeast. Although vitamin $B_{12}$ is generally insufficient either in foods or waters, some bacteria are able to synthesize this vitamin. However, other bacteria inhibited the growth of the rotifer (Yu et al. 1990b).

## ROTIFER CULTURE FED ON $B_{12}$-ENRICHED *CHLORELIA*

In traditional rotifer culture, $B_{12}$ levels both in foods and culture waters are too low to support the growth of the rotifer just after the inoculation. It takes time for the propagation of $B_{12}$-producing bacteria. This is one of the reasons for the poor growth of the rotifer. To get stable mass production of the rotifer, it is desirable to develop a food source that can support rotifer growth nutritionally by itself.

Freshwater *Chlorella,* a unicellular green alga, is commercially produced in Japan. If the alga could be used for mass culture of the rotifer, it would save labor, reduce coasts, and advance stability. Maruyama et al. (1989), however, found that the vitamin $B_{12}$ contents in some *Chlorella* strains are less than 0.26 $\mu$g/(100 g dry weight). When the algal strains were cultured in the medium containing $B_{12}$, 5 strains of them without secondary carotenoid productivity could absorb the vitamin and store it in their cells. The levels of $B_{12}$ inside the cells were 171–234 $\mu$g/(100 g·dry) after 4 days of culturing. Successively, Hirayama et al. (1989) cultured the rotifer with the $B_{12}$-enriched *Chlorella* and found out that the nutritional value of *Chlorella* is greatly improved, and indexes (r and Ro) of population growth of the rotifer were almost equal to those fed with *N. oculata*.

Mass culture feeding on $B_{12}$-enriched *Chlorella* was carried out by Maruyama and Hirayama (1993). When the rotifer was cultured in 100 $l$ tanks, growth was different from controls (Table 4). The highest yield was obtained from the group cultured with the *Chlorella* containing more vitamin $B_{12}$ in the cells. In the case of commercial distribution, the recommended $B_{12}$ content was 200 $\mu$g per 100 g dry matter of the *Chlorella*.

Table 4. Rotifer yields from 100 $l$ tank culture provided with two types of concentrated *Chlorella* (Maruyama and Hirayama 1993).

| Food ($B_{12}$ ng/ g·day) | Tank no. | *Chlorella* +yeast** (g·day) | Total yield of rotifer ($\times10^7$ ind.) | $B_{12}$ in rotifer (pg/ ind.) | Total yield of rotifer per g food ($\times10^5$ ind.) |
|---|---|---|---|---|---|
| $B_{12}$ *Chlorella* | 1 | 196(28+168) | 11.37 | 1.5 | 5.8* |
| (4,500) | 2 | 194(28+166) | 11.39 | 1.6 | 5.9* |
| *Chlorella* | 3 | 186(28+158) | 9.01 | 0.6 | 4.8 |
| (0.6) | 4 | 190(28+162) | 8.41 | 0.7 | 4.4 |

*: Significant difference between foods ($p<0.05$).
**: $B_{12}$ in the yeast was 0.43 ng/g·day.

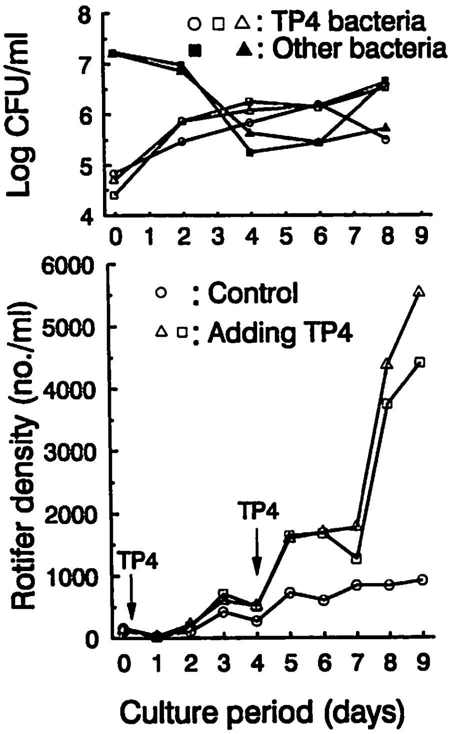


Figure 4. Changes of rotifer (below), total and TP4 bacterial densities (above) in three 2 *l* beaker cultures. Arrow indicates the addition of TP4 bacteria. Triangle and square illustrate the cultures with TP4 bacteria addition; circle represents the control.

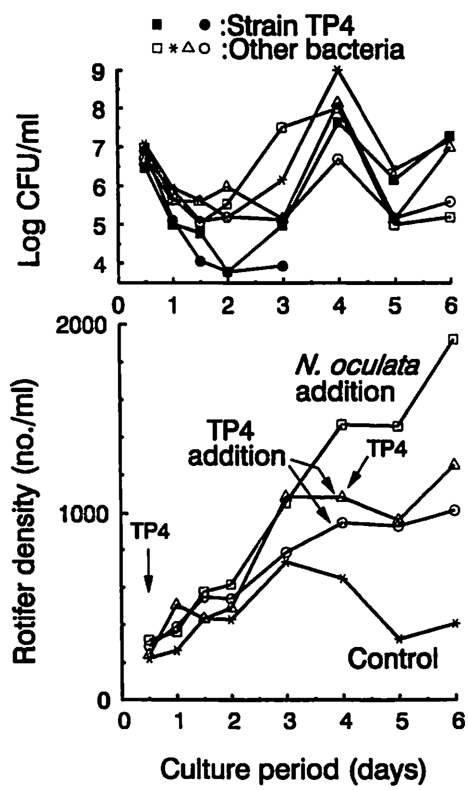


Figure 5. Changes of rotifer (below), total and TP4 bacterial densities (above) in four 500 *l* tank cultures. Arrow indicates the addition of TP4 bacteria. Square represents the culture with *N. oculata* addition; triangle and circle illustrate the cultures with TP4 bacteria addition; star is the control.

## CONCLUSION

Rotifer needs vitamin $B_{12}$ for its growth. However, the vitamin content in foods is not enough for the rotifer under axenic culture condition. In mass culture of the rotifer, a complex microbial ecosystem exists. Some bacteria produce $B_{12}$ and support the growth of the rotifer. The results of culture are, however, sometimes unstable, because of rapid succession in microbial flora. In other words, the present rotifer culture systems can be considered as an "ecosystem-dependent" form. Freshwater *Chlorella* can uptake $B_{12}$ from a medium and supplements the lack of the vitamin. Also, $B_{12}$ content of the rotifer is improved through addition of $B_{12}$-enriched *Chlorella*.

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# BIOCONTROL OF THE LARVAE REARING BIOTOPE IN AQUACULTURE

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## ABSTRACT

A microbial technique of biocontrol using the interaction of microorganisms to repress the growth of deleterious microbes or pathogens was developed in the aquaculture biotope. The bacterial strain used in this work also improved the growth of crustaceas. Protozoa were found to have a significant role in controlling the bacterial population.

## INTRODUCTION

There are several million microorganisms in 1 ml of seawater. They affect each other as prey and predator and by antagonism, commensalism, and parasitism. The more complicated these interactions are, the more intense the diversity of the microbial species. The health of organisms in nature depends primarily on their inherent resistance to microbial invasion and the biological equilibrium between competing beneficial and deleterious microorganisms at the interface of the organism as mediated by the environment. Biocontrol is a microbial technique using the interaction of microorganisms to repress the growth of deleterious microbes or pathogens. Since the late 1960's, quite a few works have been reported in which pathogenic bacteria, insects and viruses have been prevented from breeding and exterminated by using bacteria, viruses, and nematode to control them in agricultural science.

Although the control of the microbial communities with high species diversity in nature has been regarded as difficult, we hypothesize that the (matured) communities with high species diversity might accept (to a certain extent) input of information from the outside because many pathways occur. Such communities can disperse the effect caused by the invasion or addition of extrinsic organisms. Based on this point, addition of profitable microorganisms to a certain environment can be expected to produce good results and to repress the growth of pathogenic microorganisms in seawater. Herein, the bacterial strain (PM-4), which promotes the growth of prawn larvae, *Penaeus monodon,* and crab larvae, *Portunus trituberculatus,* and, at the same time, represses the growth of pathogenic bacteria, *Vibrio* spp., was used to improve the aquaculture biotope and increase the production of the larvae.

## ISOLATION AND ASSAY OF FUNCTIONAL BACTERIA

### Promoting effect on the crustacean growth

Many bacterial strains were isolated from aquaculture environments, which were purified to a single cell. Each strain isolated was added to the prawn and crab culture water with the diatom, *Navicula* sp. The survival and molt rates of prawn and crab larvae were determined. Most of the bacterial strains tested seemed to be ineffective in promoting the growth of the larvae. The Strain PM-4, however, gave higher larva survival and molting rates compared to those in the reference experiment which contained only diatom, *Navicula* sp. (Figure 1). The activity of the larvae, as determined by the ability of the larvae to access the light source, was also higher in the presence of the PM-4 strain.

### Repression of the growth of pathogenic microorganisms

Two rectangular smears of bacteria to be tested (4 cm in length with a 3 cm gap between the smears) were made on a plate of 2216E Marine Agar (Difco Co. Ltd) and a 2-cm long rectangular smear of *Listonella* (*Vibrio*) *anguillarum* was made between the two larger smears. To determine vibriostatic activity the width of the smear of *L. anguillarum* was measured. The bacterium for tested was incubated for certain periods. *L. anguillarum*

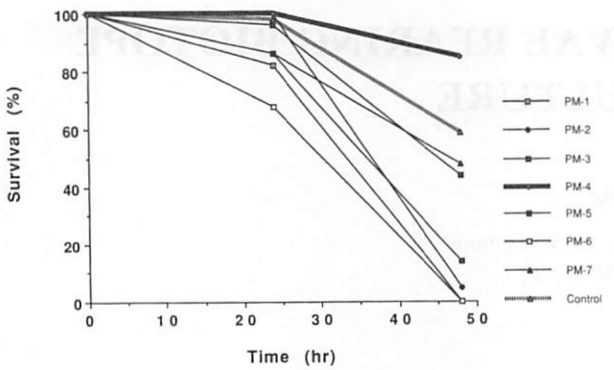


Figure 1. Survival of the larvae, *Penaeus monodon*, in the presence of various bacterial strains.

was inoculated between the two smears and incubated for 15 days before measurement. The width of *L. anguillarum* smear should be smaller than that of the control plate, if the bacteria tested indeed repress *L. anguillarum*. In this assay, the bacterium PM-4 repressed the growth of this pathogen (Figure 2).

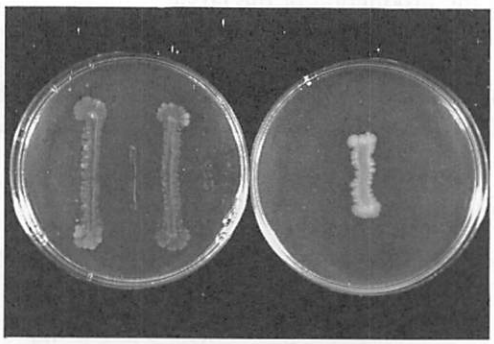

Figure 2. Assay of the Vibrio-static activity. Left medium plate: The bacterial smear tested and *Listonella* (*Vibrio*) *anguillarum* between the smears. Right medium plate: Control plate contained only *L. anguillarum*.

Population size of bacteria in aquaculture

We have now obtained the bacterial strain which is useful in controlling the aquaculture environment biologically. Before applying these bacteria to aquaculture on a large scale, we should consider the characteristic phenomena of the number of bacteria in several areas. If we count the number of bacteria in the Pacific Ocean, in both the eutrophicated area, and the uneutrophicated coastal sea areas, nearly the same numbers, about $10^5$–$10^6$ cells/mL, are found in both areas of the sea. The difference in the two areas is the number of protozoa that repress the increase of bacterial population when the bacterial number reaches more than $10^6$ cells/mL (Figure 3). This phenomenon means that even in the aquaculture ecosystem the maximum population of bac-

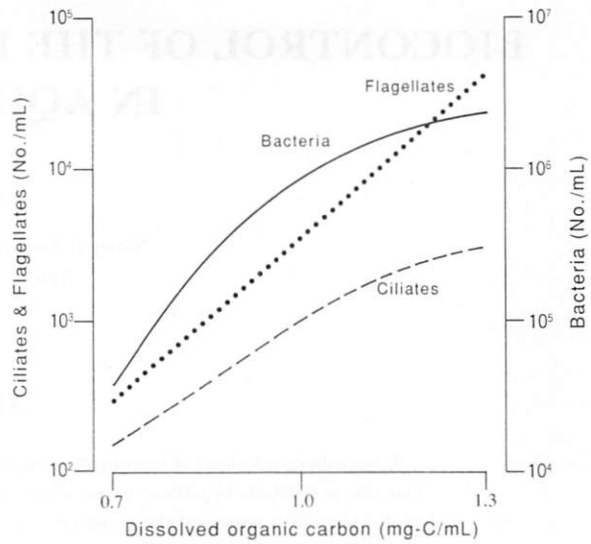


Figure 3. Numbers of bacteria, flagellated protozoa and ciliated protozoa in seawater of the various organic carbon concentrations.

teria seems to be up to $10^6$ cells/mL. By adding the bacterial strain to aquaculture water and maintaining that population at the concentration of $10^6$ cells/mL, other microbes of the same biotype might be considerably diminished.

Use of the functional bacterium in aquaculture

In Tamano Station of the Japan Sea Farming Association, which has been producing millions of larva of the crab, *Portunus trituberculatus*, every year, a large proportion of several-day-old larva was infected by *Vibrio* spp. in June, 1985. The bacteria proliferated inside the larval body, and 30–40% of the larva died within a day. Using of antibiotics to repress bacterial growth was ineffective. By the morning following treatment, almost all the larvae were floating near the surface and died later that day. The dead bodies contained numerous mycelia of the fungus *Haliphthoros* sp. This same sequence of events was experienced as an unsolved problem for crab culture (Muroga et al. 1989).

To 200 $m^3$ of seawater which was sterilized with sodium hypochlorite previously, 15 litres of the bacterial culture solution was added once a day for 7 days. Initial bacterial concentrations of about $10^6$ cells/mL resulted. Crab larvae (28,000 ind. /$m^3$), diatoms (1,200 cells/mL), and rotifers (5,000 ind./L) were added to culture water on the first day of the experiment.

Adding PM-4 increased the bacterial density in the culture water to $10^6$ cells/mL despite active feeding by the Zoea I crab larvae (Maeda, 1988; Maeda and Liao, 1992; Maeda and Nogami, 1989; Nogami and Maeda,

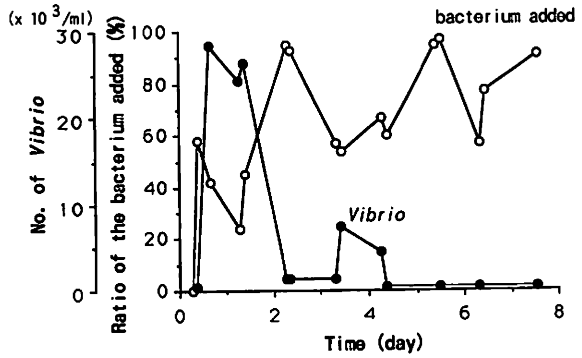


Figure 4. Fluctuation of PM-4 added and *Vibrio* spp. in culture water of *Portunus trituberculatus*.

1992). When the bacteria density increased to more than $10^7$ cells/mL, following decreased bacterial feeding by the Zoea I larvae, the protozoan population, primarily flagellates, grew rapidly and reduced the bacteria to about $10^6$ cells/mL. Among the bacterial populations occurring in culture water of the crab larvae, the numbers of *Vibrio* spp. and pigmented bacteria that also inhibited the growth of larvae decreased when PM-4 was added. In particular, there was a negative correlation between PM-4 and *Vibrio* spp. (Figure 4).

In 7 trials in 1990, the survival rates of crab larvae in a 200 $m^3$ container were 27.2% (mean value) when the bacterial strain PM-4 was added. In 6 of 9 trials in which the strain PM-4 was not added, no larvae grew into adults, resulting in an average survival rate of only 6.8% (Table 1). The same finding was obtained in the production of crab larvae in 1991, 1992 and 1993. The biocontrolling was also applied for the culture of prawn larva, *Penaeus monodon*. Without using the bacterium PM-4, the larvae died at the growth stage of mytosis I (5 days growth after hatching out from the egg). On the other hand, with the biocontrol method, 57% of the larvae survived after 13 days (Postlarva V growth stage).

## Significance of the biocontrol method

This bacterium showed the following taxonomic characteristics: negative Gram staining, no production of budding cells, negative fermentation test, positive motility, peritrichous flagella, and utilization of glucose as substrate. Based on these tests, this bacterium seems to be similar to genus *Pseudomonas* or *Deleya*, but the composition of ubiquinone was different from that of *Pseudomonas* and *Deleya*, i.e., ubiquinone 11 dominated in the total ubiquinone fraction in PM-4. These findings indicate that this bacterium belongs to a new genus and species.

In this biocontrolling method, the bacterium PM-4 used repressed the growth of *Vibrio* spp. PM-4 certainly produced the antibacterial materials. Also by adding this bacterium the effect of niche occupation or competition could be shown; that is, the size of the biotope of other bacteria was decreased. The above results suggest that controlling the bacterial population may not be very difficult, although the effect of the added bacterium may not last in a long period. We are presently trying to construct bio-reactor systems that contain these useful bacterial strains from which the

Table 1. Survival rates and production of crab larvae (*P. trituberculatus*) with (*biocontrol*) and without bacterial strain PM-4 in culture water

| Experiment | Method | Number of larvae ($\times 10^4$/200 $m^3$) | | | | | Survival rate (%) | Final production (ind./$m^3$) |
|---|---|---|---|---|---|---|---|---|
| | | $Z_I$ | $Z_{III}$ | $Z_{IV}$ | $M_I$ | $C_I$ | | |
| 1 | Without bacteria | 432 | 392 | 317 | 121 | 11 | 2.5 | 550 |
| 2 | *Biocontrol* | 387 | 383 | 281 | 168 | 100 | *25.8* | *5 000* |
| 3 | Without bacteria | 489 | 437 | 402 | 209 | — | — | 0 |
| 4 | *Biocontrol* | 503 | 457 | 457 | 257 | 78 | *15.5* | *3 900* |
| 5 | Without bacteria | 435 | 435 | 435 | 350 | 192 | 44.1 | 9 600 |
| 6 | Without bacteria | 455 | 433 | 364 | — | — | — | 0 |
| 7 | *Biocontrol* | 455 | 455 | 377 | 291 | 170 | *37.4* | *8 500* |
| 8 | Without bacteria | 538 | 450 | 419 | — | — | — | 0 |
| 9 | Without bacteria | 518 | 464 | 457 | 300 | 88 | 17.0 | 4 400 |
| 10 | *Biocontrol* | 421 | 397 | 395 | 392 | 240 | *57.0* | *12 000* |
| 11 | Without bacteria | 455 | 407 | 349 | — | — | — | 0 |
| 12 | Without bacteria | 489 | 376 | 368 | 247 | — | — | 0 |
| 13 | *Biocontrol* | 422 | 405 | 376 | 226 | 60 | *14.2* | *3 000* |
| 14 | *Biocontrol* | 442 | 402 | 434 | 306 | 9 [a] | *2.1* | *465* |
| 15 | Without bacteria | 482 | 482 | 381 | — | — | — | 0 |
| 16 | *Biocontrol* | 427 | 413 | 330 | 276 | 160 | *37.5* | *8 000* |
| *Total* | *Biocontrol* | 3057 | | | | 831 | *27.2* | |
| | Without bacteria | 4263 | | | | 292 | 6.8 | |

effective materials can be exudated in a certain period without losing the microorganisms used. Also, the artificial compound food containing these microorganisms may be useful for controlling the environment to obtain increased production of fish and crustaceas. We conclude that the biocontrolling method without using chemicals and antibiotics might be the way developing more profitable and wiser farming practices in aquaculture.

## ACKNOWLEDGMENTS

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# WASTE MANAGEMENT IN INTEGRATED RECIRCULATING SYSTEMS

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## ABSTRACT

Integrated, recirculating fish culture systems incorporate the hydroponic production of vegetables to recover waste nutrients, thereby improving water quality, producing valuable by-products, and enhancing profitability. The ratio between the daily feed input and the plant growing area must be optimal to maintain nutrient concentrations within ranges that maximize vegetable production. Preliminary research on the culture of tilapia and lettuce in a closed system has shown that nutrient salts accumulate at a rate of 135 g/kg of feed at the optimum component ratio for plant growth. When total dissolved solids (TDS) reach 2,100 mg/L, the culture water must be exchanged or diluted to prevent phytotoxicity. Culture water discharge from integrated systems, though relatively small in volume compared to other culture systems, contains a high pollutional load and requires treatment. Effluent discharge from a system with a TDS level of 1,950 mg/L contained 180 mg/L of $NO_3$–N and 35 mg/L of $PO_4$–P. Suggested treatment methods are land application as irrigation water or nutrient removal by tertiary polishing ponds. Ammonia and nitrite should be transformed to nitrate by biofilters prior to the hydroponic component. Plants utilize ammonium ions, which stimulate vegetative growth, but most of the required nitrogen should be supplied as nitrate ions to promote reproductive growth. Solid waste should also be removed from the recycle flow prior to the hydroponic component. Solids adhere to plant roots creating anaerobic zones, blocking oxygen absorption, and promoting the growth of harmful fungi and bacteria. Clarifiers or expandable bead filters are recommended, because they remove solids efficiently with minimum discharge. Screen filters have potential if water loss can be minimized. The recommended treatment sequence for sludge includes stabilization in oxidation ponds, sand filtration, and land disposal or direct land disposal in controlled amounts. Integrated recirculating systems provide much greater control over the partition and treatment of waste-product components than conventional fish culture systems. Effluents from these systems are highly concentrated and require additional treatment before they can be safely discharged into the environment.

## INTRODUCTION

Commercial interest in recirculating fish culture systems has increased dramatically. Many large facilities have been constructed and put into operation in the United States. Some have failed for a variety of reasons but others are surviving, and many new projects are in the planning or developmental stages.

Culturing large quantities of fish in small volumes of water, highly enriched with nutrients, often raises the prospect of integrating vegetable hydroponics into these systems to recover nutrients, improve water quality, and enhance profitability. The technical feasibility of integrating vegetable hydroponics with fish culture has been well documented (Lewis et al. 1978; McMurtry et al. 1990; Rakocy 1989a), but more research is needed to assess the contribution of vegetables to water quality improvement and to determine the economic potential of integration (Figure 1). Although vegetable hydroponics may appear to be a well-suited addition to recirculating fish culture systems, optimizing vegetable production requires some major changes in system management and special consideration of fish waste products.

## NUTRIENT ACCUMULATION

In closed recirculating systems, which employ very little daily water exchange (1%), dissolved nutrients accumulate and approach concentrations that are found in hydroponic solutions (Table 1). However, nutrient salts may accumulate to levels (>2,100 mg/L) that exceed hydroponic concentrations and are toxic to plants. In an experiment with 15.1-$m^3$ systems containing 13.2 $m^2$ of plant growing area, the accumulation of total dissolved solids (TDS) as a proportion of feed

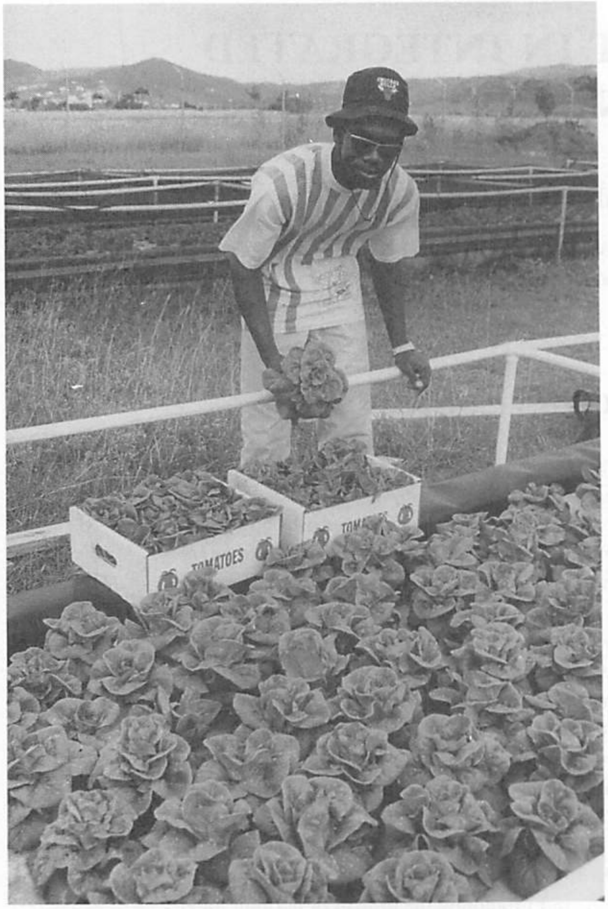
Figure 1. Hydroponic Lettuce Being Harvested from an Integrated Recirculating System.

input was 202 g/kg without plants (control), 183 g/kg with leafy green vegetables, and 178 g/kg with tomatoes (Rakocy et al. 1989). In just 12 weeks, TDS approached toxic levels and water dilutions were required (Figure 2).

Table 1. Typical hydroponic nutrient solution[a].

| Nutrient | Concentratlon (mg/liter) | |
|---|---|---|
| Calcium | 197 | |
| Magnesium | 44 | |
| Potassium | 400 | |
| Nitrogen (as $NO_3$) | 145 | (642) |
| Phosphorus (as $PO_4$) | 65 | (199) |
| Sulfur (as $SO_4$) | 197.5 | (592) |
| Chlorine | — | |
| Iron | 2 | |
| Manganese | 0.5 | |
| Copper | 0.03 | |
| Zinc | 0.05 | |
| Boron | 0.5 | |
| Molybdenum | 0.02 | |

[a] Modified after Resh, 1989.

To slow the rate of salt accumulation, the plant growing area must be enlarged relative to the daily feed input. A study was conducted in 17.8-$m^3$ systems with 13.8 $m^2$ of plant growing area to find the optimum ratio of lettuce plants to fish (feed) for maximum lettuce production (Rakocy 1989b). Among six ratios tested, the best lettuce production (3.1 kg/$m^2$/3-week crop) was achieved at a ratio of 1.9 plants/fish (2.4 g feed/day/plant). At this ratio, TDS still accumulated at a rate of 135 g/kg of feed and reached 900 mg/L in 21 weeks. The accumulation of TDS was lower at higher plant-to-fish ratios (2.5, 3.8 and 7.5), but plant production decreased.

Not all nutrients required by plants are generated from fish waste at the optimum levels. Nutrients requiring supplementation are potassium (as potassium hydroxide), calcium (as calcium oxide or calcium hydroxide), and iron (as iron chelate containing 10% iron by weight). Potassium hydroxide or calcium oxide should

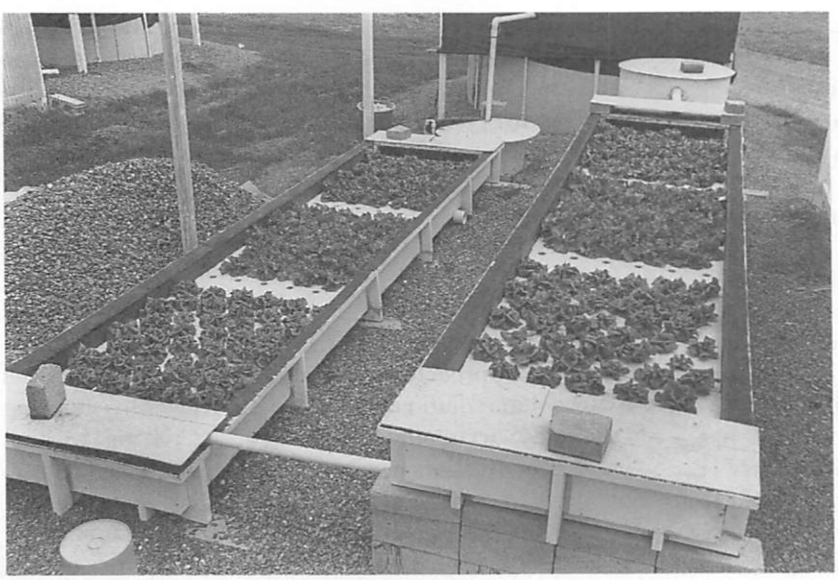
Figure 2. Experimental Integrated System Showing Rearing Tank (Background), Clarifier (Right), Hydroponic Tanks, and Reservoir (Left).

be added daily to maintain the pH at 7.5 (pH constantly declines in closed systems in response to the acid produced by the nitrification process). Potassium hydroxide and calcium oxide or calcium hydroxide should be added at a two to one ratio by weight, respectively, to maintain the correct cation balance. If gravel hydroponic substrates are used, then calcium may not require supplementation. Iron is supplemented at a concentration of 2 mg/L every 2 to 4 weeks.

Integrated systems require a water source with low TDS levels (<100 mg/L) to reduce the need for frequent dilutions or to lengthen the intervals between complete water exchanges. Rainwater collected from catchments is used for integrated system research at the University of the Virgin Islands (UVI). From work in progress at UVI with a commercial scale system (38 $m^3$) for the production of tilapia and lettuce using the optimum plant to fish ratio, it appears that the total water volume will have to be exchanged every 6 months. Whether all the water should be exchanged at one time or on a continuous basis (daily, weekly or monthly), after some desired TDS level is reached, remains to be determined.

Effluent from integrated systems contains a high pollutional load. In an experiment with 15.1-$m^3$ systems containing gravel hydroponic substrate, TDS increased from an initial value of 110 mg/L to 1,950 mg/L in 12 weeks after the fish had consumed 152 kg of feed (Rakocy et al. 1989). To reduce the concentration of nutrient salts to nontoxic levels, a 40% dilution was made by discharging 6 $m^3$ of the culture water and replacing it with rainwater. Concentrations of nitrate, phosphate, and other nutrients in this effluent were very high (Table 2). Comparable effluent from large-scale commercial facilities could exert an environmental impact (eutrophication) on receiving waters and should be treated. The simplest treatment processes are land applications as irrigation water or stabilization in tertiary (oxidation) ponds. The nutrients applied through irrigation water should approximate nutrient uptake of the irrigated crop to prevent salt buildup in the soil and groundwater contamination.

Table 2. Nutrient levels in integrated system effluent.

| Nutrient | Concentration (mg/liter) | |
|---|---|---|
| Ca | 82 | |
| Mg | 26 | |
| K | 440 | |
| Na | 192 | |
| $NO_3$–N (as $NO_3$) | 180 | (797) |
| $pO_4$–P (as $PO_4$) | 35 | (107) |
| $SO_4$-5 (as $SO_4$) | 18 | (53) |

## NITROGEN CONSIDERATIONS

Plants absorb and utilize nitrogen in the form of ammonium ($NH_4$) or nitrate ($NO_3$) ions. Ammonium ions can be used immediately for the synthesis of amino acids and other compounds containing reduced nitrogen. Ammonium ions promote vegetative growth. Nitrate ions must first be reduced before they are assimilated. This holds back vegetative growth and promotes fruit development. Ammonium ions are sometimes used in hydroponic nutrient formulations but in small amounts relative to nitrate concentrations. Larger proportions of ammonium ions are used in formulations for leafy green vegetables.

In integrated systems, ammonium levels are not only sufficient for vegetative plant growth, but a major concern is reducing the large quantities of total ammonia-nitrogen (TAN) produced by fish metabolism to levels suitable for their health and growth. TAN consists of ammonium ions and unionized ammonia gas ($NH_3$), which is toxic to both fish and plants. A variety of biofilters, employing fixed-film nitrification, is used to transform TAN and nitrite to nitrate. The biofiltration stage should be located before the hydroponic component in the waste stream flow to increase the proportion of nitrogen ions available to the plants as nitrate. In the 38-$m^3$ commercial-scale system at UVI, two 93-$m^2$ rotating biological contactors (RBCs) are used to maintain TAN levels near 1 mg/L at a constant feeding rate of 4 kg/day (Figure 3). However, in this closed system, which is supplied by rainwater, the pH must be adjusted daily to 7.5 for the RBCs to operate efficiently. When pH declines less than 7, TAN concentrations increase.

In 14.0-$m^3$ experimental systems at UVI, average TAN and nitrite-nitrogen removal rates in 93-$m^2$ RBCs have ranged from 0.17 to 0.25 $g/m^2$/day and 0.42 to 0.61 $g/m^2$/day, respectively, during growout cycles (Rakocy et al. 1991; Rakocy et al. 1992). Removal rates were higher for nitrite-nitrogen than TAN because bacteria associated with particulate organic matter in the water column oxidized a considerable amount of ammonia but not nitrite, which was removed primarily by bacteria attached to the RBC.

The hydroponic component can be designed for ammonia removal by using gravel or sand substrates, thereby eliminating the need for a separate biofiltration stage. However, Nair et al. (1985) found that gravel hydroponic media became clogged with organic matter, which short-circuited the water flow through the biofilter and reduced nitrification efficiency. This problem can be eliminated to some extent by using shallow reciprocating gravel biofilters, which alternately flood and drain, in conjunction with a false bottom that supports the gravel above the floor of the tank (Rakocy 1984). Other disadvantages of gravel are the need for

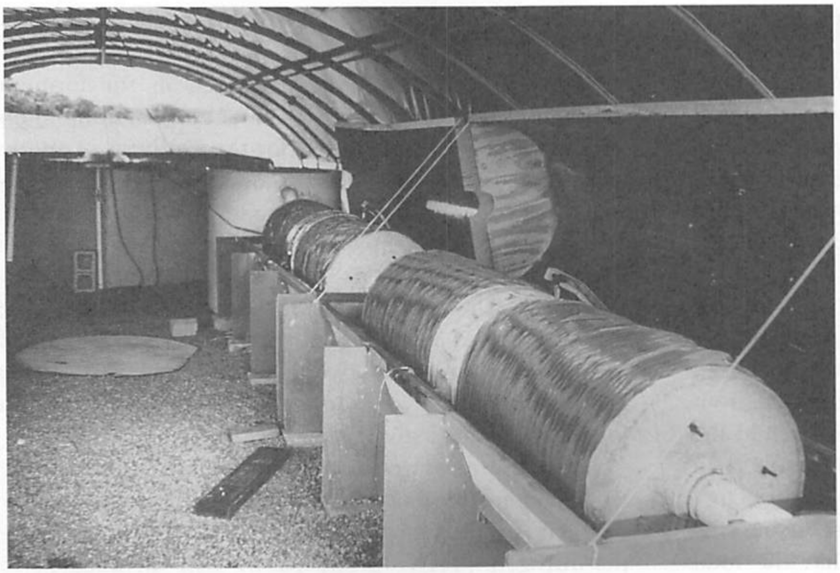

Figure 3. Rearing Tank (Left), Clarifier, and Two Rotating Biological Contactors of a Commercial-Scale Integrated System.

sturdy and expensive support structures and the difficulty of planting, especially in the coarse grades needed to prevent clogging. McMurtry et al. (1990) has obtained promising results with sand media that is furrow-irrigated with rearing tank effluent every 3 hours during daytime. As organic matter accumulates in the sand, it begins to resemble a well-drained soil. Sand is a very efficient biofilter due to its high specific surface area. However, clogging is a potential problem with media as fine as sand.

Hydroponic tanks without media may be used as biofilters. The hydroponic system at UVI consists of deep (30 cm), flowing, aerated channels that are 1.2 m wide and either 6 m long in experimental systems or 29.6 m long in commercial-scale systems (Figure 4). Plants are supported by floating sheets of polystyrene. The two hydroponic tanks per commercial-scale system provide considerable surface area (182 $m^2$) for fixed-film nitrification. One commercial-scale system without separate biofilters maintains low TAN levels (<1 mg/L) at a constant feeding rate of 2 kg/day.

The major reasons for incorporating vegetable hydroponics into recirculating systems are to recover waste nutrients in the form of valuable by-products and to reduce nutrient discharge into the environment. The effectiveness of vegetable hydroponics for nutrient recovery has not been determined, as this field is still undergoing rapid development. A preliminary estimate, based on research at UVI, indicates that leaf lettuce may remove approximately 23% of the waste nitrogen at the optimum feeding rate of 2.4 g/plant/day (Figure 5). This is a revision of an earlier estimate (8%) by Rakocy (1992) and is based on a 4.3% nitrogen content of hydroponic leaf lettuce (Resh, 1989). More

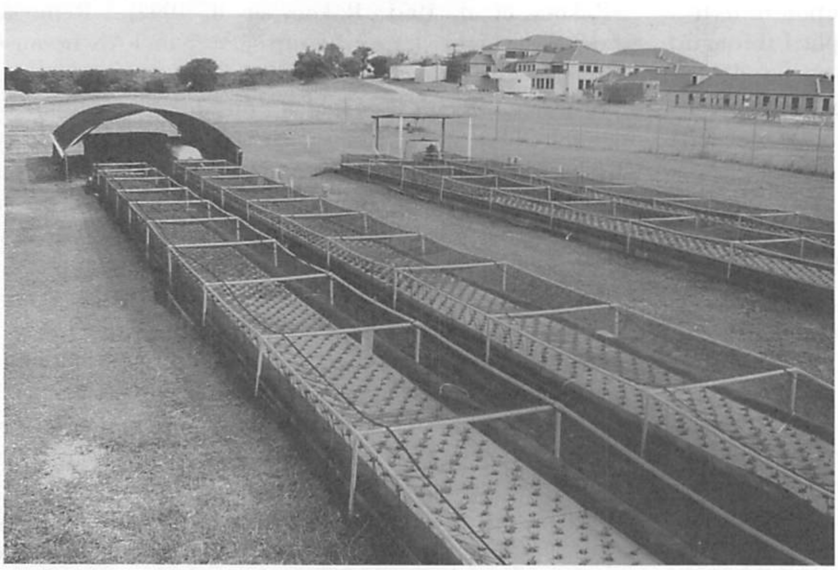

Figure 4. Two Commercial-Scale Integrated Systems.

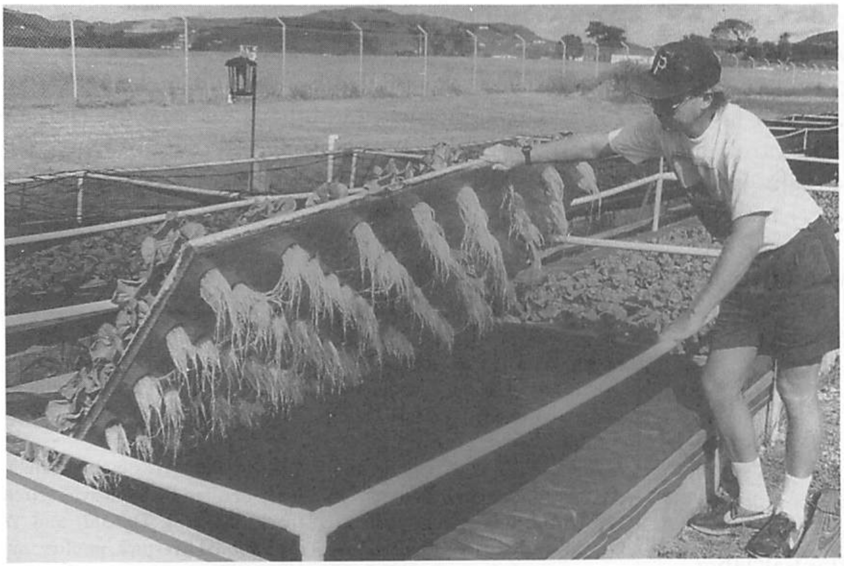

Figure 5. The Roots of Hydroponic Lettuce Plants Recover Nutrients from Fish Culture Water in Closed Recirculating Systems.

accurate nutrient budgets are needed for integrated systems. A goal of integrated system research is to increase waste nitrogen removal to a value that approaches 100%. This may require a fourfold increase in the optimum plant-to-fish ratio of 1.9 and probably a significant increase in the supplementation of other essential macro- and micro-nutrients.

## SOLID WASTE CONSIDERATIONS

Settleable solids should be removed from integrated systems in the first stage of the treatment process after culture water is discharged from the fish rearing tank. Failure to remove solids will lead to buildup of sludge blankets on the tank floor, secondary ammonia production, dissolved oxygen reduction, and the possible production of off-flavor compounds. Solids may also adhere to plant roots, creating anaerobic zones, blocking oxygen absorption, and promoting the growth of harmful fungi and bacteria.

Clarifiers are used for solids removal from the integrated systems at UVI. The clarifiers are cylindro-conical in shape with a 60° slope in the conical portion and a volume of 1.8 $m^3$. The cylindrical portion is above ground and level with the rearing tank while the conical portion is underground. Solids collect at the bottom of the cone and are discharged by hydrostatic pressure when a ball valve on the drain line are opened. About 10 to 20 tilapia fingerlings are required to graze on the clarifier walls for solids to settle to the bottom of the cone. Without the presence of tilapia, solids attach to the clarifier walls and accumulate, eventually floating to the surface in large mats. Solids are removed two to three times a day.

Dry weight solids removal by this clarifier has averaged 21% of the dry weight of feed added to the system during a production cycle (Rakocy et al. 1991). The dry weight of solids removed by the clarifier ranges from 1 to 3%, increasing in response to increases in the daily feeding rate. Solids production averages 28 liters/day in the 38-$m^3$ commercial scale system at UVI with a constant feeding rate of 4 kg/day. Each kilogram of fish production generates 9.3 liters of solids.

Although this clarifier appears to remove more than 95% of the settleable solids, the turbulence created by the fish allows the fine solids to pass through. These solids settle in the bottom of the RBC trough and on the floor of the hydroponic tank. A few tilapia fingerlings are placed in the RBCs to prevent sludge from settling there. Fingerlings have also been placed beneath the false bottoms of the reciprocating gravel biofilters in the hydroponic tanks to eliminate the development of sludge blankets.

Efficient removal of solids may also be accomplished by a new method called bead filtration (Malone and Drennan 1992). Bead filters consist of low density plastic beads that float tightly at the top of an enclosed chamber. The beads filter solids out of water that flows up through them and out of the chamber through a screen at the top. As the beads begin to clog, the flow is stopped and a propeller is activated to produce a gentle current that scours the solids off the beads. When the washing cycle is stopped, the beads float back to the chamber top while the solids settle to the conical chamber bottom. A valve is opened to remove the accumulated sludge and the flow is resumed. Bead filters require much less space than settling tanks and provide nitrification by bacteria growing on the beads.

Screen filtration is a developing technology that may also be used to remove solids from integrated systems. As rearing tank effluent flows through fine mesh (30–60 microns) plastic or metal screens, solids collect on the surface and eventually block the water flow, causing the water level to rise and activate a cleaning mechanism. For example, the screen may begin to rotate past high pressure water spray jets that wash solids into a trough that carries them out of the system. Potentially large volumes of wash water (filtered system water) may be used for solids removal, resulting in high nutrient loss from the system. Water loss could be minimized by using lower flow and solids loading rates. The advantage of screen filters in integrated systems, besides their small space requirement, is their ability to serve as effective barriers in preventing fish (e.g., tilapia fry) from entering the hydroponic tanks and eating plant roots. In the commercial-scale systems at UVI, a set of two static screens are currently used to protect the hydroponic tanks from fish entry. Every day these screens must be washed manually. Substantial labor would be saved through the automatic cleaning process of screen filters.

Sludge discharged from integrated systems and recirculating systems in general is high in total suspended solids (TSS) and biochemical oxygen demand (BOD) and requires treatment before it is discharged into the environment. Malone et al. (1992) suggested that a combination of secondary clarification, aerobic sludge digestion in lagoons, and sand filtration offers effective treatment for reasonable cost and land requirements. The stabilized sludge can then be recycled through land application. Preliminary research at UVI has shown that limited amounts of untreated aquaculture sludge may be used directly to irrigate and fertilize vegetable crops grown in soils with low levels of organic matter. Unstabilized sludge and discarded waste (vegetative matter, peat cubes) from the hydroponic component may be composted and used as a soil amendment.

Integrated systems provide much greater control over the partition and treatment of waste product components than conventional fish culture systems. They eliminate the potential for environmental pollution to the extent that they transform harmful metabolites (ammonia, raw sludge) into safer products (nitrate, stabilized sludge) and recycle nutrients into vegetables. Nevertheless, discharged culture water and sludge contain high levels of pollutants, and they require further treatment before they can be safely disposed in the environment. As integrated systems are developed and brought to commercialization, research must assess their potential environmental impact and establish treatment methods that meet or exceed environmental standards and possibly enhance the environment by employing additional integration strategies.

## ACKNOWLEDGMENTS

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# HOW TO IMPROVE THE ENVIRONMENT OF POLLUTED FISHING GROUNDS

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## ABSTRACT

The fish culture ground environments are becoming worse because of sea bottom contamination by organic matters such as remaining feed and fish feces. Dissolved oxygen of bottom water is consumed by the organic sludge on the sea bottom through decomposition processes. In a stratified season, the bottom water has little oxygen in contrast with the fully oxygen saturated surface water. As the result of this, the low oxygen water not only damages cultured fish, but also the organic and inorganic nutrient salts in the bottom mud diffuse into the water. Some of the nutrient salts, such as nitrous acid, ammonia, hydrogen sulfide, etc. are toxic. Therefore, the water quality environment becomes unsuited to the fish culture because of the pollution by itself. To prevent bottom water stagnation and nutrient salt diffusion from the bottom mud, several engineering techniques have been attempted. In this study, a new technique, called tide-dam, is suggested to improve the water quality environment by generating the vertical circulation and preventing the oxygen deficiency of bottom sea water. This simple structure is designed to control the oxygen deficient condition with the aid of phytoplankton photosynthesis by using the tidal energy. The principles and how to determine the dimensions of the tide-dam are introduced.

## INTRODUCTION

Primary factors of fishing ground pollution are generally classified into the external environment and the internal environment. The external environment consists of the geographical and geological features of the ground, the amount of precipitation, the land utilization surrounding it, and so forth. Self-contamination occurs when the fish culture pollutes the sea water, which also belongs to the external environment. On the other hand, the internal environment consists of the water circulation, the water quality, and the constituent of bed materials.

In order to improve the polluted environment, the causes of pollution, elements of the external environment mentioned above, should be identified and then excluded. If domestic or industrial waste water pollutes the sea water, for example, the sewage disposal facilities should be re-established and/or their processing capacity should be expanded. Furthermore, when fish culture brings about the self-contamination within an embayment, the contaminant load should be decreased by reducing the number of culturing fish and by modifying the feeding policy.

In Japan, environments of fish culturing grounds in bays are becoming worse by the progressive sea bottom contamination with organic matters that are attributed to remaining feed and fish feces. This contamination often causes oxygen deficiency of the bottom sea water in stratified seasons, early summer until autumn, and it also worsens the environment.

When the bottom sea water has enough dissolved oxygen, the organic matter comprising the bottom mud is decomposed into carbon dioxide and water. Ammonia produced in this process by the nitrifying bacteria is immediately oxidized into nitrate, which is soluble in sea water and nontoxic to fishes and shellfishes. Manganese and iron taking the insoluble state remain in the bottom mud. On the other hand, if the sea water has little oxygen, ammonia remains without being nitrified, and manganese, iron, and phosphorus dissolve into the water. The growth promoting matter for phytoflagellates is produced in this anaerobic decomposition process. Moreover, the organic acid such as lactic acid, which is created in the fermentation process, is the hydrogen donor to hydrogen sulfide. Finally, the oxygen deficiency of the bottom layer makes rapid progress because of the oxygen consumption by hydrogen sulfide

(Watanabe 1990).

To improve the internal environment, several means have already been attempted that prevent the organic and inorganic nutrient salts fluxes from bottom mud and flush out the stagnant water to the open sea. If the organic sludge accumulates on the sea bed, dredging, covering with sand, plowing, and lime sprinkling will often be effective. To accelerate the water exchange in a bay, one or some of following measures will be adopted (Watanabe 1990): bay mouth improving, new channel construction, water route making, feeding and draining by electric pumps, and air-bubble ejecting.

In addition to the above attempts, the authors suggested a new one called the "*tide-dam,*" which applies oxygen production ability of phytoplankton and tidal potential energy with a very simple structure, i.e., sea dike and pipelines. This method will improve the internal environment by generating the vertical water circulation in stratified seasons and preventing the oxygen deficiency of bottom sea water. This paper shows the principle of this idea and how to decide the geometrical dimensions of this facility.

## PRINCIPLE AND STRUCTURE OF THE TIDE-DAM

The sea dike is constructed at a shallow area, and the dam reservoir water is connected with a bottom sea water by pipelines as illustrated in Figure 1. The reservoir water ejected into the bay bottom at an ebb stage entrains the surrounding stagnant water upward. Then, the oxygen deficiency that occurred in a stratified season will be prevented by accelerating the vertical circulation caused by the entrainment process. Two types of the tide-dam can be considered according to the pipe setup, One-Pipe type and Two-Pipes type as shown in Figure 2; from now on, they are abbreviated as OPT and TPT, respectively.

The OPT system has a very simple structure that introduces the bottom sea water into the dam reservoir at a flood stage and the reservoir water into the bay bottom at an ebb stage. For this type, the dissolved oxygen (DO) concentration of the water ejected into the bay bottom is strongly dependent on the oxygen production rate by the phytoplankton photosynthesis in the reservoir and on the DO concentration of the bottom sea water tapped into the reservoir at the previous flood.

The TPT system is further divided into two types, TPT(a) and TPT(b), according to the pipes setup. TPT(a) consists of inflow and outflow pipes and needs some devices to control the water flow. On the other hand, TPT(b) is comprised of two pipes of different diameters arranged in series with an opening; it needs no additional device and is simpler than TPT(a).

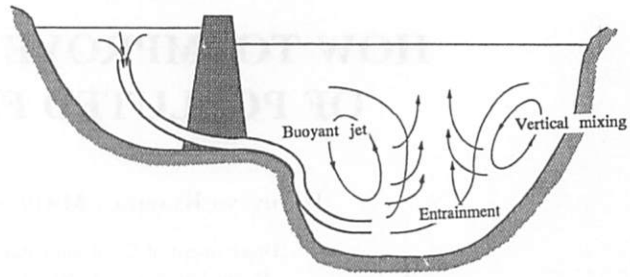


Figure 1. Schematic Illustration of the Tide-Dam and the Vetical Current Induced by a Buoyant Jet Flow.

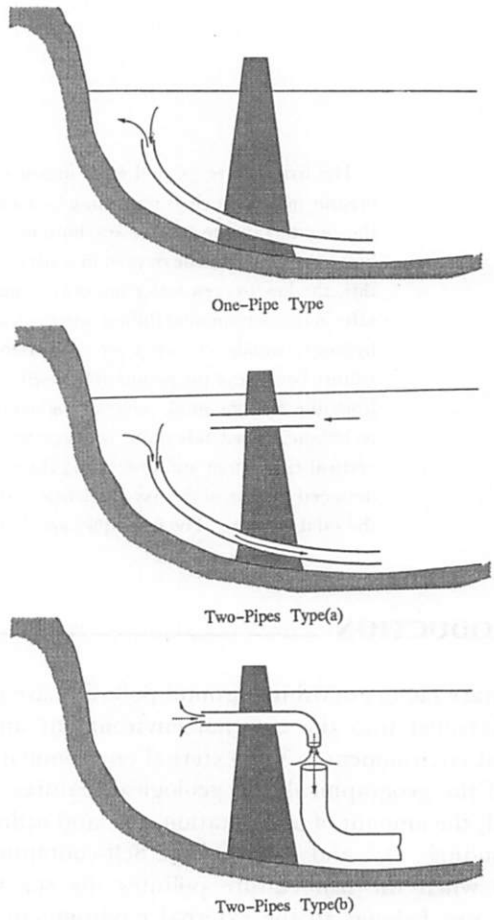


Figure 2. Types of the Tide-Dam with Different Pipe Installations.

## DAM RESERVOIR DIMENSIONS

To determine the reservoir capacity and the pipe discharge, the following quantities should be identified:

—the tidal range in a bay, $2\Delta h_B$ (m);

—the allowable minimum DO concentration in a bottom layer, $C_A$ (ppm);

—the DO consumption rate in a bottom layer, $O_C$ (g-$O_2$/day);

—entrained water volume due to ejection, $q_e$ ($m^3$/day);

—DO concentration of entrained bottom water, $C_S$ (ppm);
—the hydraulic parameters of connecting pipe flows.

If these parameters are identified, the daily discharge $q_w$ ($m^3$/day) and the surface area of the reservoir $S_D$ ($m^2$) are given by Eqs. (1) and (2), respectively;

$$q_w = \frac{O_C}{\alpha(C_S - C_A)}, \tag{1}$$

$$S_D = \frac{q_w}{4\Delta h_D}, \tag{2}$$

in which $\alpha = q_e/q_w$.

For the OPT system, $A$, the cross-sectional area of the connecting pipe, can be determined by

$$K = \frac{4}{3\pi} \frac{F\Delta h_B \omega^2}{g} \left(\frac{S_D}{A}\right)^2, \tag{3}$$

where $g$ = the acceleration due to gravity and $\omega$ = the tidal angular velocity. The parameter, $K$, is given by the broken line drawn in Figure 3 for the known parameter $\lambda$ ($=2\Delta h_D/2\Delta h_B$), the ratio of the tidal range in the reservoir to that of a bay. The friction parameter, $F$, is given by

$$F = f_i + f_o + f_b + \frac{l}{D} f_l, \tag{4}$$

where $f_i$, $f_o$, and $f_b$ are the energy loss coefficients due to inflow, outflow, and pipe bending, respectively. $D$ = the diameter of a pipe, and $l$ = the length. The friction loss coefficient $f_l$ is given by the following formula using the Manning's roughness coefficient $n$ as

$$f_l = 124.5 \frac{n^2}{D^{1/3}}. \tag{5}$$

For the TPT(a) system, the cross-sectional area of pipes are obtained in the same manner as that for OPT system. $K_o$ value is given corresponding the known $\lambda$ value using the solid curves in Figure 3, in which $K_o$ and $K_i$ are the $K$ values of the outflow and inflow pipes, respectively.

## DECISION OF GOVERNING PARAMETERS

The key parameters in determining the dam reservoir dimensions are already listed at the beginning of the previous section. The following subsections present methods on how to determine each of them.

### TIDAL RANGE IN A BAY

If the harmonic constants are already known for some principal tidal constituents, the mean tidal range is approximately twice as large as the amplitude of the semi-diurnal tidal constituent. The harmonic con-

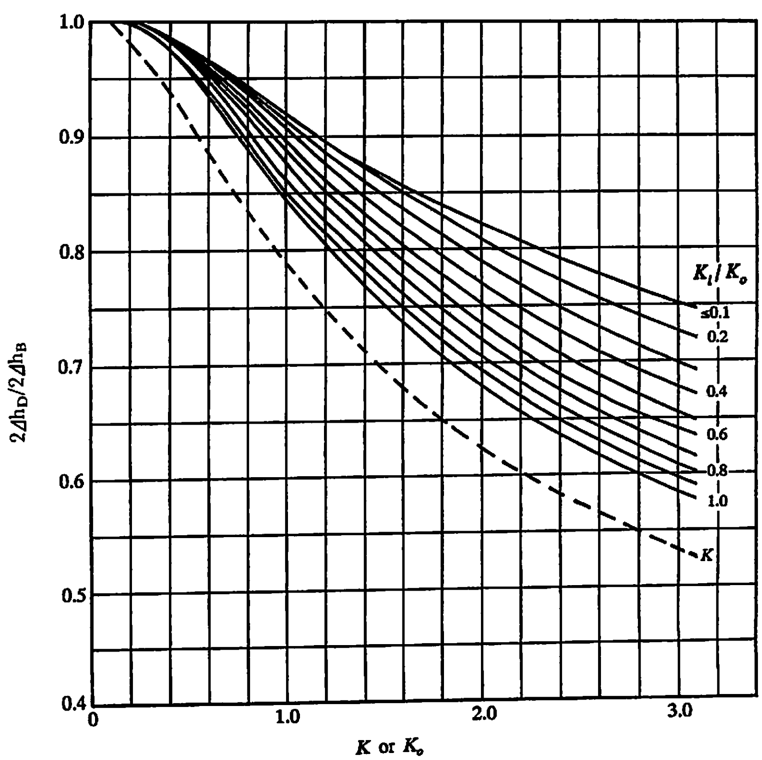


Figure 3. Relations between $K$, $K_o$ and $\lambda$ for the One-Pipe Type and the Two-Pipes Type (a).
Broken line: One-Pipe Type. Solid lines: Two-Pipes Type.

stants can be decided by the harmonic analysis of tidal data over the period of at least 15 days.

## ALLOWABLE MINIMUM DO CONCENTRATION

Benthos, who plays a great role in degradation of organic substances, is not only a useful fishery resource but the food of other aquatic life. If the sea bottom is covered with organic sludge, the allowable DO concentration should be the minimum value in which benthic organisms can be alive throughout a year. The detailed observations on benthos must be carried out to know this minimum value.

## DO CONSUMPTION IN BOTTOM LAYER

The dissolved oxygen is consumed in a bottom layer by sea water, bottom sludge, and benthic organisms. To maintain the allowable DO concentration, the same or larger amount of oxygen than this consumption should be supplied. The consumption by the sea water and bottom sludge can be estimated experimentally. However, consumption by benthos is dependent on the respiration rate of each species and on their population density.

## AMOUNT AND DO CONCENTRATION OF ENTRAINED WATER

The bottom water moves upward through the entrainment process caused by reservoir water ejection and, therefore, the same quantity of surface water moves downward into the bottom layer. At the same time, the dissolved oxygen in the surface water is transported to the bottom by this vertical circulation. The magnitude of the entrainment can be estimated as a function of the ejected water discharge on the basis of the jet flow theory. Figure 4 shows the dilution rate, $R$, in the horizontal buoyant jets, in which $d$=the ejecting nozzle diameter, $z$=the vertical coordinate, and $F_{r0}$=the internal Froude number. $R$ has the relationship, $\alpha=2R-1$, with the constant $\alpha$ appeared in Eq. (1) (Kimura et al. 1991).

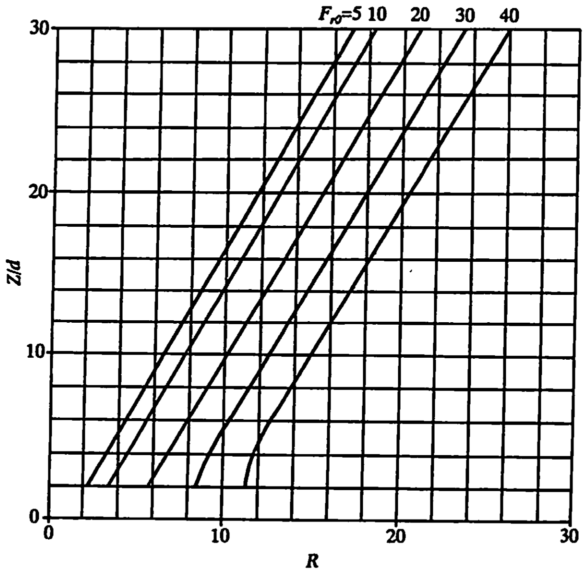


Figure 4. Dilution Ratio ($R$) for Buoyant Jets Discharged Horizontally into a Linearly Stratified Ambient.

## HYDRAULIC PARAMETERS OF PIPE FLOWS

The energy equation of a pipe flow is given by

$$\rho Al\frac{dv}{dt}+\frac{1}{2}F\rho A|v|v=\rho gA(h_D-h_B), \quad (6)$$

where $\rho$=fluid density, $v$=mean velocity (positive in reservoir to bay direction), $t$=time, and $h_D$, $h_B$=water elevations of a dam reservoir and a bay, respectively. The left-hand-side terms of the equation are the inertia and drag force, respectively; the right-hand side represents the external force due to the hydrostatic pressure. The continuity equation can be given as:

$$S_D\frac{dh_D}{dt}=-Av. \quad (7)$$

One-Pipe Type

The governing equation for the OPT system can be derived by eliminating $v$ in Eqs. (6) and (7) as

$$\frac{d^2h_D}{dt^2}+\frac{1}{2}\frac{F}{l}\frac{S_D}{A}\left|\frac{dh_D}{dt}\right|\frac{dh_D}{dt}+\frac{g}{l}\frac{A}{S_D}h_D=\frac{g}{l}\frac{A}{S_D}h_B. \quad (8)$$

If the water level fluctuations of a bay and the dam reservoir are expressed as the following sinusoidal functions, the approximate solutions of Eq. (8) are obtainable:

$$h_B=\Delta h_B\cos(\omega t) \quad (9)$$

$$h_D=h_D\cos(\omega t-\theta) \quad (10)$$

where $\omega=2\pi/T$, $T$=the tidal period, and $\theta$=the phase lag. From Eq. (10), the second term of the left-hand side of Eq. (8) can be written as the Fourier series. Neglecting the higher order terms, it is written as

$$\left|\frac{dh_D}{dt}\right|\frac{dh_D}{dt}=\frac{8}{3\pi}\omega\Delta h_D\frac{dh_D}{dt}. \quad (11)$$

Substituting Eqs. (10) and (11) into Eq. (8), the following equations can be obtained:

$$\lambda=\frac{\Delta h_D}{\Delta h_B}$$

$$\sqrt{\frac{\sqrt{(1-J)^4+4K^2}-(1-J)^2}{2K^2}}, \tag{12}$$

$$\theta=\arctan\left(\frac{K\lambda}{1-J}\right), \tag{13}$$

where $J$ is given by

$$J=\frac{l\omega^2}{g}\frac{S_D}{A}. \tag{14}$$

Taking that $J$ is far less than unity into account, $\lambda$ in Eq. (12) is approximated by

$$\lambda=\sqrt{\frac{\sqrt{1+4K^2}-1}{2K^2}}. \tag{15}$$

Moreover, the discharge $Q$ during one tidal cycle and the mean velocity, $v$, during a half tidal cycle are given by Eqs. (16) and (17), respectively;

$$Q=2\lambda\Delta h_B S_D, \tag{16}$$

$$v=4\lambda\frac{\Delta h_B S_D}{AT}. \tag{17}$$

Two-Pipes Type

For the TPT(a) system shown in Figure 2(a), the continuity and energy equations are given as follows: when $h_D<h_B$,

$$\rho l_i A_i\frac{dv_i}{dt}+\frac{1}{2}\rho A_i F_i v_i^2=\rho g A_i(h_B-h_D), \tag{18}$$

$$S_D\frac{dh_D}{dt}=A_i v_i, \tag{19}$$

and when $h_D>h_B$,

$$\rho l_o A_o\frac{dv_o}{dt}+\frac{1}{2}\rho A_o F_o v_o^2=-\rho g A_o(h_B-h_D), \tag{20}$$

$$S_D\frac{dh_D}{dt}=-A_o v_o, \tag{21}$$

in which the variables with subscript i and o denote those of the inlet and outlet pipes, respectively.

The TPT(b) system is shown in Figure 2(b) and Figure 5. One pipe ($P_1$) and another pipe ($P_2$), whose diameters are $D_1$ and $D_2$ ($D_1<D_2$), respectively, are equipped in series. The distance between them is about $D_1$ or $2D_1$. The hydraulic discussions are done for both the steady and unsteady states.

Figure 5 shows the energy head of the steady pipe flow directed from $P_1$ to $P_2$, when $\Delta h=h_D-h_B>0$. At the control section [I], the following relations are required:

$$\Delta h=h_{f1}+\frac{v_1^2}{2g}, \tag{22}$$

$$h_{f1}=f_1\frac{v_1^2}{2g}, \tag{23}$$

where the energy loss coefficient $f_1$ of $P_1$ pipe consists of the inflow loss, bending loss, and friction loss coefficients which are represented as $f_{i1}$, $f_{b1}$, and $f_{l1}$.

$$f_1=f_{i1}+f_{b1}+f_{l1}\frac{l_1}{D_1}, \tag{24}$$

in which $l_1$=the length of $P_1$ pipe. At the control sections [II] and [III], the following equations are obtained from the momentum conservation principle:

$$\rho A_1 v_1^2=\rho g A_2 h_{f2}+\rho A_2 v_2^2, \tag{25}$$

$$h_{f2}=f_2\frac{v_2^2}{2g}, \tag{26}$$

$$f_2=f_{b2}+f_{l2}\frac{l_2}{D_2}, \tag{27}$$

where $A_1$, $A_2$=the cross-sectional areas, $f_{b2}$, $f_{l2}$=the energy loss coefficients due to pipe bending and friction, and $l_2$=the length of $P_2$ pipe.

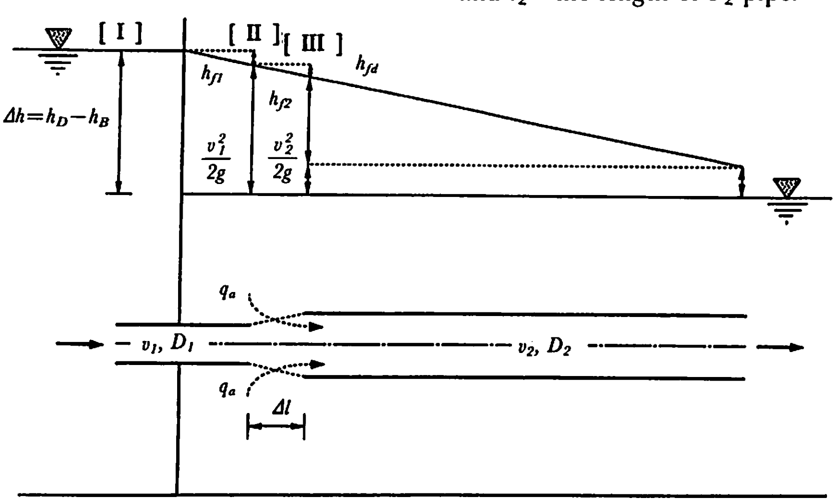


Figure 5. Profiles of energy Line in the Pipe Flow of Two-Pipes Type (b) at an Ebb Stage.

On the other hand, the continuity equation can be derived considering the discharge $q_a$ absorbed through the opening between two pipes as

$$\pi\frac{D_1^2}{4}v_1+q_a=\pi\frac{D_2^2}{4}v_2. \quad (28)$$

Using Eqs. (22), (23), (25), (26), and (28), following formulas are obtainable:

$$v_1=\sqrt{2g\frac{\Delta h}{1+f_1}}; \quad (29)$$

$$v_2=\frac{v_1}{\sqrt{1+f_2/2}}\frac{D_1}{D_2}=\sqrt{2g\frac{\Delta h}{(1+f_1)(1+f_2/2)}}\frac{D_1}{D_2}; \quad (30)$$

$$q_a=\frac{\pi}{4}\left(\frac{D_1D_2}{\sqrt{1+f_2/2}}-D_1^2\right)\sqrt{2g\frac{\Delta h}{1+f_1}}. \quad (31)$$

When $D_2/\sqrt{1+f_2/2}<D_1$, $q_a$ becomes negative. Therefore, a part of the water directed from $P_1$ to $P_2$ flows out through the opening. When $\Delta h=h_D-h_B<0$, the bay water flows into the reservoir through the opening and $P_1$ pipe, in which the velocity can be estimated by Eq. (29).

The unsteady equations of momentum are given as follows; when $\Delta h>0$,

$$\rho A_1l_1\frac{dv_1}{dt}+\frac{1}{2}\rho A_1F_1v_1^2=\rho gA_1(h_D-h_B), \quad (32)$$

$$\rho A_2l_2\frac{dv_2}{dt}+\frac{1}{2}\rho A_2(F_2+1)v_2^2=\rho A_1v_1^2, \quad (33)$$

where $F_1=1+f_1$, and when $\Delta h<0$, the equations are written as

$$\rho A_1l_1\frac{dv_1}{dt}-\frac{1}{2}\rho A_1F_1v_1^2=\rho gA_1(h_D-h_B), \quad (34)$$

$$v_2=0. \quad (35)$$

Further, the continuity equation is given by

$$S_D\frac{dh_D}{dt}=-A_1v_1. \quad (36)$$

## CALCULATION OF DAM CAPACITY FOR URANOUCHI BAY

Sample calculation to determine the dimensions of the tide-dam is attempted for Uranouchi Bay, Kochi Prefecture, Japan shown in Figure 6. In Figure 7, the vertical distributions of DO concentration observed in 1987 along the longitudinal direction of the bay are illustrated. DO concentration is higher than 4 ppm in April and May; however, it is less than 3 ppm in the layer deeper than 12 meters in July. The geometrical parameters of the bay are as follows:

| | |
|---|---|
| the water surface area | $S=1\times10^7$ (m$^2$); |
| the total volume | $V=8.5\times10^7$ (m$^3$); |
| the volume deeper than 12 m | $V_{12}=7.9\times10^6$ (m$^3$); |
| the mean tidal range | $2\Delta h_B=1.0$ (m). |

Further, the allowable DO concentration and the oxygen consuming rate are assumed as

$$C_A=3 \text{ (ppm)},$$
$$O_C=22 \text{ (mg}-O_2/\text{m}^3/\text{hr)}\times7.9\times10^6 \text{ (m}^3)\times 24 \text{ (hr)}=4.17\times10^6 \text{ (g}-O_2/\text{day)}.$$

If $\alpha=8$ and $C_s=6$ (ppm) are assumed in Eq. (1), the daily discharge $q_w$ is given by

$$q_w=0.174\times10^6 \text{ (m}^3/\text{day)}.$$

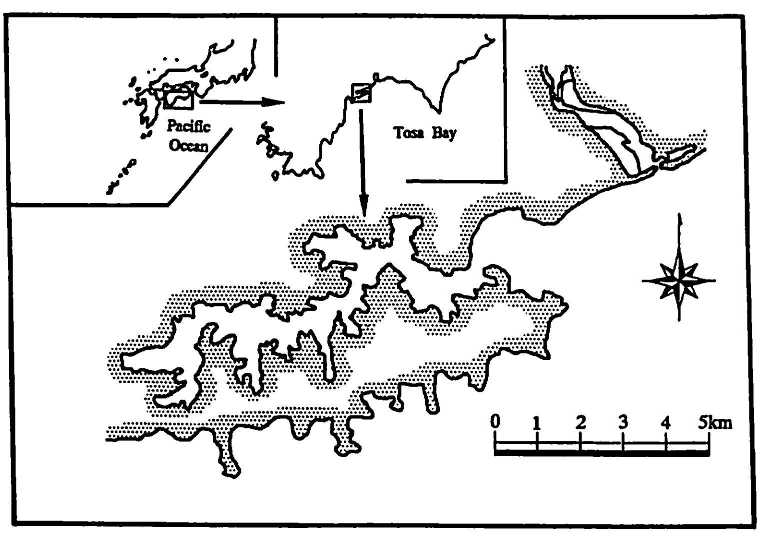


Figure 6. Location of Uranouchi Bay.

The surface area of the dam reservoir can be calculated by Eq. (2), if the tidal range in the reservoir is 80% of that in the bay;

$$S_D = 10.86 \times 10^4 \ (\mathrm{m}^2),$$

which is approximately 1/100 of the whole area of the bay.

In case of the TPT(a) system, the number of pipes, $N$, can be calculated in the following manner for the pipe lengths $l_o = 200$ (m), $l_i = 50$ (m), the diameter $D = 1$ (m), and the Manning's roughness height for the cast iron pipe, $n = 0.015$. From Eq. (5), $f_2 = 0.028$, and $f_i + f_o + f_b = 3$ in Eq. (4). Then

$$F_o = 3 + (200/1) \times 0.028 = 8.6,$$
$$F_i = 3 + (50/1) \times 0.028 = 4.4,$$
$$K_i/K_o = F_i/F_o = 4.4/8.6 \simeq 0.51.$$

From Figure 3, $K_o = 1.65$ is given as the corresponding value to $K_i/K_o = 0.51$, $\lambda = 0.8$. Moreover, the total cross-sectional area of pipes are given by Eq. (3) as

$$A_0 = S_D \sqrt{\frac{4}{3\pi} \frac{F_o \Delta h_B \omega^2}{g K_o}} \simeq 5.1 \ (\mathrm{m}^2).$$

Thus, the number of pipes and the averaged velocity during a half tidal cycle are given as

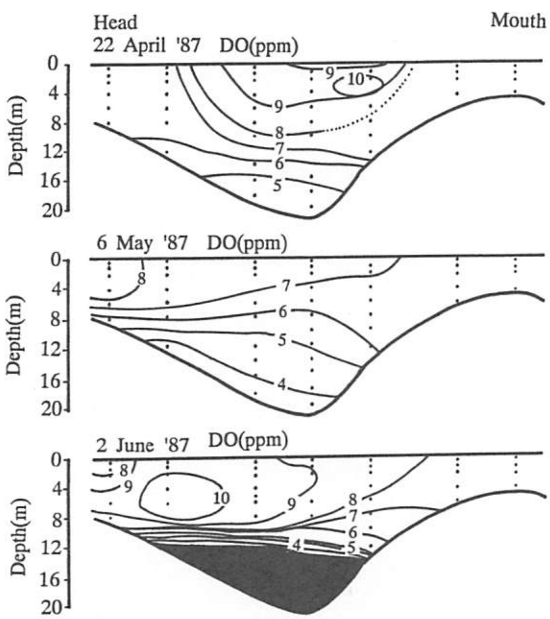


Figure 7. Seasonal Change of Dissolved Oxygen Distributions in Uranouchi Bay. Dark Area indicates that DO concentration is less than 3 ppm.

$$N = \frac{A_0}{\pi D^2/4} = 6.5 \simeq 7,$$

$$v = \frac{4\lambda \Delta h_B S_D}{A_0 T} \simeq 0.76 \ (\mathrm{m/s}).$$

Consequently, the reservoir occupies about 1/100 of the total bay area, and seven pipes of 1-m diameter and 250 m in length are enough for practical use in this bay.

## SUMMARY

The idea of the tide-dam was suggested as a new technique to improve the water quality environment of a fish culture ground. The possibility of putting it to practical use in Uranouchi Bay was discussed. If the DO concentrations of water and the DO consumption rates of water and bottom mud are known, the reservoir and pipeline dimensions can be determined by hydraulic calculations. The tide-dam has the following advantages compared with the other engineering techniques that have already been attempted. The first is its simple structure that uses tidal potential energy and needs no troublesome maintenance. The second advantage is that the forced vertical circulation accelerates the bottom stagnant water exchange between fish culture grounds and the open sea. The third is that the surplus oxygen in a surface layer produced by photosynthesis process can be used to improve the chemical environment of bottom layer and mud.

Further detailed studies, such as experimental and model ones, must be done to develop this technique as the effective one to improve the eutrophic water environments. Furthermore, the other environmental impacts that may be caused by the forced circulation should be investigated as remaining problems.

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# A SYSTEMATIC APPROACH TO PHYSICAL AQUACULTURE WATER MANAGEMENT

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## ABSTRACT

Water quality management is a major concern of aquacultural engineers. Water quality problems in intensive aquaculture systems can be traced either directly or indirectly, to nutrient inputs that are derived from feed. A kilogram of feed can consume 200 to 250 grams of dissolved oxygen (DO) and can produce about 28.8 grams of total ammonia nitrogen (Westers, 1992). Introduced feed and its residue can be found either dissolved in the water or as particulate. For those in the particulate form, they are either settleable or they are suspended. The basic goal in water quality management is to remove the feed residue from the production system once it has served its purpose. Several physical methods of aquaculture water management, including the application of the Secondary Flow phenomenon, have been reviewed. Mathematically, it can be shown that continuous flushing, the most widely used method in water quality management (Losordo, 1980), is inefficient in the removal of suspended solids and dissolved feed material. This paper presents mathematical models to optimize the scheduling of the flushing operation. A basic mathematical description of "Secondary Flow," a well known phenomenon in fluid mechanics, and its potential application to the removal of settleable particles along with the application of these models to optimize the physical management of water quality are presented. Daily flushing of ponds scheduled a few hours after feeding, and a pond design that takes full advantage of the Secondary Flow Effect (SFE) are recommended.

*I ask the reader to remember that what is most obvious may be most worthy of analysis. Fertile vistas may open out when commonplace facts are examined from a fresh point of view L. L. Whyte (in Koestler, 1967).*

## INTRODUCTION

Daniels and Boyd (1989) demonstrated the importance of flushing in aquaculture water quality management. Continuous flushing is one of the frequently used methods in maintaining aquaculture water quality (Losordo, 1980). However, maintaining the water quality in aquaculture ponds by flushing can be very expensive and wasteful of water resources. Wyban et al. (1988) reported a mean water exchange rate of 60 percent of the pond volume per day for the Oceanic Institute's experimental shrimp pond. Assuming an average depth of 1 meter, the daily water exchange would amount to 6,000 $m^3$ per hectare per day or 4,200 liters per minute per hectare. The cost of cleaning up aquaculture effluent can break an otherwise successful operation.

Aquaculture pond water should be characterized by its physical as well as its chemical characteristics. However, the chemical parameters of aquaculture pond water have always received more scrutiny in the past. Chamberlain (1988) listed dissolved oxygen, pH, ammonia and nitrite, hydrogen sulfide, redox potential, sediment core samples, phytoplankton, and bacterial counts as the parameters to monitor in a shrimp pond. Conspicuous by their absence from the list are parameters that characterize the suspended solids in aquaculture water: total weight, size distribution, and others.

For practical purposes, we can consider that all nutrients in an aquaculture production system come from feed inputs. Chamberlain (1988) stated that up to 5 metric tons per hectare of feed is given to intensive shrimp ponds during the last 45 days of growth and up to 50 percent of the feed is not immediately eaten by the shrimp. Wyban et al. (1988) reported a high feeding rate of 67 gm per $m^2$ per day, or 0.67 MT per hectare per day, for the Oceanic Institute's experimental round pond. Feed and its residue exist in aquaculture water in three basic components: (1) Dissolved Feed and Residues (DFR); (2) Suspended Fine Particulate (SFP), and (3) Settleable Solids (SS).

The presence of settleable particulate in the water leads to sediment accumulation, which is detrimental to pond water quality. On the other hand, the presence of suspended solids is beneficial to the performance of aquaculture production systems. Leber and Pruder (1988) concluded that the performance of currently available shrimp feeds are greatly improved when shrimp pond effluent is added to the culture water, regardless of feed quality. There is also a growing indication of the importance of suspended particulate in the diet of molluscs. Huntington and Miller (1989) concluded that a low concentration (50 mg per liter) of suspended sediments enhanced growth in larval *M. mercenaria,* as it does for juvenile and adult *Crassostrea virginica*. The effect of suspended solids on the oyster *Mytilus edulis* was reported by Winter (1976), Loosanoff (1962) and Murken (1976). All three authors reported an increase in weight gain when a small amount of suspended solids was added to the oysters' diet. It is therefore clear that the three components of feed (DFR, SFP, SS) in the production system's water must be managed separately.

The distinction between SFP and SS is not a clear one. Some of the smaller and lighter SS can be kept in suspension by agitating the water. Kusuki (1978) stated that a water velocity of 5.5 cm per second (10.84 ft per minute) is required to keep oyster feces in suspension. The fact that many shrimp farmers, especially those in Taiwan, are operating their aeration equipment during the day when the dissolved oxygen levels are usually above saturation gives empirical evidence that keeping water moving may in itself be the reason for the operation of the aeration equipment. Wyban et al. (1989) believes that the use of a paddle wheel contributes to the removal of dissolved organic carbon from the pond water via foam fractionation. As paddle wheel-induced air bubbles pass through the pond water, the surface active fraction of the dissolved organic carbon is absorbed onto the bubble surface producing foam at the air-water interface (Spotte, 1979). In their experiment, Wyban et al. (1989) observed that ponds with paddle wheels produced larger shrimps during identical growth periods.

In water management, it is important that the three components of feed residue and by-products be considered separately and managed in a systematic manner. Figure 1 gives an overview of the problem, with this paper being concerned with only the unshaded parts of Figure 1. Optimal strategy for the reduction of dissolved and suspended fine particulate and the removal of settleable solids will be developed and presented below.

## THE CASE OF FLUSHING

To derive upper and lower bounds for the concentration of DFR and SFP in the water, two cases must be distinguished: (1) feeding more frequently than exchanging water, and (2) exchanging water more frequently than feeding. For both cases we will assume:

❶ Pond volume is one unit of liquid volume
❷ Instantaneous and complete mixing of feed with the pond water at each feeding "event"
❸ Instantaneous water exchange at each exchange "event"

### A. CASE 1:

For the case of feeding more frequently than exchanging water, we will further assume:

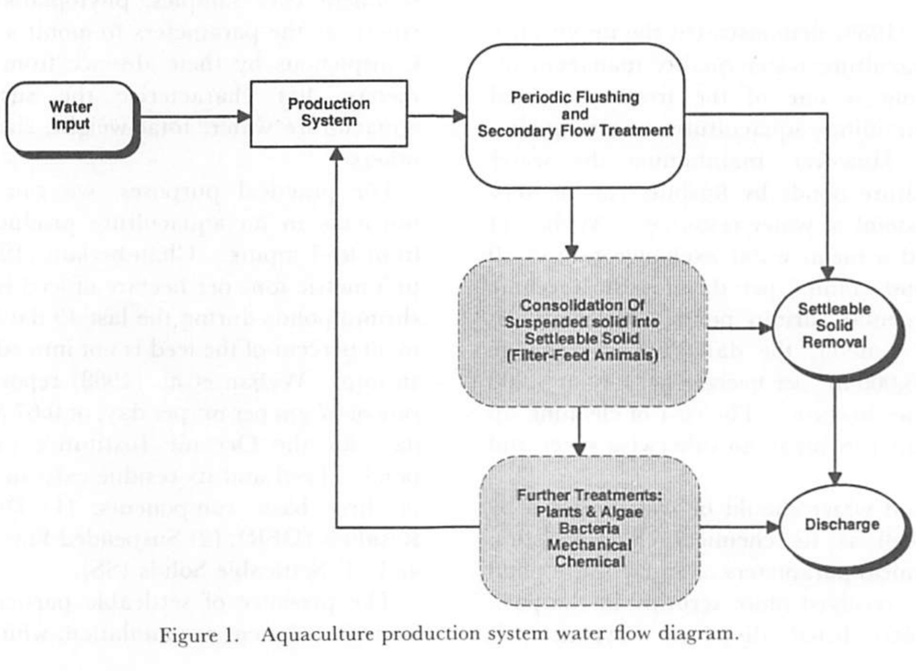


Figure 1. Aquaculture production system water flow diagram.

4. Time interval between feeding "events" constitutes the base unit of time
5. A feeding rate of C units of feed per pond volume unit per time unit (i.e., C units of feed are put into the pond every unit of time, which constitutes a feeding "event")
6. An exchange of $Y<1$ pond volume unit at the end of every $n\geq 1$ units of time constitutes an exchange "event" and corresponds to an "average" exchange rate of Y/n (volume/time), so flushing will occur at the end of $n$ units of time, $2n$ units of time, and mn units of time, $m$=integers, and
7. When n is an integer, implying the simultaneous occurrence of feeding and exchange events, we assume that feeding occurs first, followed by water exchange.

Now, letting $Z=1-Y$, the following derivation gives $F(t)$, the concentration of DFR and SFP in the water as a function of time:

| $t$, time | $F(t)$ |
|---|---|
| 1 | $C$ |
| 2 | $2C$ |
| $n$ | $nC$ |
| $n<t<n+1$ | $ZnC$* |
| $n+1$ | $ZnC+C=(Zn+1)C$ |
| $2n$ | $(Zn+n)C=(Z+1)nC$ |
| $2n<t<2n+1$ | $Z(Z+1)nC=(Z^2+Z)nC$* |
| $mn$ ($m$=integer) | $\lim_{m\to\infty} nC\sum_{i=1}^{m-1} Z^i$ (1) |
| $mn<t<mn+1$ | $\sum_{i=1}^{m} Z^i$ (2)* |

*Note*: *=*Flushing.*

Now, steady-state corresponds to the limit $t\to\infty$, which is equivalent to the limit $m\to\infty$. Since $Z<1$ and since the summations are simple geometric series, limits do exist and are given by:

$$\lim_{m\to\infty} nC\sum_{i=1}^{m-1} Z^i=nC\left(\frac{1}{1-Z}\right)=\frac{nC}{1-Z}=\frac{nC}{Y} \quad (1')$$

$$\lim_{m\to\infty} nC\sum_{i=1}^{m} Z^i=nC\left(\frac{1}{1-Z}-1\right)=\frac{ZnC}{1-Z}=\left(\frac{1-Y}{Y}\right)nC \quad (2')$$

Since (1′) corresponds to the limit just *before* exchange and (2′) to the limit just *after* exchange, (1′) is the upper bound and (2′) is the lower bound for the steady-state feed concentration, when feeding more frequently than exchanging water.

**B. CASE 2:**

When we exchange water more frequently than we feed the animals, we have a similar but significantly different set of assumptions to supplement 4 to 7:

8. The time interval between exchange events constitutes the base unit of time
9. We still designate the volume exchanged, but now at the end of every unit of time, by $Y<1$ pond volume units
10. We still feed $C$ units of feed per pond volume unit, but now we do it at the end of every $m>1$ units of time (for an "average" feeding rate of $C/m$). For simultaneous feeding and exchange events, when $m$=integer, we exchange the water first, then put in the feed.

Again letting $Z=1-Y$, we have:

| $t$, time | $F(t)$ |
|---|---|
| 0 | $C$ |
| 1 | $ZC$ |
| 2 | $Z^2C$ |
| $m$ | $Z^mC$ |
| $m<t<m+1$ | $Z^mC+C=(Z^m+1)C$* |
| $m+1$ | $Z(Z^m+1)C=(Z^{m+1}+Z)C$ |
| $m+2$ | $(Z^{m+2}+Z^2)C$ |
| $2m$ | $(Z^{2m}+Z^m)C$ |
| $2m<t<2m+1$ | $(Z^{2m}+Z^m+1)C$* |
| $km$ | $C\cdot\sum_{i=1}^{k} (Z^m)^i$ (3) |
| $km<t<km+1$ | $C\cdot\sum_{i=0}^{k} (Z^m)^i$ (4) |

*Note*: * *denotes feeding events*

Again we have geometric series with a ratio $(Z^m)$ less than 1 and thus the limits as $m\to\infty$ (again corresponding to the limit as $t\to\infty$=steady state) are:

$$\lim_{k\to\infty} C\sum_{i=1}^{k} (Z^m)^i=C\left(\frac{1}{1-Z^m}-1\right)=\frac{CZ^m}{1-Z^m} \quad (3')$$

$$\lim_{k\to\infty} C \sum_{i=0}^{k} (Z^m)^i = C\left(\frac{1}{1-Z^m}\right) = \frac{C}{1-Z^m} \quad (4')$$

where (3′) is the lower bound (because it corresponds to just before feeding) and (4′) is the upper bound for the feed concentration in pond water, when water exchange takes place more frequently than feeding.

If the amount of water exchange is no longer determined by the DO level in the tank water, the rate of the water exchange rate is simply that amount required to sufficiently remove SS in the tank every day. Depending on the water exchange schedule, we can estimate maximum and minimum feed concentration in the tank water from equations 1′ to 4′.

The manner by which water is exchanged from the tank is very important in water management. For a daily 50 percent average water exchange rate, we can either: (1) exchange all the tank water at the end of every other day; (2) exchange 50 percent of the water at the end of every day; or (3) exchange 25 percent of the water at the end of every half day. If we drain off 50 percent of the tank's water at the end of every day and then refill the tank, we can remove 50 percent of the SS in the tank. The concentration of Total Suspended Solids (TSS) in the tank's water will vary between a relative scale of 1 and 2. The scale of 1 represents the concentration of SS in the tank's water at the end of the first day of operation, had that tank been given the same amount of feed and stocked with the same number and bio-mass of shrimp. On the other hand, if we exchange water every other day, then the concentration of the SS in the tank would vary between 0 and 2. Finally, if we opt to operate on a half day schedule, but still use the same average water exchange rate, then the SS concentration would vary between approximately 1.286 and 2.286.

To completely drain down the ponds every other day seems to be impractical. A daily one time water exchange of 50 percent of the tank's volume seems to be a good guideline to compare the relative efficiency of the other management schemes.

For the purpose of comparison, the equation for continuous water exchange is:
$C=C_o^{-xt}$, for $=1$, $C_o=1$, and $C=1/2$, $x=0.69374$, which is greater than the 0.50 water exchange volume, if we were to exchange 50 percent of the water at the end of every day.

## SECONDARY FLOW

It has been observed that, when a "rigidly" rotating flow is maintained in a right-circular cylindrical container, the "secondary" flow extant in the viscous boundary layer at the bottom of the container is distinguished by a significant component directed radially inward toward the axis of the container (Secondary Flow [Motion Picture], 1964). "Rigid rotation" means that the primary flow moves as if it were a solid disc: the horizontal flow field is depth independent, and any given fluid particle is characterized by the absence of a radial velocity component and by a tangential velocity component proportional to its radial distance from the axis. This phenomenon is frequently called the "tea cup" effect, because it is easily demonstrated by stirring a cup of tea in which there are several tea leaves and observing the movement of the tea leaves toward the center of the bottom of the cup.

In 1921, Theodore von Kármán published a paper entitled "On Laminar and Turbulent Friction," in which he examined the laminar flow field due to an infinite disk rotating in an incompressible medium. He was able to produce an exact solution for the Navier-Stokes equation (von Kármán, 1921). The similarity transformation approach used by von Kármán to reduce the equations of motion to an amenable set of non-linear, ordinary differential equations has been generalized and applied to a wide variety of boundary conditions. Axisymmetric rotating flows, in general, are particularly suited to this method and have been widely studied.

Bödewadt (1940) obtained a numerical solution for the secondary flow pattern produced by an infinite fluid rotating with constant angular speed w over an infinite disc suspended at depth $z=0$. Using modern computers, Nydahl (1971) gave an improved solution to the Bödewadt problem King and Lewellen (1964) discussed the laminar boundary layer produced by the rotating

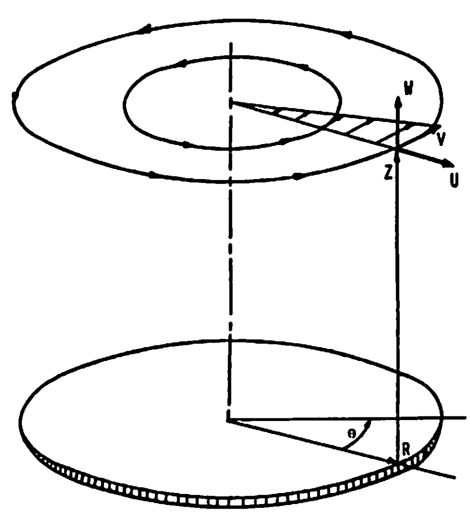


Figure 2. Schematic sketch of coordinate system and velocity components. (Source: Nydahl, J.E. 1971. Heat Transfer for the Bödewadt Problem, p. 44).

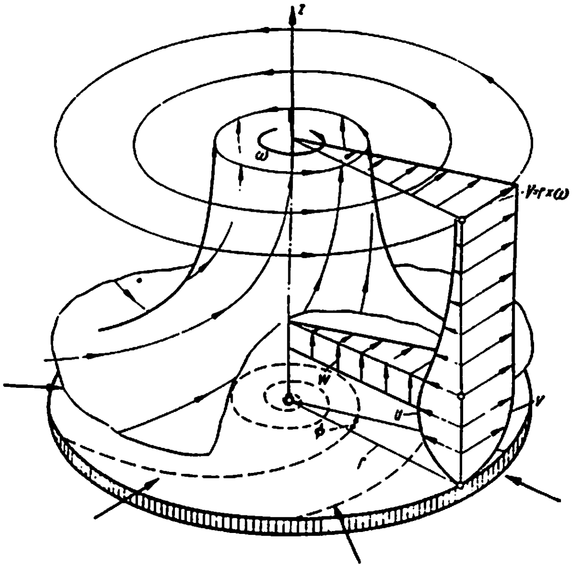

Figure 3. Rotation of flow near the ground. *Velocity components:* u=*radial*; v-*tangential*; w-*axial*. *Owing to friction, the tangential velocity suffers a deceleration in the neighborhood of the disk at rest. This gives rise to a secondary flow which is directed radially inwards.*

flow of a viscous incompressible fluid over a very large stationary disk. In their solution they have assumed the external velocity to be tangential and to vary as some power of the radius, that is, $V_\infty \approx r^n$. They have concluded, that in the region of the outer edge of the disk, the loss of centrifugal force in the boundary layer, due to the tangential shear exerted by the disk, forces flow into the boundary layer and radially inward. This happens independently of the particular radial variation of the tangential velocity in the primary flow as predicted by Stewartson's (1958) similarity solution. As the radial flow in the boundary layer builds up, convection in the boundary layer becomes important as does the radial variation of the tangential velocity in the outer flow. Convection in the boundary layer tends to conserve angular momentum and thus to increase $v$ with decreasing radius. This effect is in direct opposition to the tangential shear of the disk. Thus, convection in this region reduces the loss of centrifugal force in the boundary layer, and the rate of growth of the flow into the boundary layer is retarded. If angular momentum is conserved in the outer flow, this is all that results; however, if angular momentum decreases with decreasing radius, i.e., $n < -1$, the radial velocity can grow until angular momentum is more nearly conserved within the boundary layer than it is outside the boundary layer. At the center, where n must go to one, the flow should approach that predicted by Bödewadt (1940).

The case discussed by King and Lewellen models well an aquaculture round tank, or pond, for we have observational evidence that $v$, the tangential velocity profile in an aquaculture pond or tank, is very well approximated by $v \approx r^n$, though not necessarily with $n=1$.

## PREVIOUS OBSERVATIONS OF SECONDARY FLOW EFFECT (SFE) IN AQUACULTURE

Larmoyeux et al. (1973) and Burrows and Chenoweth (1955) discussed the effect of the Secondary Flow phenomenon due to primary swirl flows in a cylindrical container with regard to container design for salmon production. Both studies concluded that a cylindrical container provided the greatest amount of "self-cleaning." A significant concern in both studies was the short retention time provided by the cylindrical container. Both these papers studied ponds or tanks equipped with center surface drains and continuous flow-through water exchange.

The Oceanic Institute (OI), using a round pond in shrimp production, observed that "the circular flow developed by the paddle wheel system seems to have a beneficial effect in concentrating waste organic materials near the center of the tank (Noda, 1987). This is attributed to the condition that the flow velocity is highest near the outer wall and lowest near the center."

Table 1. Initial rotational velocity at different initial tank water depth

| Depth (Inches) | Rotational Velocity (Seconds/Rotation) | Average (Seconds/Rotation) | Standard Error |
|---|---|---|---|
| 6 | 13.61, 9.54, 12.45, 10.07, 12.50, 11.37, 12.08, 11.23, 13.21, 11.58 | 11.76 | 1.29 |
| 12 | 10.55, 12.17, 11.33, 12.24, 11.23, 12.98, 11.74, 12.20, 11.76, 11.77 | 11.80 | 0.67 |
| 18 | 12.07, 12.12, 15.85, 14.37, 10.48, 13.00, 13.17, 13.06, 13.37, 12.60 | 13.01 | 1.43 |

[a] Funded in FY 90–92; with a grant from the U.S. Department of Agriculture under Project 406; Cooperative Agreement No. 90-34135-5183. Hawaii Institute of Tropical Agriculture and Human Resources.

In this case there is a lack in understanding of the Secondary Flow Effect (SFE).

The measured rotational velocity near the center of the OI round pond was $w=0.0036$ rev per second when two sets of one horse power paddle wheels were used with the 20 meter diameter pond. While the rotational velocities of the pond water varied with the diameter, it did not show any appreciable variation with the water depth. Mr. Noda did report that radial inflow velocities were detected at a distance of 2 inches from the pond bottom.

It appeared that previous investigators did not formally identify their observations to be caused by SFE. As a result, available theoretical work on SFE was neither utilized to help design the experiment nor used to help explain the observed effects.

## EXPERIMENTS TO DETERMINE MINIMUM ROTATION NECESSARY FOR USEFUL SFE

### EXPERIMENTAL APPARATUS:

An experimental tank, 68″ in diameter ×20″ in height, was constructed using plywood sides, sitting on a sand bottom, with a plastic liner, and a smooth disc over the center of the bottom liner. There is a 5 degree incline from the outside edge of the tank bottom to the center drain (1.5″ I.D.). Water supply comes from a 1/2″ (nominal) PVC pipe capped at the end, and with a 1 3/8″ * 1/16″ slit cut across the end. The slit was placed 3″ above the bottom such that its spray plane was parallel with the bottom plane. The flow rate was estimated to be 1.92 liters per second.

The tank was filled to either 6″, 12″, or 18″. When the selected height was reached, the input pipe was shut off and removed from the tank and the drain stopper was removed. A 37 second waiting period was allowed for the dissipation of standing waves created by the input water jet. A floating marker was then placed onto the water surface at a 24″ in radius, ninety degrees before the line at which the timing commenced. The time measured was that required for one rotation. Ten measurements were taken at each height.

Using the water jet as the only input energy, data in Table 1 suggest that the initial rotation rate can be regarded as independent of the initial tank's water depth. However, statistically, the initial rotation rate at $h=18$ inches ($h$ is the initial depth of the tank's water) is different from that at $h=6$ inches at a significance level of 97.2%, and from that at $h=12$ inches at a significance level of 98.6%, based on Student's tests of the differences of the means being zero with pooled standard errors.

There is clear indication that the relationship between the initial tank's water depth and the initial rotation rate is not linear, and even though the differences are statistically significant, they are very small.

### First Experiment:

The tank was filled with water to a depth of 15 inches and then left undisturbed for 5 hours, allowing the water to come to a complete rest. Across the tank's bottom, 184 popcorn kernels were distributed evenly. The spe-

Table 2. Rotational velocity required to initiate secondary flow effect

| $w_{18}$, Second$^{-1}$ | Drain Opened | Observation |
|---|---|---|
| 0 | No | No inward movement observed |
| 0.0145 | No | Popcorn kernels distributed between 12″<R<18″. 40 kernels moved into R<6″. 16 kernels moved into 6″<R<12″. |
| 0.011 | No | No movement observed. |
| 0.0089 | Yes | 6 kernels left in R<6″, 16 kernels in 6″<R<12″. All kernels (sp.g.<1.10 gm/cm$^3$) removed form the tank by the draining water. |
| 0.0263 | Yes | Only 2 kernels dropped into the range 18″<R<30″ exhibited movement. |
| 0.024 | Yes | Slow inward movement observed. |
| 0.017 | Yes | 67 kernels removed. Sp.g.<1.13 gm/cm$^3$. |
| 0.036 | Yes | All but 3 kernels removed. Sp.g.<1.20 gm/cm$^3$. |

[b] Funded in FY 90–92; with a grant from the U.S. Department of Agriculture under Project 406; Cooperative Agreement No. 90-34135-5183. Hawaii Institute of Tropical Agriculture and Human Resources.

cific gravity of the popcorn kernels varied from 1.02 to 1.20. The drain stopper was then removed and the tank was allowed to drain down to a depth of 6 inches. During repeated trials, not a single kernel of popcorn was observed to exhibit any significant radial or tangential movement.

Draining alone has been shown to be insufficient to develop enough rotational water movement to start the SFE for popcorn kernels with a specific gravity as low as 1.02. An initial rotational movement (net angular momentum) of the tank water is necessary.

Second Experiment:

In this experiment, a total of 184 popcorn kernels were used. First, the tank was filled and the water rotational velocity was adjusted using either the water jet to slightly increase the rotational velocity or by letting the water slow to the desired rotational velocity. The rotational velocities were measured at the water surface at a radius of 18 inches, w18, and the popcorn kernels were then distributed on the bottom of the tank. At these low rotational velocities, the kernels would sink to the bottom and, if the inward movement of the water in the bottom boundary layer was sufficient, the kernel would then move inward.

The lowest $w_{18}$ at which inward motion of popcorn kernels was observed was $0.0089_{\text{sec-1}}$. At this rotational velocity, only kernels in the region $R<6''$ exhibited movement. The highest w18 at which no kernel movement was observed was $0.0263_{\text{sec-1}}$, when kernels were located within the range $18''<R<30''$. All kernels were readily removed with $0.036<w18<0.038_{\text{sec-1}}$.

## FLOW PATTERN

Using colored popcorn kernels, we have confirmed that, while there is rotational velocity, there is no inward radial flow either on the surface of the water or in the water column, until the bottom boundary layer has been reached. The inward radial velocity existed only in the bottom boundary layer. For any given flow pattern, the tangential velocity of the surface water exhibits a marked gradient. In other words, $w$ is a function of the radius.

The centrally located drain, whether placed at the bottom or close to the surface, did not seem to affect the flow pattern to any large degree, except that with a bottom drain and sufficient rotation popcorn kernels were sucked into the boundary layer and hence into the bottom drain and removed. But with a surface drain, the heavy kernels remained close to the base of the drain and could not be moved out of the tank—while light kernels were so removed.

## HYDROMECHANICAL PROPERTIES OF DETRITAL PARTICLES

Smayda (1971) gave an excellent overview of the range of physical properties of suspended solids in natural oceanic water that can be assumed to approach the physical properties of aquacultural detritus. He stated that the size (nominal diameter) of marine phytoplankton generally ranges from 2–2,000 microns (0.0002–0.2 cm) and are of diverse shapes. He also provides: (1) the density of cytoplasm in marine organisms ranges from 1.03–1.10 gm per $cm^3$; (2) various encasements range in density from 1.5 gm per $cm^3$ for cellulose to 2.6 gm per $cm^3$ for the opaline cell wall of diatoms and up to 2.95 gm per $cm^3$ for the calcium carbonate plates of some cocolithophorids; and (3) a total-organism density of 1.34 gm per $cm^3$ for *Cyclotella nana*.

In our experiments, we used popcorn kernels with a density from 1.02 to 1.20 gm per $cm^3$. The sinking rate of these popcorn kernels varied from 2.5 cm per second to 12.5 cm per second.

## CONCLUSION

Feed introduced into an aquaculture production system will persist in the system in three forms: (1) dissolved solids, (2) suspended solids, or (3) settled solids. For the dissolved material, the only physical means of removal them from the system is flushing. For those fine particulate suspended in the water, mechanical filtering is generally much more costly than flushing. This paper has clearly demonstrated that, contrary to current practices, periodic flushing is more efficient than continuous flushing.

Filter feeding animals can convert fine particulate in the water into settleable solids. This paper has shown that settled sediment can be efficiently removed from the production system by applying the Secondary Flow phenomenon.

Hence, it appears that periodic flushing combined with the Secondary Flow Effect (SFE) would be the most efficient physical water management strategy for aquaculture production systems. Experimental results obtained in the University of Hawaii Aquacultural Engineering Laboratory indicate that from 5 to 20 percent of water is required to remove sediment by SFE.

Because bottom sediment has become a serious problem in intensive aquatic farming, many farmers, including shrimp farmers in Taiwan, and researchers, including the Oceanic Institute in Hawaii, have begun to investigate the need to keep the water agitated in order to keep the particulate from settling to the bottom. It is interesting to note that both the Taiwan farmers and the

Oceanic Institute were practicing continuous flushing, while trying to keep the particulate from settling. Results from the present study would recommend that settlement of sediment be encouraged and the sediment be removed from the pond periodically by the application of the SFE at the same time that periodic flushing is applied.

To take advantage of the SFE, a square or round pond is preferred. A flat and lined bottom with a centerdrain would eliminate the bottom scouring problem and allow the the removal of relative heavy particles from the pond. Paddle wheels and other aeration equipment should be used only for aeration and not to keep the particulate in suspension. Daily flushing should be sufficient for most conditions. The flushing should be scheduled to occur a few hours after feeding so that fecal materials can be removed as soon as possible from the production system.

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# LABORSAVING SYSTEMS AND THE TECHNOMETRIC MANAGEMENT OF THE REARING ENVIRONMENT FOR THE MASS PRODUCTION OF LARVAL FISH

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## ABSTRACT

Mass breeding technology has been developed to allow for liberation of more than million young of *Pagurus major* and *Paralichthys olivaceus* in a local mariculture farm. This technological development identified difficult problems. Mass production often requires a great deal of work. In addition, most management depends on empirical judgment.

To elucidate such problems, a research and development project has been conducted from 1985 to 1990 with close co-operation between the public research center and the private developing company. This project provided us with the following good systems:

Laborsaving systems: (a) an automatic scavenger for rearing tanks; and (b) an automatic feeder of enriched rotifers. Technometric systems for a quantitative management: (a) a continuous monitor for water quality; and (b) a database system for managing files. These systems have worked effectively since 1990 at the Kanagawa Prefectural Fish Farming Center.

## THEME AND OBJECTIVES

Our theme for this project is research and development focused on a laborsaving system for the important breeding tasks as well as a technometric system for the quantitative management of the larval fish production. When planning a fish farming center, this kind of study was found to be important in decreasing labor and cost for larval fish production in Japan. Fujita et al. (1982) and Morizane (1991) recognized this importance when constructing the Kagoshima Prefectural Fish Farming Center and the Ehime Prefectural Fish Farming Center, respectively. In the case of the laborsaving system, we paid special attention to streamlining tasks that require a large effort, such as cleaning bottom of the fish rearing tank and concentrating, cleaning, and supplying rotifers.

This laborsaving systems is comprised of three important parts: the scavenger that automatically removes harmful deposits on the bottom of rearing tanks; the concentrator that concentrates and cleans live rotifers as an essential food for fish in the early stages; and the feeder that automatically transfers fed rotifers quickly to the rearing tanks of larval fish. With respect to the technometric system, several types have been developed including the device by Hiramoto et al. (1986; cf. Fushimi 1989.) Our goal is to develop a device that may be inexpensive in both initiation and maintenance.

Two integrated management devices have been developed; a continuous monitor for water quality, and a database system for managing files that include the water-quality monitoring data. The continuous monitor measures water quality in each of four rearing tanks once each hour. The water quality data measured include temperature (°C), dissolved oxygen, cell number ($ml^{-1}$) of *Nannochloropsis* added into rearing tanks, concentration of detritus, and concentration of dissolved matters accumulated in the rearing water. The database is integrated with water-quality monitoring data and data on rearing procedures both incorporated into the menu.

## COMPOSITION OF THE DEVICES AND SYSTEMS

### AUTOMATIC SCAVENGER

This device is composed primarily of a driving unit for

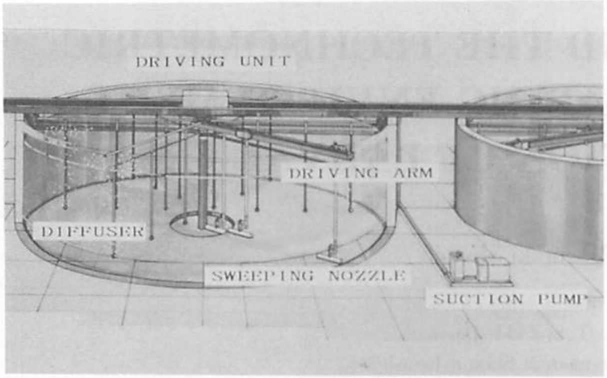



Figure 1. Composition of the automatic scavenger system.

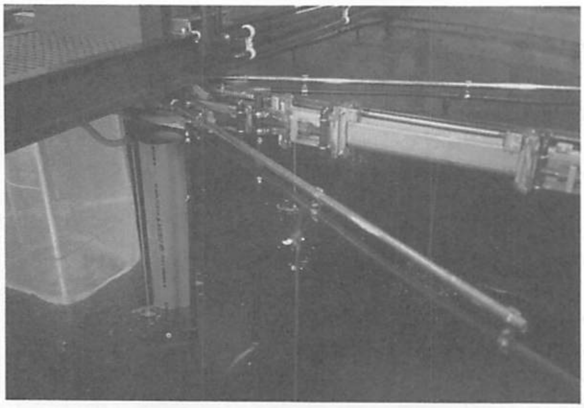


Figure 2. Important parts of the automatic scavenger: the driving arm and the radials (both to the right of the axis) as well as the planktonnet basket (to the left of the axis).

two rotating parts: a driving arm for sweeping nozzles and 6 radials for diffusers which function as aerators (Figures 1 and 2). Of the sweeping nozzles, two are mobile and slide one by one on either side of the arm, depending on their pedestral part, the other and the innermost one is fixed on the arm. The nozzles are spiraled on the bottom by means of both rotation of the driving arm and their reciprocation along the arm, except the innermost one, which sweeps exclusively within the harvesting-pool area. Three diffusers are attached to each radial vertically at regular intervals. Detritus is sucked through the nozzles and discharged by a drainage pump. The pump is a secondary part in the composition. Installing a trap net at the outlet of the pump allows 1) control of excessive flow to avoid sucking living fish; 2) observation of the hygienic condition of the dead fish discharged.

To accommodate water exchange, a plankton-net basket is set in the center of the rearing tank or at the upper part of the driving axis. It is useful as an outlet part of the drainage duct, because the net keeps smaller fish of earlier stages from being sucked by the pumping, and as an inlet part of the flooding duct, because the net moderates the current's strength into the tank.

The device is developed with major emphasis on the following; 1) to clean as completely as possible, without missing any area on the bottom, especially in the harvesting pool at the center of the tank; 2) to position the sweeping nozzle as closely as possible to the bottom to avoid sucking live juveniles, and 3) to combine the functions of aeration, water exchange, and inspection of dead fish.

## AUTOMATIC FEEDER

This semiautomatic system consists of a rotifer culture tank, a concentrator, an intermediate tank, a density control tank, and a distributor (Figure 3).

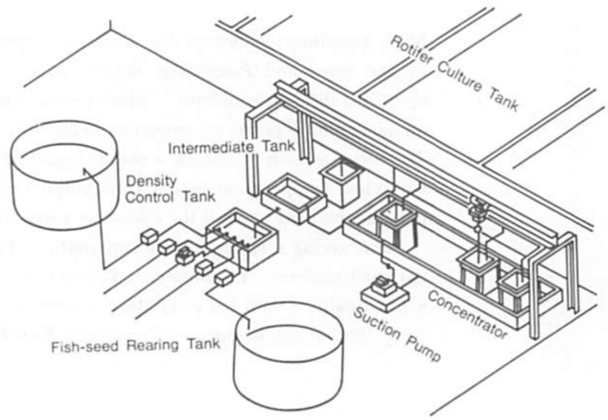



Figure 3. Diagrammatic arrangement of the automatic feeder with the rotifer concentrator.

Rotifers are pumped from the culture tank into the concentrator lined with the plankton net (NXX17) in the form of a basket. Concentrated rotifers are transferred to the intermediate tank, from where they are supplied as needed by the distributor (Figure 4) with the diaphragm pump to the rearing tank through the density control tank. The distributor is regulated at a control panel and well automatically supply enriched rotifers by volume and time.

The basket effectively concentrates and cleans rotifers by a constant washing treatment by the filtered sea water (Figure 5) on the outside of the net. This also avoids the net being blocked by rotifers. The efficiency of the concentrator is estimated to be 500 to 800 million individuals per hour.

Rotifer concentration and supply is done daily and represents a very difficult task in the rearing of fish. The device was developed especially to reduce the work of concentrating and clearing rotifers without damaging the animal in any way, as well as to simply and hygienically maintain the concentrator.

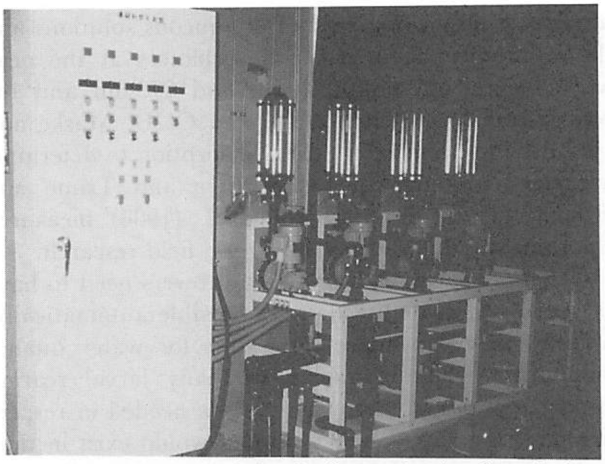


Figure 4. Arrangement of the distributor showing four diaphragm pumps (right) and their control unit.

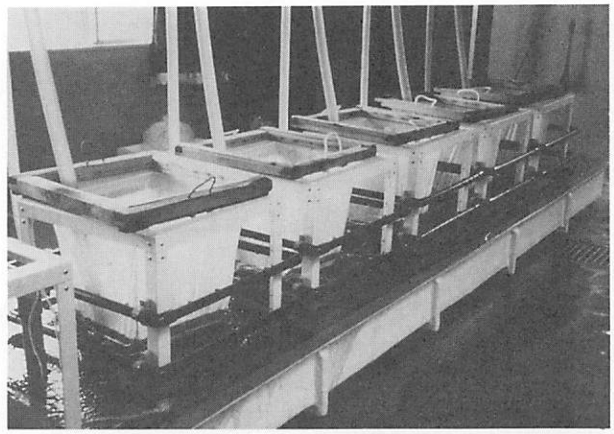
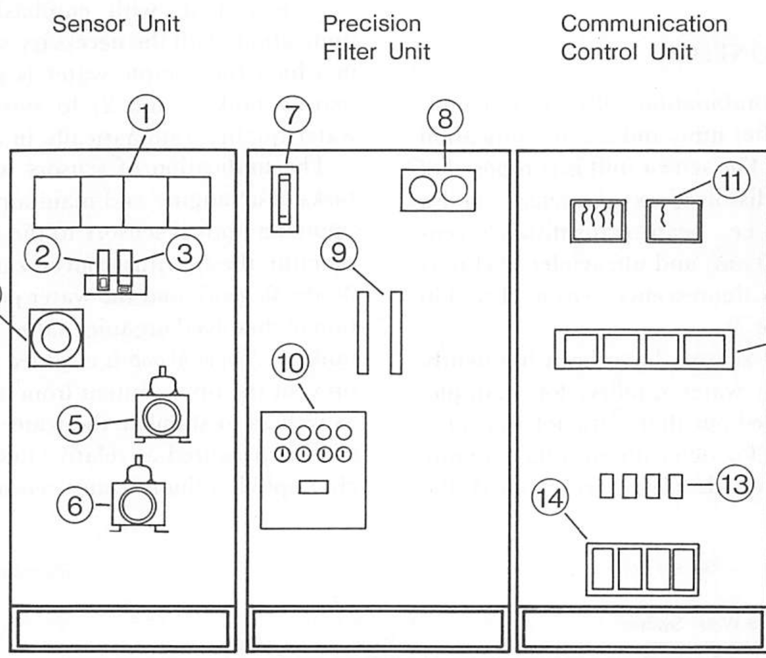


Figure 5. Concentrator of the rotifer in a unit of five tanks.




| No. | Equipment |
|---|---|
| ① | Intermediate Tank |
| ② | Temperature Sensor |
| ③ | Dissolved Oxygen Sensor |
| ④ | Fluorescence Sensor |
| ⑤ | Beam Transmittance Sensor (660nm) |
| ⑥ | Beam Transmittance Sensor (254nm) |
| ⑦ | Flow meter |
| ⑧ | Presseure Gauge |
| ⑨ | Hollow Yarn Film |
| ⑩ | Control Unit |
| ⑪ | Recorder |
| ⑫ | Controller of sensors |
| ⑬ | Switch of Sampling Pump |
| ⑭ | Communication Controller |

Figure 6. Diagrammatic arrangement system of the water quality monitoring system.

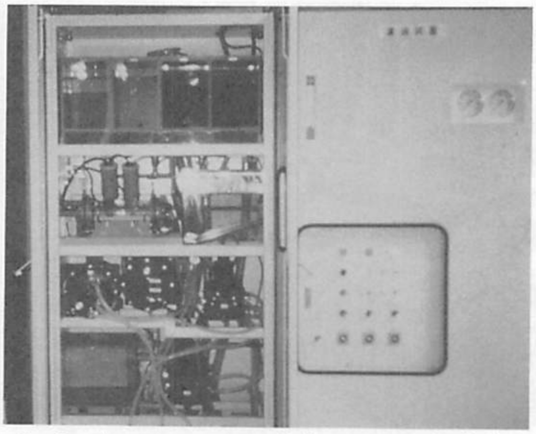


Figure 7. Interior arrangement of the sensor unit (left) and the precision filter unit (right) in a set. (Cf.Fig 6 for devices in each shelf of the former unit.)

## WATER QUALITY MONITOR

This device works in combination with a sensor unit, an automatic precision filter unit, and a communication control unit (Figure 6). The sensor unit is composed of a temperature sensor, a dissolved-oxygen sensor, and a group of optical sensors; i.e., beam transmittance sensors for near infrared (660 nm) and ultraviolet (254 nm) rays and a chlorophyll *a* fluorescence sensor (Ex: 436 nm; Em: 685 nm) (Figure 7).

Such models of optical sensors have been frequently used in recent studies of water quality; for example, Dobbs et al. (1972) pointed out that ultraviolet absorbance at 254 nm is useful for determining total organic carbon (TOC); Urano et al. (1981) researched the ultraviolet absorption spectra of aqueous solutions and the relationship among the absorbances at the peak wave length, 220 nm, 254 nm, and 275 nm and the concentration of TOC, TOD, and COD; Maske and Haardt (1987) studied detrital absorption to determine accurate phytoplankton absorption; and Tsuno and Hosomi (1979) and Kostko et al. (1988) measured chlorophyll *a* fluorescence in vivo in field research.

Generally speaking, larval fish growers need to have as much water quality data as possible automatically, because they can spare little time for water quality monitoring while managing so many larval rearing tanks. Besides, if many sensors are needed in respective rearing tanks, a heavy burden would exist in time and cost for arranging and maintaining them all.

To overcome these problems, a water quality monitor was developed, with emphasis on the following 1) unification of all the necessary sensors in a compact unit in which the sample water is pumped from respective rearing tanks; and 2) to store realtime data of tank water quality automatically in a database.

The unification of sensors will effectively lessen the tasks of arranging and maintaining a set of sensors, and applying optical sensors to the device makes it easier to monitor the detritus concentration, the cell number of *Nannochloropsis,* and the water pollution by an accumulation of dissolved organic matter (Figure 8) in the rearing tanks. *Nannochloropsis* is added into the rearing water to prevent the lipid content from decreasing in the rotifers, as well as to stabilize the water quality. Cell numbers can be measured as relative fluorescent intensity by the chlorophyll *a* fluorescence sensor. This will give detri-

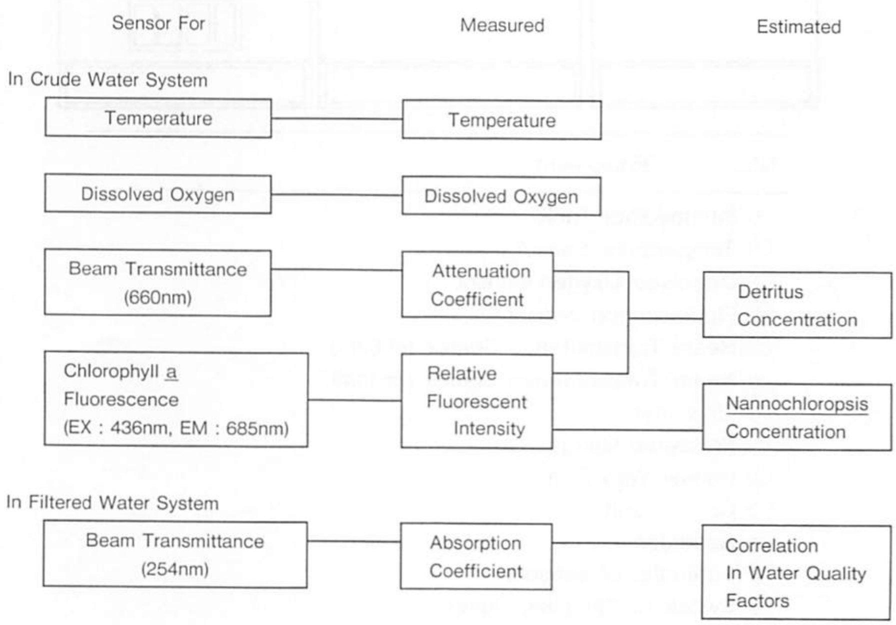



Figure 8. Flow in the water quality monitoring. Columns left, sensor series; middle, measured properties; right, estimated properties.

tus concentration in conjunction with the beam transmittance (660 nm) sensor that indicates the attenuation coefficient.

The beam transmittance (254 nm) sensor measure the purity of filtered rearing water that by recording the absorption coefficient.

The filtered water is constantly supplied to the sensor through the precision filter which contains hollow yarn film that percolates particles to a maximum size of 0.25 $\mu$m (Figure 9). The ultraviolet beam transmittance is regarded here as an indicator of the water pollution corresponding to the optical absorption of the dissolved organic matter. It is noted that a preliminary solution for the correlation of the absorption coefficient with the amount of pollutants such as dissolved organic matter (dissolved COD, DOC) and $NH_4$–N allows the concentration of the pollutants to be estimated by standard curves derived from measured data.

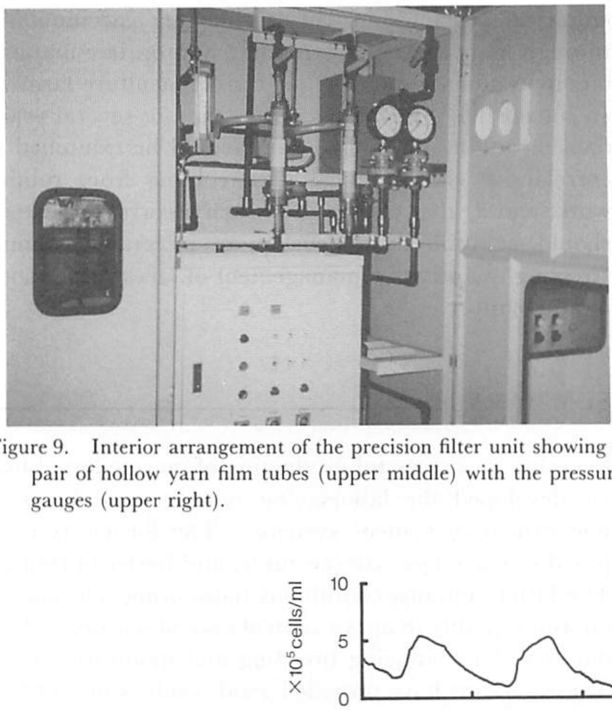


Figure 9. Interior arrangement of the precision filter unit showing a pair of hollow yarn film tubes (upper middle) with the pressure gauges (upper right).

## DATABASE SYSTEM

The database applied here is designed as a relational one that provides the following functions by means of a menu system:

1) management of data on breeding of fish juveniles;
2) management of data on culture of rotifer;
3) management of data on culture of *Nannochloropsis*;
4) management of continuous monitoring data on water quality;
5) data retrieval and automatic drawing of various bulletins and diagrams;
6) initial setup on corrective coefficient for each sensor and value range of axis for output diagrams;
7) maintenance (selection, backup, and compression) of the database.

This system provides us with information based on monitoring and practical data, such as abundance diagrams (Figure 10). According to 6 days of data beginning on the 15th day after hatching of *Paralichthys olivaceus* in 1990, the diagrams indicates: 1) that the cell number of the planktonic algae (Figure 10, top) and detritus concentration (Figure 10, middle) as estimated follow distinct trends, as noted below; and 2) that the absorption coefficient (Figure 10, bottom) as a measured value is always held below 2 $m^{-1}$ by means of controlling water exchange.

It is noted 1) that the cell number indicates a gradual decrease dependent on the feeding of rotifers as well as the lowering in population density by water exchange, and secondly, a rapidly increase in cell numbers caused by regular injection of a fixed volume of the plankton after a definite drop in quantity; and 2) that the detritus concentration fluctuates in relation to the attenuation

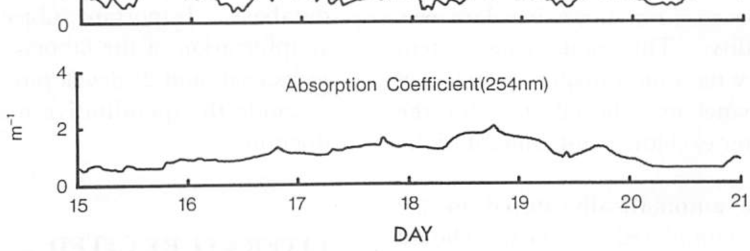



Figure 10. A series of visual data records given by the technometric system.

Table 1. Working effect and efficiency of the laborasaving and technometric systems.

A. Laborsaving Effect

| Device | With System Manpower (per/d) | With System Time (hr/h) | Without System Manpower (per/d) | Without System Time (hr/d) |
|---|---|---|---|---|
| Automatic scavenger | 1 | 0.5 | 7 | 23 |
| Automatic feeder | 2 | 5 | 7 | 28 |

B. Uplift of the Work Efficiency

| | With System | Without System |
|---|---|---|
| Laborsaving System | Concentrated management effective on working accuracy | Large personal difference occurs in working accuracy |
| Technometric System | Based on availability of successive presentation and recording of environmental data, rearing management dependable upon automation controlled by an appropriate manual | Because of difficulty in successive gathering of environment data, rearing management depends upon personal techniques of experience |

coefficient. This shows how the turbidity fluctuation is affected by the concentration of detritus.

## WORKING EFFECT OF THE SYSTEMS

The laborsaving and technometric management systems were together in a positive manner at the Kanagawa Prefectural Fisheries Experimental Station, Miura, where the systems became operational only recently. The functions in Table 1 are divided into two categories: 1) cleaning the bottom of five round tanks of 30 $m^3$ in volume, and 2) supplying enriched rotifers. This means treating as much as 120 $m^3$ of culture water. In this case, work has been reduced from 7 to 1 in manpower (person/days) and 1/46 in total time per day, while the latter was reduced from 7 to 2 person/days, and 1/6 in total time.

Estimates of work efficiency estimated at the same time showed increases by application of the systems.

The laborsaving system provides a better and more homogeneous efficiency in the functions performed. It is noted that the device developed here can remove harmful deposits more completely than humans do. Concerning the management of water quality, the technometric system affords a decided contrast to the old days. Before applying the monitoring system, the rearing depended mostly on the empirical knowledge of technicians in charge, because no successive data was available on water quality. The monitoring system provides all the necessary data on a display panel, and the indication on the panel may be effective for the real-time use such as water exchange and amount of the microbe supply.

The displayed data are automatically stored in the database. The data accumulated for years should eventually be useful in providing a careful review of annual records, including environmental factors by comparative studies. This management system will play a still more important role in the practical use of empirical conclusions of technology accumulated through many years for compiling appropriate manuals on environmental management in aquaculture farms.

In conclusion, it is pointed out 1) that for several years, data on the monitoring system should be examined in correlation with practical data coming from routine work; and 2) that the result of such a correlation study should be utilized to develop an integrated manual stressing quantitative management of larval production in aquaculture.

## SUMMARY

Focusing on successful production of marine larval fish, we developed the laborsaving systems and the technometric management systems. The former is composed of scavenger, concentrator, and feeder of rotifers. The latter contains continuous monitoring information on water quality in application of optical sensors and the database for managing breeding and monitoring data. These systems have provided good results since 1990 at the Kanagawa Prefectural Fish Farming Center; the laborsaving systems have shown remarkable and desired working effects, and the technometric management systems have successfully introduced useful data into the database. Important subjects for a future study are: 1) simplification of the laborsaving system with reduction in its cost; and 2) development of an integrated manual to guide the quantitative management of juvenile production.

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# COMPUTER AUTOMATION AND INTELLIGENT CONTROL FOR AQUACULTURE

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## ABSTRACT

An automated control system has been installed and utilized to manage closed, recirculating seawater systems and associated filtration. The control system monitors pH, temperature, salinity, dissolved oxygen, ORP, flow rates, water line pressure and water levels. These inputs are used to control water addition (deionized water for evaporation and sea water for losses), pump speed, chillers and heaters, aeration, photoperiod and buffer addition. The aquaculture systems and all variables are displayed graphically on computer monitors so that the control state of the systems can be quickly determined visually. All functions have alarms that notify personnel of problems with system function both locally (networked personal computers) and remotely (a notebook computer with modem). The control system will interface an expert system shell (a computer program that mimics the human thought process) in order to integrate the aquaculture and filtration systems. The expert system can use both rule-based (when control relationships are well known) and fuzzy logic (when control relationships are not well known) methods to monitor and control the aquaculture systems analogous to a human manager. Initial results indicate that the system is efficient and requires low initial installation costs and low operating costs.

## INTRODUCTION

The culture of aquatic animals dates back 3,000 years in the Orient (Bardach et al. 1972), but even today the management of culture systems is based upon the varying expertise of the managers and scientists involved. This has resulted in management by "feel" rather than by using scientific data with support from defined mathematical and logical relationships that describe the function and regulation of the culture operations (i.e., the process). Consequently, efficiency has been less than optimal and perturbations in culture systems have been difficult to predict (Piedrahita 1987; Fridley and Bordner 1989). The development of pragmatic management models relies upon the quality of data collection, identification of state variables (biological and engineering parameters) and transfer coefficients (rates of material and energy flow) and a clear understanding of their relationships. Furthermore, the greater the interaction between managers and the system model (i.e., interactive models using on-line data collection), the fewer problems encountered in model building (Tysso 1987). Today's microcomputers and process control software are ideal for this use.

The application of process control technology and the concurrent need for aquaculture-specific expert systems is essential to the continued development and intensification of aquaculture worldwide (Palmer 1989; Lee 1991, 1993). Many industries (e.g., food processing, chemical and petrochemical plants) use process control to reduce costs, eliminate failures and maximize production (Adams 1989). These control systems: (1) acquire real-time data directly from production systems, (2) transform the inputs mathematically into process models, (3) apply decisions of the control system to critical processes and (4) integrate expert systems that assume the role of a human expert.

Aquaculture has been slow to embrace the use of on-line instrumentation and computer automated control (Fridley and Bordner 1989; Lee 1991, 1993). This can be attributed in part to previously high costs of the sensors and computer systems and low reliability of the sensors. Cost is rapidly becoming less of a factor with the availability of inexpensive high-speed microcomputers and improved sensor design (Wyban and Antill 1989; Lee 1991, 1993). Unreliability is still a major factor impeding the use of on-line sensors but advances in pH, ORP and dissolved oxygen probes have been made recently (Gary 1989; Dartez 1989). Managers and scientists that practice aquaculture have also been reluctant to trust supervisory control systems since implementation requires that a certain degree of the manager's control be relegated to the system. There are instances of aquaculture laboratories installing state-of-the-art monitoring and control systems, only to abandon them at the first failure or because of perceived increases in labor needed to calibrate probes and perform maintenance on such systems (Lee 1991). There will never be a control system that does not require maintenance but modern process control systems are relatively maintenance-free and 24-hour supervisory control usually far offsets maintenance costs. Success in designing a pragmatic and affordable automated control system for aquaculture would be widely applicable because it would enhance water management greatly, reduce costs associated with manual monitoring and reduce significantly the chance of catastrophic system failures.

## DESIGN AND MATERIALS

The most important lesson to remember when designing an automated system for the first time is to start with a system that has a reasonable chance for success. There are two ways in which to begin designing an automated control system, from the "Top Down" or from the "Bottom Up." Design from the "Bottom up" emphasizes the "how" in the installation while design from the "Top Down" emphasizes the "what." For example, it should be clear "how" the control system should be designed to make a tank system easier to manage but "what" will that mean economically to the aquaculture manager. First, will the system prevent catastrophic losses; second, will the control system reduce the labor needed to manage their project or third will it increase production by improving efficiency of energy and feed expenditures? Managers and their staff should evaluate carefully their objectives for the economic performance of the control system before any designs are evaluated.

### CONTROL SYSTEM COMPONENTS

The components required to construct a supervisory control and data acquisition (SCADA) system can be divided into 6 main categories: (1) sensors or transducers; (2) meters, transmitters and signal conditioners; (3) output devices; (4) communication devices or multiplexers; (5) computer hardware and (6) computer software.

The selection of sensors represents the most important step in the design of an automated system. It is the sensors that translate the needed environmental variables into quantitative output and they are located in the most hostile environment (submerged), receiving the greatest wear-and-tear. Sensors must be selected not only for performance but durability; non-metallic sensors (glass and plastic) will outlast metal probes. Sensor failure is the second major reason for false alarms in an automated system (setting the control limits too narrow is the number one cause of nuisance alarms). As a result, the sensors will require periodic replacement and this replacement and the labor for scheduled calibration/maintenance comprise the major expense for system maintenance. Sensor type and location will be specific for each installation since the measured environmental variables in cold freshwater raceways for trout will not be the same as for warmwater marine shrimp pond production. Finally, buy with compatibility in mind since you may want to install a different brand of sensor on your meter or transmitter in the future.

Once the sensors have been chosen, the need for particular types of meters or transmitters will be clear. A meter contains all the electronics required to convert the sensor's electrical signal into a visual display but it must also include a proportional output signal (voltage or current) for the control system. Transmitters provide proportional output signals without displays so that selecting transmitters in most cases will save you money unless a local display of the information is required. All electronics, wiring and communication lines should be protected in corrosion resistant cases or conduit (preferably PVC, Plexiglas or fiberglass) meeting NEMA standards; the added costs of the cases will be offset by the extended life of the electronics.

Output devices share many performance criteria with sensors in aquaculture systems since they are located in harsh environments and reliability is essential. They also have the additional disadvantage of containing moving parts. Corrosion can easily freeze a pump or valve if it remains off or in one position for too long. Redundancy is again a solution. A practical method to verify that a pump starts/stops or a valve opens/closes is to place an inexpensive on/off flow sensor downstream. The enclosure is of major importance, and plastic valves and sealed pumps should be used exclusively.

Most aquaculturists use sensors, meters and pumps daily and are familiar with their operation. The first tier of the SCADA system that is unfamiliar, therefore, are the communication devices (multiplexers, programmable controllers, and data loggers). The need for redundancy and local control (distributed control) versus centralized control (from host computer) are the main issues to be considered, and this affects installation and operation costs. Redundancy is your best insurance against system failure, but increasing the number of intelligent devices used without justification will quickly double or triple the installation cost for an automated control system. Critical functions, e.g., monitoring dissolved oxygen and controlling liquid oxygen injection for high density raceways, may justify local control and high redundancy.

The selection of computer hardware is perhaps the easiest and least expensive of the decisions that is required. The first choice to be made is between IBM compatible or MacIntosh microcomputers. Most of the commercial control software packages are written for IBM compatibles but some very good packages are becoming available for the MacIntoshes. The recommended specifications for a SCADA computer in an automated control system are: (1) a 80486-50 MHz central processor (a 80386SX-20 MHz is the minimum), (2) 4 Megabytes (Mb) of RAM memory, (3) a math coprocessor card if the computer is not a 80486, (4) a 100 Mb hard drive, (S) VGA graphics card (512 Kb of memory) and VGA monitor (EGA is the minimum), (6) both 1.2 and 1.44 Mb floppy drives, (7) a mouse or trackball pointing device, (8) 1 parallel and two serial communications ports, and (9) a tower or larger desktop case with 6 expansion slots. Useful options are a printer (for reports and hard copy outputs of data), a modem (for a phone alarm), an uninterruptable power supply (to avoid systems failures during power outages) and a tape drive (for operating system backups and for long-term database storage).

The proliferation of process control software is evidence of the expanding role of computer control in manufacturing, pharmaceutical and food processing (Wolske 1989; Parks 1989). The diversity, user-friendliness and relative low cost ($1,000-3,000) of the packages provides real solutions to the earlier problems associated with custom computer programs (Plaia 1987; Eberling and Losordo 1988). The process control software should include: (1) drivers that communicate directly with the control system's I/O multiplexers, (2) a variety of control functions, i.e., high-low setpoints, logical and mathematical expressions, and proportional-integral-derivative control, (3) menu-driven subroutines for set up of the control loops and screen displays, (4) real-time pictorial displays for aquaculture system functions, (S) real-time alarms, display updates, audible and remote phone alarm, (6) event logging and storage and management of historical databases, (7) statistical analysis (mean values, ranges, etc.) and graphical trending, (8) interactive control and batch control subroutines, (9) compatibility with diverse computer hardware (video adapters, coprocessors, etc.), (10) on-line modifications to the system to avoid shutdown for minor changes and (11) local vendor support and inexpensive upgrades. The most important point in choosing software is to evaluate carefully your current needs and to predict future needs since after-the-fact software costs can exceed 4 or 5 times that of the original purchase price. A properly designed system will not require much support but vendor support can avoid later abandonment of the control system.

## RESULTS AND DISCUSSION

### AUTOMATED CULTURE TANK SYSTEM

A SCADA system was installed on a 15,000 L closed, recirculating seawater culture system (Figure 1). The design of the electronics conformed to the National Institute of Science and Technology Model of Automation (Yingst 1988; Adams 1989). Sensors monitor dis-

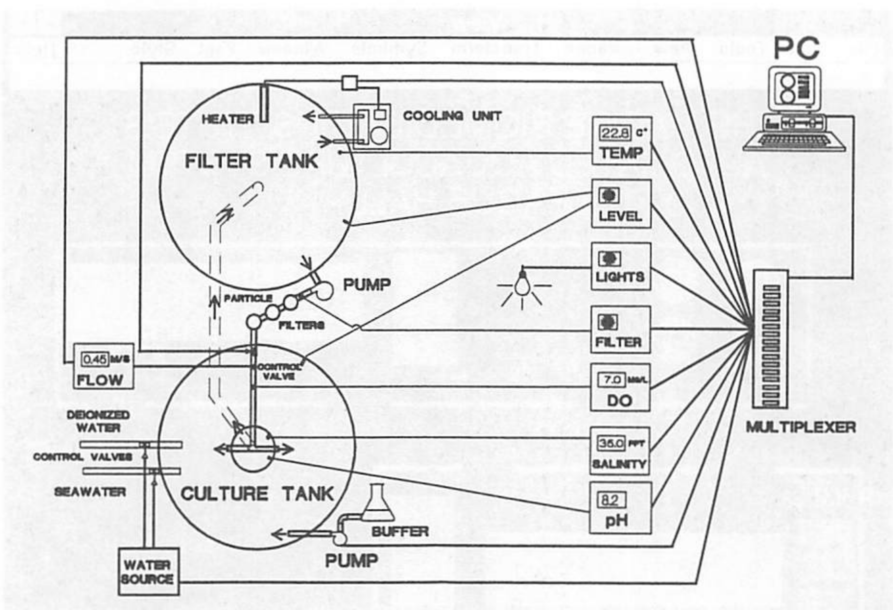


Figure 1. Control system design including aquaculture tanks, communication lines, and microcomputer host (Lee, 1991;1993). See text for description.

solved oxygen (YSI, OxyGuard™, Royce and Omega Engineering), pH, conductivity/salinity (Omega Engineering), oxidation/reduction potential (Omega Engineering), temperature (Omega Engineering), water level (Harwil), flow rate (Great Lakes Instruments and Metron), and prefilter head pressure (Omega Engineering). The sensors connect to indicating meters or non-indicating transmitters that produce a digital or proportional analog output signal (i.e., 4–20 mA or 0–1 V). Output devices include electrically actuated on/off and proportional ball valves (Asahi/America and Capitol Controls Company, respectively), variable speed pumps (March Manufacturing and Cole Palmer Instrument), heaters (Gloquartz Electric Heater) and chillers (Universal Marine Industries). The inputs and outputs interface through a 16 channel I/O multiplexer (Dutec) to a microcomputer host, 80486-50 MHz, 8 Mb RAM, mouse, 213 Mb hard disk and xVGA graphics. The host loads set-points for alarm and control functions, uses algorithms to relate multiple inputs, controls multiple outputs and provides graphics for trending and modeling.

## SCADA SYSTEM

A commercially available process control software package (Intellution's THE FIX™) integrates the I/O and control system. It is modular and extremely cost-effective (run-time package is less than $1,900). The microcomputer is connected to a microcomputer local area network (ethernet LAN) that is composed of 20 personal computers (IBM-compatibles, MacIntoshes and Digital Equipment MicroVAX 2000). Thus, data on aquaculture system function and alarm conditions can be accessed readily from the LAN and many culture routines are controlled remotely from the laboratory manager's desk or automated entirely. The installation of a flexible microcomputer and data network within a facility should be considered the first step in operating an automated control system since monitoring and control cannot be accomplished without proper communication between devices.

The control software include a specific driver/interface to the I/O multiplexer (Dutec), eliminating the need to program any custom subroutines for communication between devices that has been typical in past systems (Plaia 1987; Ebeling and Losordo 1988; Rusch and Malone 1989). Most microcomputer-based process control packages have drivers for many different multiplexers or input devices. Once communication was established between the I/O devices and the control software, the calibration of the sensors began. This can be simple if the I/O device is digital (on/off) but it is more complicated for analog I/O devices. The latter required that the zero off-set (establish a O reading) and the signal range be set. For example, an oxygen meter with a 0–20 ppm range and an output voltage of 0–1 V must transmit O V at O ppm and 1 V at 20 ppm. Once the I/O devices were calibrated then the control software set up began.

The first step in configuring the host computer's software involved building the needed databases and the display screens (graphic modeling tools are included in the software). These screens can be as complicated or

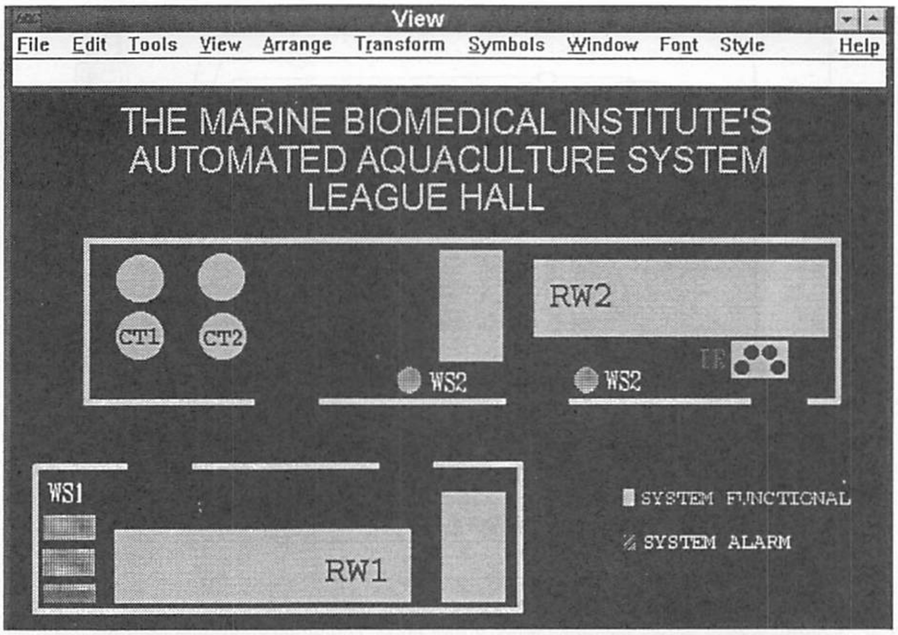


Figure 2. Introductory screen to automated aquaculture control system.

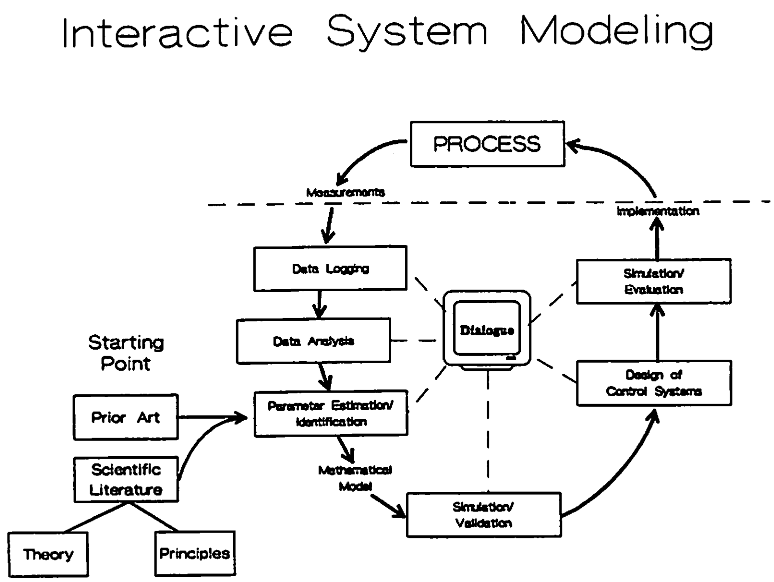


Figure 3. Interactive modeling paradigm.

as simple as the manager desires (Figure 2). They can be nested so that pointing to an object on one screen will take you to another screen for a more comprehensive overview of a particular subsystem. The screens can represent floor plans with color coding, simulated meter displays, numeric tables, x-y graphs of current or historical conditions or any combination. The most useful management screens represent the floor plan of the aquaculture facility (Figure 2) with all systems that are functioning within their set points displayed in one color while those functions out of limits (alarm conditions) display a second color. The control software includes audio alarms, and a portion of any screen can be dedicated to alarm notices.

The second step in configuring the control software required the representation of the actual control relationships. The inputs and outputs are labeled with alphanumeric labels and then the appropriate input channel is linked to its output channel with intermediate control blocks. The control blocks can be simple set points or more complicated logical operations and/or algorithms relating multiple inputs to multiple outputs. This step may be the most confusing in the system set up but it can be simplified by planning (identifying the control relationships that are needed immediately) and on-site training by the vendor.

## INTELLIGENT CONTROL

Description of the process to be automated (Sheppard 1980; Tysso 1987; Hansen 1987; Ying et al. 1988) is the foundation for closed-loop control and expert systems. Interactive modeling allows identification, simulation, and time-series analysis, and it reduces the number of problems associated with model building (Figure 3). The automated culture system has been operated with simple intelligent control algorithms and logical statements that were formulated as part of the prototype control model. Improved data resolution, a result of the real-time data acquisition system, has led to a better understanding of the dynamic interactions between the process variables (Malone et al. 1987). The development of a system model requires two steps. First, the state variables must be identified using existing information on the biology of the cultured organism and general filtration function. Dynamic models require all variables to be independent and measurable with analytical techniques. Second, controlled experiments are conducted to estimate the transfer coefficients using the real-time data collected with the SCADA system and appropriate statistical methods (Sokal and Rolf 1969). The transfer coefficients then become part of the mathematical model and simulation/validation, design of control systems and model evaluation can begin. This cycle will be repeated often before the system model is completed since the dynamics of interactive models require constant fine tuning.

Concurrent with the description of the process, expert system development began with a simplified control model. Considering the substantial expertise that is extant relative to our aquaculture filtration systems (Yang et al. 1989; Lee 1991, 1993) and the regulation of the process variables, the techniques of expert systems are particularly useful and a rule-based, multiple-input, multiple-output control system (Ritchie et al. 1987) is being developed. In cases where the relationship between process variables are not well known, fuzzy logic techniques are being applied (Zimmerman 1987; Ying et al. 1988). Special attention is being focused on the user interface so that other aquaculturists can add to the rule-base and define new control functions as needed.

## SUMMARY

Many aspects of modern global industrial growth and competitiveness have been based on the application of process control technology to manufacturing. Agriculture in the United States has become the world leader in productivity through intensification, mechanization and automation. A similar path is appropriate for aquaculture since automation of aquaculture systems will allow US companies to: compete with world commodity markets by locating production closer to markets; improve environmental control; reduce catastrophic losses; avoid environmental regulations on effluents; reduce production costs; and improve product quality. The MBI has established an interdisciplinary research project involving aquaculturists, bioengineers and industry: (1) to construct, operate, automate and evaluate the cost of operation for a production-scale closed, recirculating aquaculture system; (2) to implement an intelligent control system that will integrate the operation of aquaculture systems, automating management and maintenance routines; and (3) to transfer the results to the rapidly expanding aquaculture industry. Initial results confirm the labor and costs saving potential of automated control systems for aquaculture and have provided real-time databases on system function that were unavailable previously.

## ACKNOWLEDGMENTS

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# AQUACULTURE AND THE MARINE ENVIRONMENT: POLICY AND MANAGEMENT ISSUES AND OPPORTUNITIES IN THE UNITED STATES

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## ABSTRACT

Aquaculture in the United States coastal zone is a relatively new form of agricultural activity. As such, it must compete with a number of traditional businesses and industries for its "raw"material needs: land, clean water, (semi-) exclusive use of public waters, financing, and government support. Although touted as a "clean" industry requiring high-quality waters, aquaculture has more recently come under attack for its impacts from coliform bacteria, dissolved oxygen, suspended solids, biological oxygen demand, from the use of chemicals (e.g., drugs and pesticides) and introduced species, and from disease outbreaks. Effluent discharges are the source of these effects and are monitored at both the federal and state levels, primarily through the National Pollutant Discharge Elimination System permit program.

Scientists and resource managers have for several years been examining a number of remedial strategies to deal with aquaculture effluent impacts. These can be classified into four major categories: chemical, biological, mechanical, and management manipulations. However, each on its own will not lessen the problems associated with aquacultural effluents. Instead, the development of aquacultural best management practices (BMP's) is introduced as a means to deal with the effluent problem in a comprehensive fashion.

## INTRODUCTION

Aquaculture continues to play an increasingly prominent role in many regions of the world. Total worldwide production was 14 million metric tons in 1988, 14.3 percent of total seafood taken by all means and technologies. The aquaculture industry continues to expand primarily due to the (1) introduction of new technologies, (2) expansion of suitable sites for culture, (3) improvements in feed technology, (4) a better understanding of the biology of the species and (5) high water quality in farming systems (Rosenthal 1985a). While economic factors have driven these developments, environmental concerns are threatening to constrain further gains in aquaculture's growth.

A number of finfish, shellfish, and crustacean species are cultivated in the United States, including catfish, trout, salmon, striped and hybrid bass, tilapia, hard clams, oysters, mussels, crawfish, and penaeid shrimps. The industry is technologically diverse, with ponds, raceways, silos, circular pools, closed (water reuse) systems, cages and net-pens, searanches, rafts, and long lines used according to the species cultured (Joint Subcommittee on Aquaculture 1983). Aquaculture remains a relatively young scientific discipline that is developing rapidly, with incorporation of a variety of modern technologies, most not yet fully adapted for widespread use (Rosenthal 1985). Indeed, there has been a trend toward intensification in both traditional and contemporary culture systems. Aquaculture in the United States remains a young and emerging industry; production from U.S. commercial farms approached 300,000 metric tons in 1988. Many have extolled the virtues of expanding this industry as a means of supplementing seafood supplies, reducing the U.S. trade deficit in seafood products, and creating economic opportunities. Reductions in commercial fisheries landings and increases in seafood imports are two of the major justifications offered by proponents of an enhanced and expanded aquaculture industry. However, resource managers, scientists, and even some aquaculturists recognize that an industry very recently touted as environmentally "friendly" is becoming recognized as a source of possible negative impacts on the environment.

Aquaculture practices range from extensive, with few inputs and modest output, to intensive, with high inputs

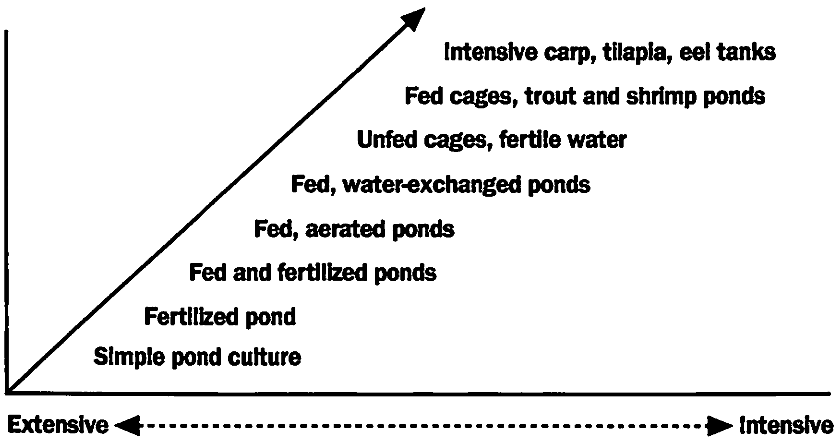


Figure 1. Aquaculture production according to intensity (adapted from Muir 1985).

and output. On an annual yield per hectare of water basis, increased-intensification requires greater resource use, ranging from simple pond culture to intensive tank and closed system aquaculture (Muir 1985) (Figure 1). In terms of labor costs, the least to most intensive systems are (1) transplantation from poor to better habitats without intervention of hatcheries, (2) hatchery cultivation where juvenile stages of organisms are reared to a sufficiently large or mature stage of development prior to release (to increase their chances of survival in the wild), (3) trapping, as in the case of coastal impoundments, (4) artificial enclosures to enhance control over stocking and stocks, (5) ocean ranching, and (6) raft culture (Dodge and Jolly 1978). These varying technologies are what make aquaculture the diverse industry it is, but they produce differing environmental impacts and the need for a range of technological and management responses.

Although aquaculture practices are diverse, what is common to all forms of aquaculture are the resources used (water, food, land, labor, and capital) and how competitively and effectively they are consumed (Muir 1985). What is implicit by definition is the need for high-quality waters. Aquaculturists require locations where the availability and maintenance of high-quality waters are assured (DeVoe and Mount 1989). Operations require protection from current and future uses of adjacent waters that might reduce the water quality where species are cultured. It is somewhat ironic that even though aquaculture is based on the natural exploitation of high quality water resources, its practice can result in environmental impacts. If these are major, the results will be negative, not only for the environment, but also for the cultivation. Thus, aquaculture can be "self-regulating" to a certain extent and depends on the maintenance of good water quality (Swedish Council 1983).

Most aquaculture operations release water back into the environment (except in closed systems where technological development on a commercial scale is needed to prove economic feasibility) (National Research Council 1992). Water, therefore, not only serves as the medium for culture but also acts as a transfer mechanism for a variety of organic and inorganic substances. It is the outfall "pipe" that is now receiving a great deal of attention by resource managers and the conservation community because of concerns related to water resources and ecological health of the aquatic environment. The purpose of this paper is to review the key environmental issues related to aquaculture development in the United States, to examine in more detail relevant government policies and regulations, and to propose the development of aquacultural best management practices as a major step toward enhancing industry development and environmental protection.

## ENVIRONMENTAL IMPACTS OF AQUACULTURE

Aquaculture practices can generate environmental impacts as a function of (1) the applied technique, (2) site location, (3) size of the production, and (4) capacity of the receiving body of water (Ackefors and Sodergren 1985). These can include impacts on water quality, the benthic layer, and the native gene pool, and impacts from non-native species, disease, and chemicals.

### WATER QUALITY IMPACTS

Water exchange has traditionally been required in all forms of marine aquaculture to prevent self-pollution from organic wastes and resulting oxygen depletion. An emerging problem (especially in intensive systems with minimal circulation) is the stimulation of toxic algal blooms (National Research Council 1992). Of most concern are the high concentrations of nutrients, nitrogenous wastes, and biochemical oxygen demand (BOD) that can be produced (especially from high-density pond or tank culture systems) and discharged in effluent waters (Brown and Nash 1981, National Research Council 1992). However, information on the effect of marine fish farms on water quality in and around culture facilities is insufficient to allow a detailed evaluation (Rosenthal et al 1988). Released phosphorus is responsible for the greatest effects in inland waters; nitrogen is usually of most importance in coastal areas (Swedish Council 1983). In addition, low quality feeds can present a special problem, readily releasing their nutrients into the water and their fiber into the effluent (Rosenberry 1991).

## IMPACTS ON THE BENTHIC LAYER

All forms of aquaculture produce organic-rich particulate wastes. Oysters grown in rafts can produce tons of fecal and pseudofecal material (Rosenthal et al. 1988). The impacts of uneaten food and feces falling on benthic communities beneath salmon cage operations is a worldwide issue (National Research Council 1992). Finfish operations not only generate fecal waste, but also, feed not ingested adds to the particulate load in those operations where feed is provided. Rosenthal et al. (1988) noted the following physical and chemical changes in the substrate: (1) increased organic carbon, (2) increased sediment oxygen consumption rates, (3) decreased sediment redox potentials, (4) generation of hydrogen sulfide and methane, (5) increased organic and inorganic nitrogen content, (6) increased phosphorus, (7) increased silicon, and (8) increased sodium, copper, and zinc.

## GENETIC IMPACTS

The contamination of wild stocks through the escape or release of mariculture organisms can be problematic. Potential impacts are believed to be severe (National Research Council 1992, Lester1992); however, very little documentation exists. These impacts can be grouped into two categories. First, the potential exists for overwhelming the "wild" gene pool with the more restricted gene pool of a hatchery stock through repeated and massive intentional stock enhancement efforts (e.g., salmon and striped bass) (National Research Council 1992), and second, the possibility for weakening the "wild" gene pool as a result of interbreeding among native wild stocks and accidentally released non-native culture species (Lester 1992).

## IMPACTS FROM NON-NATIVE SPECIES

In the United States, much of the production from agriculture is based on introduced species (Bixby 1992; Steirer 1992). Many times in aquaculture, exotic species exhibit more highly desirable characteristics (e.g., growth rates, hardiness, disease resistance) than native populations. However, introductions require careful thought and screening and must consider the political, environmental, and cultural implications, as well as production values (National Research Council 1992). Non-native species can be introduced via (1) translocation beyond their natural range by water traffic, (2) deliberate transplantation of organisms into new areas, (3) accidental introductions in connection with the transfer of other species, and (4) escape of organisms transferred for purposes other than deliberate introduction (Rosenthal 1985a). Concerns with non-native species introductions include the potential for "genetic pollution," ecosystem disturbances (e.g., competition with native populations), and introduction of disease. See Mann (1978) and DeVoe (1992) for a discussion of these issues in greater detail.

## DISEASE IMPACTS

Disease remains a major concern for the culturist and can also become a problem in the surrounding environment. Many states have some form of disease testing or certification program for animals being imported across state lines; however, the established programs are limited primarily to freshwater species (National Research Council 1992). Salmon egg and smolt importation are highly regulated and, in some states, a quarantine period exists prior to introduction. For marine species, the necessary expertise to undertake inspections effectively is lacking (National Research Council 1992). Also, routine shipments of live oysters, clams, and crabs, intended for direct sale to consumers, are seldom ever checked for diseases, parasites, and competitors, nor are most shipments of bait organisms.

Diseases within an aquaculture operation also represent a potential problem. Outbreaks can occur with little or no warning and spread rapidly throughout the often highly dense culture population. Water-borne diseases can be transferred out of the production unit via the normal water exchange protocol used by many culturists. Internal pathogens can be transferred with accidental (or intentional) release of organisms into the natural environment.

## IMPACTS FROM CHEMICALS USED IN AQUACULTURE

A wide variety of chemicals used in aquaculture represent a potential threat to the health of the cultured organism, the indigenous biota, or the human consumer (Rosenthal et al. 1988). Twenty-four chemicals were registered or approved for use in foodfish culture in the United States in 1985 (Schnick et al. 1986). Beveridge et al. (1991) presented an update on this list, which included therapeutics, vaccines, hormones, flesh pigments, anesthetics, disinfectants, and water treatment compounds. Rosenthal et al. (1988) categorized these chemicals as:

(1) Biocides and biostats—which are deliberately introduced into the culture system with the intent of eliminating predators or protecting the health of the cultured organisms (e.g., therapeutics, pesticides);
(2) Chemicals—which are introduced in the construction materials (e.g., tributyltin); and
(3) Hormones—used to alter the reproductive viability, sex, or growth rates of cultured organisms.

Antibiotics, usually administered as feed additives, are used to reduce mortality from bacterial fish diseases such as vibriosis and furunculosis. They are used in marine aquaculture as prophylaxis and as therapy for disease outbreaks. At present, only three antibiotics are approved for use during disease outbreaks on fish farms in the United States—oxytetracycline(OTC), sulfamerazine, and Romet 30 (National Research Council 1992). Concerns with treatment include (1) development of drug-resistant strains of bacteria, (2) accumulation of antibiotics in sediments and subsequent inhibition of microbial decomposition, (3) accumulation of antibiotics in fish and shellfish, and (4) possible impacts on human consumers from antibiotic residue in fish (Whitely and Johnstone 1990; National Research Council 1992).

Therapeutics are used primarily as therapy for some disease outbreaks, not as a preventative. Little information exists that supports the arguments for or against the use of therapeutics in aquaculture facilities. The use of hormones and transgenic animals in aquaculture is becoming a contentious issue. Public concern and legal limitations may delay or prevent the use of hormones in the aquaculture industry, while transgenic fish raise even great ethical, environmental, and safety concerns (Heyward and Hammond 1990).

The state of knowledge regarding the environmental impacts of aquaculture is rapidly improving. Whereas two decades ago very little research data were available, there has been a surge in the number and scope of research and monitoring programs seeking to document these effects. Much work worldwide has focused on the effects of net-pen culture on the environment, with the International Council for the Exploration of the Seas (ICES) leading the way (see, for example, Rosenthal 1985b; Ervik et al. 1985; Ackefors and Sodergran 1985; Rosenthal et al. 1988; also see Weston 1986). In the United States, early research efforts dealt with fish hatchery effluents and catfish ponds. As the domestic industry diversified, so did environmental research, with major federal studies examining the effluent characteristics of marine shrimp pond culture and salmon net-pen culture and the issues regarding species introductions, the use of chemicals in aquaculture, and effluent discharges.

The following discussion will focus on the policy and management issues related specifically to effluent discharges from aquaculture facilities, in keeping with the theme of the 1992 UJNR Conference.

## REGULATION OF EFFLUENT DISCHARGES

Aquaculture operations have the potential to discharge significant quantitites of dissolved and particulate wastes in large volumes of effluents to surface waters. The effluent stream also represents the most direct route for accidental escape of non-native species, chemical, drug and pesticide residues, and disease organisms. As a result, the aquaculture industry has faced heavy scrutiny from federal, state, and local resource officials who are concerned about the impacts of aquaculture on the aquatic environment.

### FEDERAL (UNITED STATES) POLICIES

Effluent discharges into waters of the United States are regulated by the U.S. Environmental Protection Agency (USEPA) to maintain and improve potability, aesthetics, and recreational quality of the receiving waters, under provisions of the Clean Water Act (CWA), including the Federal Water Pollution Control Act as amended in 1972 (PL 92–500) (U.S. Congress 1972), the Clean Water Act of 1977 (PL 95–217) (U.S. Congress 1977), and the Water Quality Act of 1987 (PL 100–4) (Bastian 1991). The 1972 amendments created the National Pollutant Discharge Elimination System (NPDES) program which requires that anyone discharging wastewater from a point source to a "water of the United States" apply for a discharge permit. Under NPDES regulations (40 CFR Part 122), which are generally administered at the state level, a "concentrated aquatic animal production facility" is defined as "a hatchery, fishfarm or other facility which meets the criteria in Appendix C" (outlined below), or "any such facility which the Director determines is a significant contributor of pollution to the waters of the U.S. based on a non-site inspection of the facility" (Bastian 1991). Under Appendix C, a hatchery, fishfarm, or other facility is a concentrated aquatic animal production facility if it contains, grows, or holds aquatic animals in either of the following categories:

(1) Cold-water fish species or other cold-water aquatic animals (including the Salmonidae family of fish; e.g.,trout and salmon) in ponds, raceways, or other similar structures which discharge at least 30 days peryear, but does not include:
   (a) Facilities that produce less than 9,090 harvest weight kilograms (~20,000 pounds) of aquatic animals per year; and
   (b) Facilities that feed less than 2,272 kilograms (~5,000 pounds) of food during the calendar month of maximum feeding.

(2) warm-water fish species or other warm-water aquatic animals (including the Ameiuride, Centrarchidae, and Cyprinidae families of fish; e.g., catfish, sunfish, and minnows, respectively) in ponds, raceways, or other similar structures that discharge at least 30 days per year, but does not include:
   (a) Closed ponds that discharge only during periods of excess runoff; or
   (b) Facilities that produce less than 45,454 harvest weight kilograms (~100,000 pounds) of aquatic animals per year.

The legislation required the EPA to develop and implement maximum technology-based direct discharge standards for industrial discharges. However, NPDES permit program regulations promulgated in 1973 revised the classification of fish hatcheries from the "critical industry" status to that of an agricultural facility. Although proposed regulations were published in the Federal Register in 1974 (40 CFR Part 115), the EPA has not issued effluent guidelines and minimum levels of treatments for aquaculture discharges, nor are there plans to issue them in the near future (Ziemann et al 1990). As a result, permit requirements for aquaculture are established on a case-by-case basis, taking into consideration related guidance that has been issued and any specific water-quality standards applicable to the receiving waters (Bastian 1991). Additionally, states are authorized to place additional requirements on these discharges, and, in some cases, effluent monitoring in aquaculture facilities is required even if the production capacity is less than the limits defined in the NPDES protocol (National Research Council 1992).

The lack of a properly prepared EPA guidance document for effluent discharges from aquaculture operations has resulted in inconsistencies in regulating such activities. This is not a recent phenomena; EPA's regional offices and the states administering the NPDES permit program were using different criteria for aquaculture discharge permits during the 1970's (Harris 1981). For example, in Hawaii, it became extremely difficult to discharge aquaculture effluents due to misunderstanding, mis-information, or mis-interpretation in the following areas: (1) characteristics of aquaculture species and technology, (2) economic feasibility of conventional waste water treatment alternatives before discharge, (3) environmental impacts, both positive and negative, of nutrient-rich effluent on the nearshore clean environment, (4) time and cost involved in completing the permit application (e.g., consultant costs for reports and environmental assessments), and (5) inexperience and uncertainty in granting and administering the permit (Corbin and Young 1988).

## STATE NPDES POLICY AND SITUATION: THE SOUTH CAROLINA EXAMPLE

South Carolina is a state that has been delegated the authority to issue federal NPDES discharge permits by the U.S. Environmental Protection Agency. The S.C. Department of Health and Environmental Control (SCDHEC) is the designated state agency mandated under The Pollution Control Act (Act No. 1157, Chapter 1, Title 48, 1976 Code) to administer the NPDES discharge permit program.

The Pollution Control Act requires that "a person discharging or proposing to discharge wastes into the waters of the State shall promptly make application for and obtain a valid NPDES Permit ..." SCDHEC requires that all proposed aquaculture facilities submit a NPDES application along with a detailed plan describing the scope of the operation, including: location of the project; location of upstream and downstream discharges or users; facility size; species to be cultured; projected annual production; type and amount of feed; operational protocol to be employed; and the type, amount and frequency of effluent discharges. The normal processing time for a NPDES permit is stated to be approximately 2 months; however, if a public hearing is necessary or the permit is adjudicated, the processing time could be extended. In addition, SCDHEC requires annual fees ranging from $200 to $800, depending on the discharge volume, for environmental operating permits.

NPDES permitting for aquaculture facilities in South Carolina (as well as in many other states) has been a source of contention between the SCDHEC and the aquaculture industry. The S.C. Farm Bureau has listed it as one of its top policy concerns each year since 1986, and the state's *Strategic Plan for Aquaculture Development in South Carolina* (JLSA 1989) identified the NPDES permitting process as one of the major constraints to growth of the aquaculture industry. There are three specific issues that have fueled this conflict.

Classification of the Aquaculture Industry

South Carolina's young aquaculture industry has only developed since 1980, led by catfish, hybrid striped bass, crawfish, marine shrimp and hard clam culture. The characteristics of this emerging industry were unfamiliar to many, including state agency representatives. For example, SCDHEC orginally classified aquaculture operations as industries and regulated their effluents as "industrial discharges" (National Research Council 1992), effectively lumping aquaculture with such industries as paper mills and steel plants. Aquaculturists, maintaining that their activities were more appropriately agricultural in nature, felt that the industrial classification subjected them to more rigorous requirements, prolonged permit processing times, and low-priority treatment.

There have been some marked changes due in large part to an improved dialogue between the state and the aquaculture industry. Aquaculture requires high-quality waters. These waters are subject to the highest levels of protection where discharges from any domestic, industrial or agricultural waste treatment facilities are prohibited (Reg. 61–68, SCDHEC). Thus, aquaculture was effectively "zoned" out of these areas. Amendments to Regulation 61-68 promulgated in 1990 now allow permitted discharges from aquaculture facilities, if water quality is maintained for existing and classifed uses.

A second change occurred as a result of action by the S.C. General Assembly, which approved legislation designating aquaculture as an agricultural activity, subject to the benefits that accrue to agricultural enterprises (e.g., sales tax exemptions). This was formally recognized by SCDHEC in early 1991, when aquaculture effluents were reclassified as agricultural discharges, and are now regulated through the agricultural waste water division of the department.

A major jurisdictional question emerged between the state's major agricultural and natural resource agencies (the S.C. Departmentof Agriculture and the S.C. Wildlife and Marine Resources Department) over the aquaculture industry, each desiring lead agency responsibility. After many months of debate, the S.C. General Assembly approved legislation that provided each agency with different but major responsibilities.

NPDES Permit Processing Delays

The time required for an applicant to obtain a NPDES permit varies according to the complexity and sensitivity of the proposed permit (Figure 2). The process can become quite involved and may take a minimum of 50 to more than 650 days or longer, depending on whether the permit action is subject to a public hearing, an adjudicatory hearing, or an appeal to the Circuit Court.

The flow chart in Figure 2 documents the process from the point when a draft permit is prepared by the SCDHEC and sent to the applicant. The initial amount of time required by SCDHEC to develop a draft permit must also be considered. In 1989, for example, 12 companies submitted applications for NPDES permits. The time SCDHEC needed to develop draft NPDES for public notice ranged from 43 days (and draft permit denial) to 217 days, with an average of 147 days.

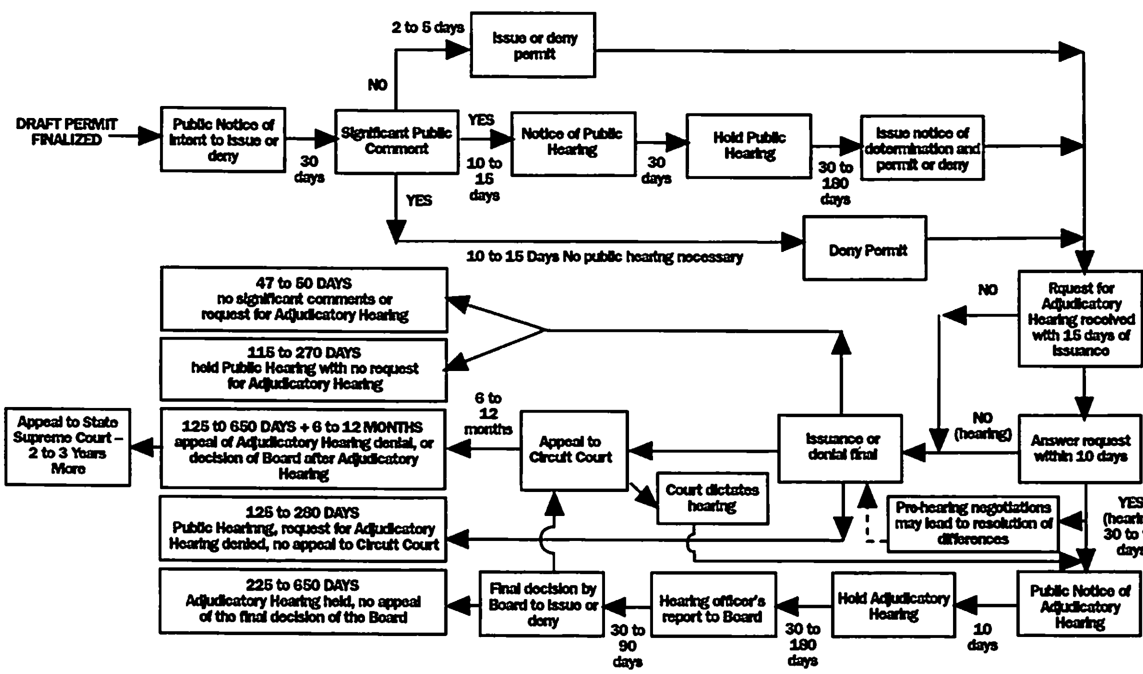


Figure 2. Possible NPDES and no discharge system permit processing paths with estimated times frames shown.

In reality, aquaculturists in South Carolina have had to spend a minimum of 4 months to acquire NPDES permits. The relatively low priority given aquaculture vis-a-vis other dischargers accounts for most of the delay. Characteristics of aquaculture effluent were not well known; the NPDES process for aquaculture has taken more time than like applications for more established users.

NPDES permit-processing delays can create a burden on the aquaculturist due to pressures from financial backers seeking to begin operations quickly, the availability and purchase of aquaculture sites, and the dependence on seasonal requirements of the species cultivated.

Progress is being made to reduce time delays for issuance of NPDES permits. SCDHEC has initiated a basin-wide approach to NPDES permitting, whereby each basin will be monitored, total wasteland determinations will be made based on hydrodynamic and water-quality modeling, and NPDES permits for all dischargers (new and renewal) in the basin will be collectively considered. This action should expedite the permitting process and enable SCDHEC to administer all 1,400 NPDES permits in South Carolina in a more timely fashion.

Lack of Standards and Criteria for Aquaculture NPDES Permits

Aquaculture is recognized under South Carolina's Water Classifications and Standards regulations (R.61-68, S.C. Code of 1976, as amended) as "the cultivation, production, or marketing of domestic aquatic organisms which are any fish, aquatic invertebrates, or aquatic plants that are spawned, produced, or marketed as a cultivated crop in the waters of the State." However, as is the case at the federal level, no specific criteria exist upon which to base NPDES permitting decisions. Instead, applicants are required to negotiate NPDES standards with SCDHEC to be placed on the proposed culture operation and, in some instances, to develop the most appropriate standards. As a result, decisions made by SCDHEC staff on NPDES permit applications for aquaculture are based on the interpretation of the regulations, which leads to inconsistencies in decision-making and staff level policy-setting.

## AQUACULTURE AND BEST MANAGEMENT PRACTICES

Much has recently been written about the aquaculture industry and its relationship with the environment. It is ironic that although aquaculture depends on high-quality waters, it has the potential to generate large amounts of pollutants which can affect the water quality of not only downstream users, but of the culture operation itself (Rosenthal 1985). Further, Iwana (1991) emphasized the need to, when examining the aquaculture/environment relationship, distinguish the difference between the "output or consumption of products by the aquaculture facility or cultured organism, and the significant effects that output has on the physical and biological community receiving the effluent." A great deal of time and financial resources is being spent on studying these interactions (see, for example, reviews by Alabaster 1982; Weston 1986; Rosenthal et al. 1988; Ziemann et al. 1990), but the need for solutions remains great.

Ameliorating the environmental impacts from aquaculture depends to a large degree on a combination of local conditions and production configurations that prevents the development of a simple set of rules to cover all aquaculture practices (Iwana 1991). However, the development of "best management practices" (BMP's) for dealing with aquaculture effluent impacts may serve as a mechanism whereby certain fundamental standards and practices can be agreed to, adopted, and implemented by the aquaculture industry and natural resource agencies. The use of BMP's to ameliorate environmental impacts is not a new idea; it is becoming common place in industries such as silviculture and agriculture. Application of BMP's to the aquaculture industry is a concept not yet fully explored, but with the potential to ensure regulatory consistency and reduce time delays in the permit process.

The U.S. Environmental Protection Agency recognizes BMP's as "schedules of activities, prohibitions of practices, maintenance procedures and other management practices to prevent or reduce the pollution of 'water of the United States.' BMPs also include treatment requirements, operating procedures, and practices to control plant site runoff, spillage or leaks, sludge or waste disposal, or drainage from raw material storage." Thus, BMP's can be considered a set of guidelines that complement (or replace) regulations covering particular activities. For aquaculture, BMP's may focus on the design or redesign of facilities, and the use of treatments, technologies, and management techniques to reduce, capture, treat, and recycle effluents and waste products (Table 1).

The development of aquaculture-effluent BMP's should recognize the diverse technologies and techniques used throughout the industry. Therefore, a set of BMP's could be developed for each of the following operational categories: 1) hatcheries, 2) net-pen finfish culture, 3) pond culture, and 4) molluscan shellfish culture. In the case of coldwater fish hatcheries and net-pen finfish culture, significant research and development has been undertaken to provide the basis for the preparation of BMP's. On the other hand, characteris-

Table 1. Remedial strategies for aquaculture facilities.

| Treatment Type | Treatment Methods |
|---|---|
| Chemical | Copper Sulfate<br>Polymers (Coagulants) |
| Biological | Use of Natural Systems<br>Polyculture<br>Integrated Aquaculture/Agriculture Systems |
| Mechanical | Settling Ponds<br>Wastewater Treatment Facilities<br>Closed Systems |
| Management Innovations | Controlled/No Draining<br>Water Recycling<br>Pond Screening/Monitoring<br>High Conversion Feeds |

tics of pond culture are just now beginning to be understood; these information needs can provide a focus for new aquaculture and environmental research for use in BMP development. Molluscan shellfish culture and growout typically involves little or no external inputs (e.g., feeds, chemicals, etc.) and may not require extensive treatment.

## COMPONENTS OF AQUACULTURE EFFLUENT BMP's

The components of aquaculture-effluent BMP's (Table 2) may vary with the operational category, but all should include the following:

### SITE SELECTION

The selection of an aquaculture site is probably the most critical decision an aquaculturist will make. Neither regulation nor BMP's will resolve an effluent discharge problem if the receiving water body can not adequately assimilate the anticipated pollutant loading. This was the case in South Carolina when a private company was permitted to site 200 acres of shrimp ponds along a small tributary. However, SCDHEC, in reviewing the company's application for a NPDES permit, only allowed 10 acres of ponds because of the small size and limited assimilative capacity of the tidal tributary.

Although siting criteria have not been yet established for hatchery or pond culture operations, they have been suggested for open-water culture (Dutrieux and Guelorget 1988; Rosenthal et al. 1988, O'Conner et al. 1991). Rosenthal et al. (1988) suggest that the following might be considered in choosing environmentally appropriate sites for aquaculture:

(a) Water movement—Good water flow will result in better dispersion of waste materials;
(b) Retention times—The area should be well flushed;
(c) Water-column stability—A highly stratified water column will limit the volume of water into which soluble wastes are disposed;
(d) Natural levels of nutrients—Potential negative impacts on the receiving waters will depend on its quality; and
(e) Water depth—The greater the depth, the greater the lateral movement of waste particles.

Table 2. Possible components of best management practices for aquaculture (hatcheries, net-pen culture, pond culture, shellfish culture).

| Components | Considerations | Methods |
|---|---|---|
| Site Selection | Water movement<br>Retention times<br>Water quality stab.<br>Natural nutrient levels<br>Water depth | Water quality modeling<br>Aquaculture location maps<br>Basic water quality sampling |
| Design Requirements | Water reuse sytems<br>Pond construction specifications<br>Retention ponds | Sedimentation<br>Filtration<br>Aeration<br>Heating/Cooling<br>Sterilization<br>Ion exchange |
| Operational Protocols | Chemical<br>Biological<br>Mechanical<br>Management schemes | (see Table 1) |
| Effluent Limitation/ Monitoring | Suspended solids<br>Biological oxygen demands<br>Nitrogen<br>Phosphorous<br>Coliform levels | |

Weston (1986) suggests that the "environmental carrying capacity" for aquaculture should be determined through the design and use of mathematical models to predict changes in water chemistry parameters as a function of mariculture development, as the Japanese have done. In South Carolina, SCDHEC considers stream classification and effects of effluents on a receiving water body through the use of a comprehensive water quality model (CWQM) which can be applied as a one-, two- or three-dimensional, tidally averaged steady-state water quality model. It is used to predict biological oxygen demand, dissolved oxygen, nutrients, and other parameters (e.g., salinity) with a decay rate proportional to its concentration (Brune 1990). If the CWQM predicts a dissolved oxygen reduction of more than 0.1 mg/l, permits are denied. Another approach recently adopted by the SCDHEC is the development of a Watershed Water Quality Management Strategy (WWQMS) (SCDHEC 1991). This strategy should strengthen comprehensive water-quality planning and water-quality protection on a watershed basis through basin-wide modeling and wasteland allocations. As previously mentioned, NPDES permit applications are collectively examined and decided by watershed. Planning on a watershed basis allows the coordination of activities so that all actual and potential impacts on water quality can be evaluated. Waste assimilative capacities can be determined and allocated in a more equitable fashion since all activities are taken into account. Additionally, focused monitoring activities on priority watersheds will enable SCDHEC to develop waste load allocations and total maximum daily loads to provide an equitable assessment of all actual and potential water-quality impacts from point and nonpoint sources (SCDHEC 1991), including aquaculture.

## DESIGN REQUIREMENTS

Managing wastes and effluents can be achieved through well designed and operated recycling programs that beneficially use the waste products as resources (National Research Council 1992).

Such design requirements could include technologies to use the organic solids to improve or fertilize soil as animal feed supplements, or recycle the waste water as irrigation water, cooling water or for reuse to the same or other aquaculture production systems (Mudrak 1981). Provisions for reuse system design might include one or more of the following treatments: sedimentation, mechanical filtration, biological filtration, aeration, extended aeration, activated sludges, pH control, heating, cooling, sterlization, de-gassing, and ion exchange (Liao and Mayo 1972).

In salmon hatcheries, filters were shown to be desirable and more reliable. The effluent water from a hatchery-water reconditioning filter system was ready for discharge into the river without further treatment, as more than 85 percent of BOD and suspended solids were removed from the effluent stream (Liao and Mayo 1974). Biofilters are a key component in the design and construction of commercially viable recirculating systems, and research in this area remains very active (National Research Council 1992). A major drawback to this technology is cost, which prevents many culturists from adapting it to their operations. A parallel course of action is the development of improved and more efficient feed formulations for aquaculture species, thus reducing the amount of waste produced by the facility.

Properly designed production and treatment facilities can greatly reduce effluent impacts and should be specified in aquaculture BMP's. In Florida, for example, a General Permit for Fish Farms (Chapter 17-660.820, Florida Administrative Code) has been issued authorizing a general permit for "any person constructing or operating a fish farm designed and operated according" to the rule. The General Permit includes design requirements for pond construction (set according to the U.S. Department of Agriculture, Soil Conservation Service Standards) and retention or detention facilities, which are required for each aquaculture farm. All production pond discharges from existing facilities must be routed to a detention facility designed and constructed to provide at least a 1-day residence time in the facilities so that the suspended solids are retained on site. Specific criteria are provided for fish farms that use ditch systems for this purpose, including a minimum ditch length (100 feet), minimum ditch cross-section (1 square foot for each acre-foot of discharge), the need for a water control structure at the point of discharge, and minimum ditch depth (1 foot). For new operations, all pond designs must be approved by the Soil Conservation Service or a professional engineer (P.E.). Each aquaculture operation must also include (or have access to) a retention facility, capable of retaining all production pond discharges on site, or a detention facility. The detention facility must be designed and constructed to be able to provide either a 1- or 5-day residence time for all pond discharges, include a littoral zone for growth of rooted aquatic vegetation and, for all operations that discharge to surface waters of the state, a water control structure at the point of discharge. Design requirements should be based on the best available technology that is economically feasible to the aquaculturist.

## OPERATIONAL PROTOCOLS

Aquaculture effluent BMP policies should identify allowable methods of treatment. There are a number of remedial strategies available to culturists or under development (see Table 1).

Traditional treatment methods, including the use of copper sulfate (to control algal blooms) and settling ponds, have not been totally successful in addressing the effluent problem. Biological methods, including the use of polyculture and integrated aquaculture/agricultural systems, may address effluent concerns. The primary function of aquatic animals in treatment systems is to harvest algae, detritus, insects, and other particulate matter contained in the waste (Brown and Nash 1981). In marine systems, bivalve mollusks (oyster, clams, and mussels) can filter nutrients out of the pond water and show promise as a biological method of treating shrimp pond effluent (Rosenberry 1991). Closed system aquaculture, which involves recirculating systems capable of treating wastes, are receiving significant attention by the research community (National Research Council 1992), although many systems remain cost prohibitive.

The use of innovative management strategies in aquaculture systems continues to show promise in dealing with effluent problems, at a much lower cost to the culturist, and are incorporated by several states in their criteria for obtaining General Permits. Minimum operational requirements are stipulated in the Florida General Permit for Fish Farms. For instance, in individual production ponds that discharge off-site through a detention facility with 1-day residence times, feed application rates are set at a maximum of 180 pounds of dry feed per acre per day and production standing crop at a maximum of 6,000 pounds of fish per acre. In those ponds with retention or detention facilities designed for a 5-day residence time, these maximums are raised to 360 pounds of dry feed per acre per day and 12,000 pounds of fish per acre. Waivers are allowed for ponds with synthetic liners or having soils with minimal seepage. Limitations are placed on the use of registered chemicals, fertilizers, and other substances. Methods for the adequate timing and release of effluent waters are stated, as are they for sludge removal and disposal.

Work in South Carolina may also lead to the development of operational protocols to minimize or eliminate the environmental impacts of effluents from marine shrimp ponds. Hopkins et al. (1991) found that water exchange in intensive pond culture can be dramatically reduced without sacrificing growth or survival, and, in less intensive systems, water exchange could be eliminated. With little or no water exchange, impacts from effluents may be ameliorated and production levels could be maintained through the use of innovative pond management techniques for aeration, feed application, water recycling, and sludge treatment.

## EFFLUENT LIMITATIONS AND MONITORING REQUIREMENTS

Aquaculture BMP's should include general effluent limitations and monitoring requirements for the four types of aquaculture facilities (hatcheries, net-pen finfish culture, pond culture and molluscan shellfish culture). For most aquaculture operations, general effluent limits for biological oxygen demand, suspended solids, pH, and dissolved oxygen should be set. Due to the diverse nature of both the aquaculture industry and receiving waters, specific limits should continue to be set on a case-by-case basis.

Pennsylvania is in the process of drafting a General Permit for private animal aquaculture activities to authorize discharges under the NDPES program. The state's Department of Environmental Resources (PA.DER) has identified flow (in mgd), total suspended solids (mg/l), and pH as key parameters for which limitations are established (Pennsylvania Department of Environmental Resources 1992). Facilities that receive general permits will be required to monitor those parameters once per month and report the results to the PA.DER on a semi-annual basis.

| MARINE CULTURE SYSTEM SIZE | MONITORING PARAMETERS DURING MARINE CULTURE OPERATIONS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | WATER COLUMN | | | | | BOTTOM | | |
| | CURRENT | TURBIDITY | | | | | | |
| NET-PEN CULTURE | DIRECTION & SPEED | SECCHI DISK | AERIAL PHOTOS | DISSOLVED OXYGEN | SALINITY | CHEMICAL OXYGEN DEMAND | TOTAL NITROGEN | BENTHIC SAMPLE |
| SMALL PRODUCTION LEVEL (135 tons or less of feed per net-pen system per year) | Continuous | Daily | Semi-Annually | Daily | Daily | Annually–Maximum of 20 sampling sites with 3 replicates at each site | Annually–Maximum of 20 sampling sites with 3 replicates at each site | Annually–Maximum of 20 sampling sites with 3 replicates at each site |
| LARGE PRODUCTION LEVEL (Greater than 135 tons of feed per net-pen system per year) | Continuous | Daily | Semi-Annually | Daily | Daily | Quarterly–Minimum of 20 sampling sites with 3 replicates at each site | Quarterly–Minimum of 20 sampling sites with 3 replicates at each site | Quarterly–Minimum of 20 sampling sites with 3 replicates at each site |
| MOLLUSCAN CULTURE | | | | | | | | |
| SMALL PRODUCTION LEVEL (100 acres or less) | Continuous | Not Required | Semi-Annually | Determined on case-by-case basis | Determined on case-by-case basis | Annually–Maximum of 20 sampling sites with 3 replicates at each site | Annually–Maximum of 20 sampling sites with 3 replicates at each site | Annually–Maximum of 20 sampling sites with 3 replicates at each site |
| LARGE PRODUCTION LEVEL (Greater than 100 acres) | Continuous | Not Required | Quarterly | Determined on case-by-case basis | Determined on case-by-case basis | Quarterly–Minimum of 20 sampling sites with 3 replicates at each site | Quarterly–Minimum of 20 sampling sites with 3 replicates at each site | Quarterly–Minimum of 20 sampling sites with 3 replicates at each site |

Figure 3. Marine Environmental Monitoring Program (MEMP)-State of Mississippi.

The State of Mississippi adopted guidelines for aquaculture in the marine environment within the last year (Peel 1991). Although the state has no plans to require proposed marine aquaculture facilities to obtain NPDES permits, it does require its permittees to conduct pre-operational environmental surveys and implement Marine Environmental Monitoring Programs (Figure 3).

The guidelines, which cover net-pen and molluscan culture operations, require the monitoring of water currents, turbidity, dissolved oxygen, salinity, chemical oxygen demands, total nitrogen, and benthic communities. They also specify particular siting requirements for aquaculture in net-pens and for off-bottom, and on-bottom culture in offshore waters, and on-bottom culture in nearshore waters.

## AQUACULTURAL BMP'S: ADDRESSING THE NATIONAL AGENDA

Much has been written about the United States aquaculture industry and its problems. In 1978, the National Research Council stated that constraints on the development of the nation's aquaculture industry "tend to be political and administrative, rather than scientific and technological. Advances are needed in all areas, but for overall progress, the essential requirements are policy decisions and administrative actions" (National Research Council 1978). The National Research Council re-visited this issue again when it convened a committee under its Marine Board to assess technology and opportunities for marine aquaculture in the United States. It similarly concluded, 14 years later, that "solutions to the environmental problems constraining marine aquaculture will involve approaches that combine technological 'fixes' with improved regulatory and management structures, as well as public education about the value of marine aquaculture to the nation" (National Research Council 1992). It appears that a significant amount of effort is being placed on identifying the problems associated with aquaculture, but little on developing appropriate solutions. Politically speaking, aquaculture in general remains a modest industry with limited resources to instigate significant changes.

The authority of state and federal natural resource agencies to address the environmental issues vis-a-vis aquaculture already exists in law and regulation. As illustrated in this paper, several states are taking steps to develop regulatory frameworks for the aquaculture industry; however, the lack of an overall national set of standards thwarts consistency among states. It also results in piecemeal approaches and "quick fixes."

The formulation of national effluent BMP's for aquaculture could establish these standards. Indeed, best management practices to deal with escape of organisms from aquaculture hatcheries, net-pens, and ponds may also be desirable to deal with other environmental concerns, including potential genetic or disease impacts, especially in facilities where non-native species are being cultured.

The development and implementation of BMP's for aquaculture should be undertaken with consideration given to the following (modified from Hopkins et al. unpub. manu.):

- The twin goals of the BMPs should be the protection of the aquatic environment and continued growth of the aquaculture industry;
- The BMP documents should be drafted and approved by a committee composed of commercial aquaculturists, researchers, and senior environmental managers;
- The documents should address differences in aquaculture production technology by including sections on hatcheries, net-pen culture, pond culture, and molluscan shellfish culture;
- The BMP's should describe, in reasonable detail, guidelines for the design, construction, and operation of aquaculture facilities, taking into account the best available and cost-effective technologies and information;
- The documents should serve as useful references and sources of information on efficient and sustainable aquaculture production;
- The BMP's should be adopted by natural resource agencies and serve as a basis for informed, consistent decision-making in the NPDES permit review process;
- The methodologies outlined in the BMP documents should be adhered to as provisions stipulated in all approved permits;
- The BMP's should be treated as "living" documents which can (and should) be revised and updated as new information and technologies develop.

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# ADMINISTRATIVE MEASURES TO CONSERVE THE ENVIRONMENT FOR AQUACULTURE GROUNDS IN JAPAN

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## ABSTRACT

Marine aquaculture in Japan has developed steadily, along with Japan's economic growth, since the 1960's. Production in 1991 represented 12.9 percent of the total Japanese marine fisheries production and 25.1 percent of the total value. But economic growth has also brought water pollution to the coastal waters of Japan. Expanding marine aquaculture has also contributed to the pollution. This paper outlines several Japanese government administrative measures that address these pollution problems.

## INTRODUCTION

Aquaculture has a very long history in Japan, beginning with the culture of "nori" seaweed in the 16th century. The artificial feeding of marine species was initiated with the yellowtail in the 1920's. In the decades following World War II, new culture technologies were gradually applied to an increasing number of species. For some species, notably those of high quality and market value, cultured production accounts for the majority of the total supply on the Japanese market. For example, cultured nori, oysters, and coho salmon account for 100 percent of the domestic supply for those species, and cultured yellowtail and red sea bream account for 80 percent of the domestic supply of those species (Table 1).

In 1991, marine aquaculture production in Japan amounted to 1.26 million metric tons valued at 641 billion yen and represented 12.9 percent of the total Japanese marine fisheries production in volume and 25.1 percent of the total in value (Tables 1 and 2). Dividing Japanese marine fisheries into four major sectors (distant-water, offshore, coastal, and aquaculture), aquaculture production volume exceeded that of the distant-water fishery in 1991 (Figure 1). The value of aquaculture production has exceeded that of the distant-water fishery since 1988 (Figure 2). The distant-water fishery held a major position in value prior to the 200-mile zone era.

Today, marine aquaculture is a major food production industry in Japan. Aquaculture products generally meet the tastes of consumers and consist mainly of medium- to high-quality seafood which, unless artificial-

Table 1. Position of Aquaculture in Japan in 1991

| | | Volume 1000 mt | Value Billion Yen |
|---|---|---|---|
| Marine Fishery | (A) | 9,773 | 2,551 |
| Distant-water Fishery | | 1,179 | 427 |
| Offshore Fishery | | 5,438 | 704 |
| Coastal Fishery | (B) | 1,894 | 780 |
| Aquaculture | (C) | 1,262 | 641 |
| Inland Fishery | | 205 | 164 |
| Fishery | | 107 | 68 |
| Aquaculture | (D) | 97 | 96 |
| Total | (E) | 9,978 | 2,715 |
| C/A | | 12.9% | 25.1% |
| (C+D)/E | | 13.6% | 27.1% |
| C/(B+C) | | 40.0% | 45.1% |

Source: DSI (1993)

Table 2. Rate of Aquaculture to Total Fishery Production in 1991

| Species | Aquaculture(A) (mt) | Fishery(B) (mt) | Total(C) (mt) | A/C (%) |
|---|---|---|---|---|
| Yellowtail | 161,077 | 50,995 | 212,072 | 78.0 |
| Red Sea Bream | 60,127 | 13,277 | 73,404 | 81.9 |
| Olive Flounder | 6,515 | 6,276 | 12,791 | 50.9 |
| Coho Salmon | 23,730 | — | 23,730 | 100.0 |
| Scallop | 188,834 | 179,077 | 367,911 | 51.3 |
| Oyster | 239,217 | — | 239,217 | 100.0 |
| Kuruma Prawn | 2,491 | 2,875 | 5,368 | 48.4 |
| Nori (Laver) | 403,363 | — | 403,363 | 100.0 |
| Wakame (Kelp) | 99,092 | 4,582 | 103,674 | 95.8 |

Source: DSI (1993)

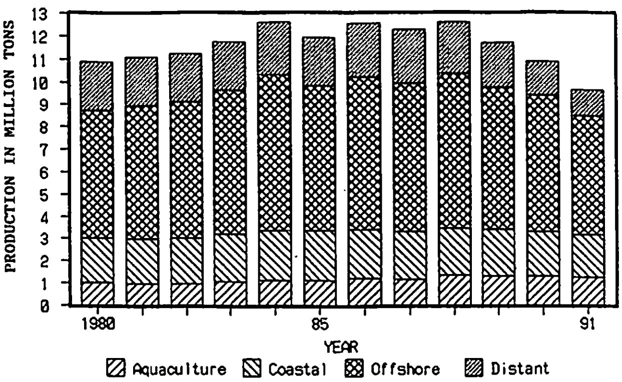

Figure 1. Production by type of fishery.

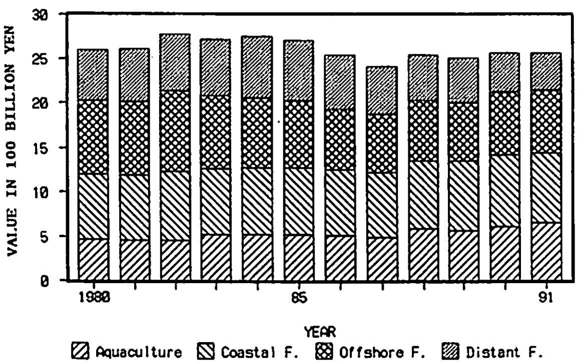

Figure 2. Production value by type of fishery.

ly reared, might not otherwise be affordable to consumers. As marine aquaculture continues to develop and expand, protecting the marine environment from the effects of water pollution is vital to the health of the industry.

## ECONOMIC GROWTH AND WATER POLLUTION CONTROL

The effects of water pollution from rapid economic growth beginning in the 1960's became more widespread and severe as marine aquaculture developed and expanded during the same period. Successively, serious water pollution incidents occurred. The destruction of cultured yellowtail occurred in 1972 as a result of a large-scale red tide within the Seto Inland Sea. Accelerated water pollution in the Seto Inland Sea caused by increasing coastal zone population density and industrial activity led to increased frequency of red tides.

Against this background, the Basic Law for Environmental Pollution Control was enacted to promote comprehensive measures against environmental pollution. In 1970, a new reinforced Water Pollution Control Law was enacted. In 1973, the Law for Conservation of the Environment of the Seto Inland Sea was enacted. To solve remaining problems related to organic pollution, legislation was enacted to limit the total allowable pollutant load factor in effluent with respect to the Seto Inland Sea, Tokyo Bay, and Ise Bay (Figure 3).

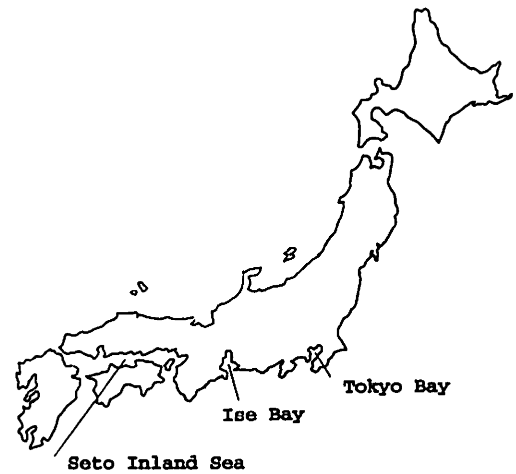

Figure 3. Designated water areas under total pollutant loads control system in Japan.

## 1. ESTABLISHING WATER QUALITY STANDARDS

Under the Basic Law for Environmental Pollution Control, environmental quality standards (EQS) are set for the public water areas as target levels to be achieved and maintained for desirable water quality. Under the provisions of the Law, these standards are set based on two major objectives: the protection of human health and the conservation of the living environment.

For the protection of human health, national uniform standards are set and apply to all public waters (Table 3). For conservation of the environment, sea areas are classified according to water usage, and EQS values for chemical oxygen demand (COD), dissolved oxygen (DO), pH, fecal coliform group, and N-hexane extracts are established for each sea area classification (Table 4).

In order to improve the water quality of large enclosed water areas, efforts are focused on cutting the pollutant load. The Water Pollution Control Law was amended for this purpose in 1978 to implement a control system on total pollutant loads flowing into the water areas. Under this system, the Seto Inland Sea, Tokyo Bay, and Ise Bay have been designated as water areas where specific programs for reducing total pollutant loads have been implemented (Figure 4). Total pollutant load control standards have been applied to the effluent from factories and other industries exceeding a specified scale of operation, and the improvement of sewage systems and other measures have been under-

Table 3. Environmental quality standards for the protection of human health

| Substance | Standard Value |
|---|---|
| Cadmium | 0.01 mg/l or less |
| Cyanide | Not detectable |
| Organic phosphorus | Not detectable |
| Lead | 0.1 mg/l or less |
| Chromium (VI) | 0.05 mg/l or less |
| Arsenic | 0.05 mg/l or less |
| Total mercury | 0.0005 mg/l or less |
| Alkyl mercury | Not detectable |
| PCBs | Not detectable |

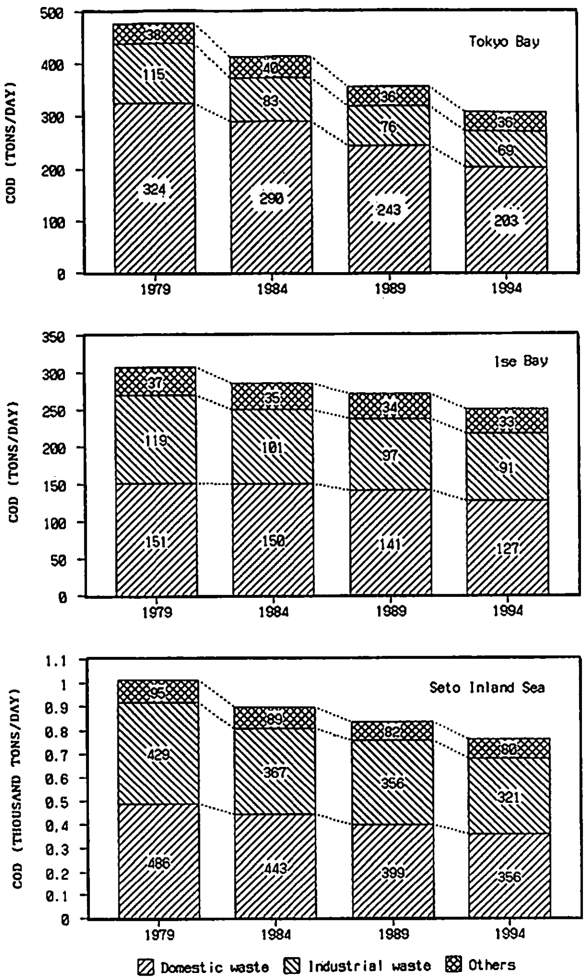


Figure 4. Changes in pollutant loads (COD) and reduction targets.

taken to reduce pollutant loads.

## 2. EFFECTS OF WATER QUALITY STANDARDS

Recently, there has been general improvement in water quality. In particular, the incidence of toxic substances such as cadmium and cyanide has decreased remarkably (Figure 5). However, attaining EQS for

Table 4. Standards for conservation of the living environment in coastal waters

| Category | A | B | C |
|---|---|---|---|
| Purpose | Fishery class 1<br>Bathing<br>Conservation of natural environment | Fishery class 2<br>Industrial water | Conservation of environment |
| Item | | | |
| pH | 7.8–8.3 | 7.8–8.3 | 7.0–8.3 |
| COD | 2 mg/l or less | 3 mg/l or less | 8 mg/l or less |
| DO | 7.5 mg/l or more | 5 mg/l or more | 2 mg/l or more |
| Number of Coliform group | 1000 MPN/100 ml or less | — | — |
| N-hexane Extracts | Not detectable | Not detectable | — |

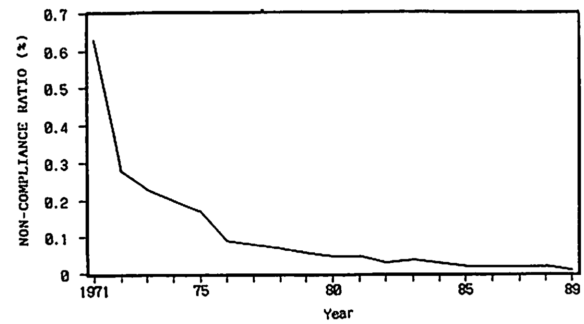


Figure 5. Non-compliance ratio with EQSs on health items source: environment protection agency.

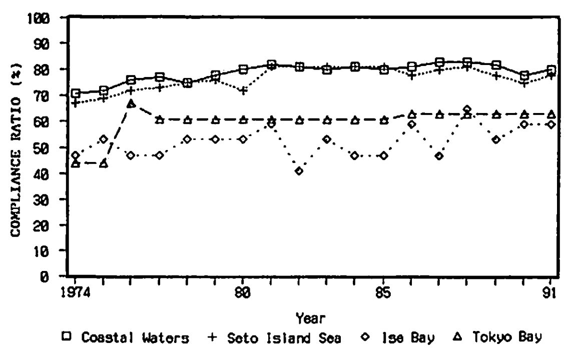


Figure 6. Compliance ratio with EQS on COD source: environment protection agency.

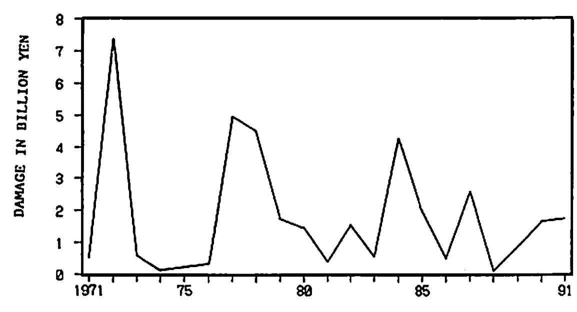


Figure 7. Fishery damage caused by red tide source: fisheries agency.

organic soluble pollutants in enclosed water areas still lays behind other water areas. As for the quality of water indicated by COD in designated water areas, the ratio for achieving EQS is 80% in coastal waters, 63% in Tokyo Bay, 59% in Ise Bay, and 78% in the Seto Inland Sea (Figure 6).

The occurrence of red tides and the amount of damage to the fisheries have decreased since the mid 1970's (Figure 7). Still, there have been occurrences of red tides in enclosed sea areas. In order to counter these occurrences, surveys and studies have been undertaken and measures have been implemented for the purpose of forecasting red tides and, thereby, preventing damage.

## ENVIRONMENTAL IMPACTS OF AQUACULTURE DEVELOPMENTS

### 1. CUMULATIVE DEGRADATION OF THE AQUACULTURE GROUNDS

Culture farms may generate a so-called "senile" condition when excessive production continues for many years without adequate control of wastes. Problems that arise include the degradation of water quality and the accumulation of bottom sediments. These are accompanied by slow growth of the cultured organisms, the increased occurrence of disease, or increased mortality. The degradation of water quality and the accumulation of sediments can be one of the causes of red tide. Although the extent of the problem varies among culture sites, many sites in the internal bays now suffer from these complex problems. In order to solve these problems, the Fisheries Agency is developing new feeds which are less harmful to the environment and establishing guidelines for aquaculture.

### 2. FEED AND FEEDING TECHNOLOGY

Two key factors that determine the effect of aquaculture on the environment are the quality of the feed and the feeding techniques. In intensive aquaculture production, pollution caused by the input of nutrients from feed constitutes the main environmental problem. In Japan, the development of marine culture species has grown by taking advantage of the abundant supply of inexpensive spotlined sardine as feed (Figure 8). Although the use of raw fish as feed has more potential than formulated feed to release nutrients and biodegradable wastes into the natural environment, many fish farmers have used raw or frozen fish as feed because of the availability, cost, and efficiency.

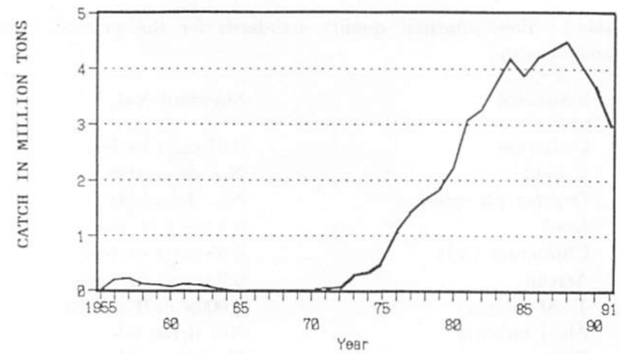


Figure 8. Catch of spotlined sardine.

#### 2.1 Development and Promotion of Moist Pellets

The Fisheries Agency conducted an intensive study from 1979 to 1981 to develop moist pellets to be used for marine fish culture. The results of the study showed that using moist pellets could reduce nutrient discharge significantly. The Fisheries Agency then promoted the use of moist pellets, which became commercially available in 1980 for red sea bream, and in 1985 for yellowtail. Although their use is still limited, the commercial production of formulated feeds has been increasing year by year (Figure 9). However, moist pellets are a mixture of raw fish and formulated feeds and the problems of using raw fish as feed still remain. The amount of raw fish used in the pellet can be adjusted and is usually 50% but sometimes as high as 90%.

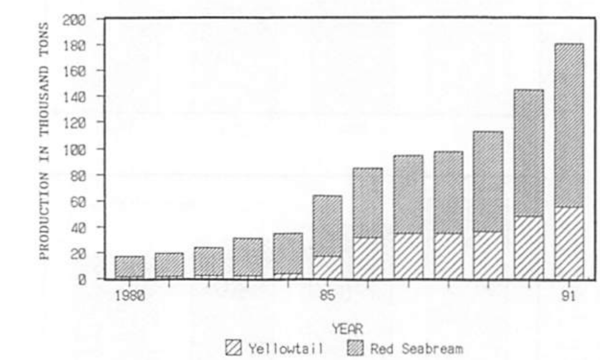


Figure 9. Trends in production of formulated feed source: Japan fish feed producers association.

#### 2.2 Development and Promotion of Dry Feed

Increased prices and insufficient supply of raw fish for feed now give cause for serious concern. Many efforts have been made to develop dry feed for marine fish culture. Watanabe et al. (1989) developed an extruded dry pellet for yellowtail that can be used successfully as feed from juvenile to market-size adult fish. Dry feed has several advantages. It minimizes uneaten feed and the loss of nutrients from leaching. As the composition is adjusted and stabilized, it can rationalize the feeding strategy. It is convenient to handle and store. The problem is the cost of the feed. The primal raw material of dry fish feed is fish meal which is a rather expensive protein source. There is some concern about future security of the supply of fish meal. Another problem is that many fish farmers are still not confident about the feed conversion efficiency of dry feed for rearing marine fish.

In response to these concerns, the Fisheries Agency initiated research on the development and improvement of dry feed and on the possibility of blending vegetable ingredients such as soybean meal into formulated dry feed. Soybean meal is an inexpensive, very abundant source of protein. The use of vegetable ingredients could reduce the demand for fish for processing into feeds and could reduce the cost. Therefore, it is expected that use of vegetable ingredients could ease the problems inhibiting the promotion of dry feed. The interim results of the research indicate that commercially defatted soybean meal can substitute for fish meal up to 30% in the feed for yellowtail. Technical developments regarding the production of feeds have advanced rapidly in the last few years, and commercial production of formulated feeds for marine animals has been increasing (Figure 10).

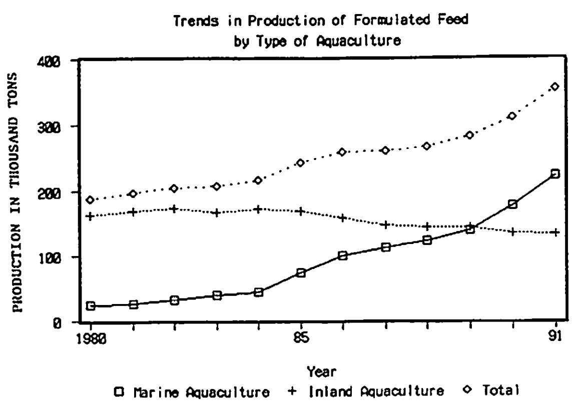


Figure 10. Trends in production of formulated feed by type of aquaculture source: Japan fish producers association.

### 2.3 Feeding Technology

Another method to reduce pollutant loads is to avoid overfeeding in order to improve feed conversion coefficients. The optimization of feeding is one useful way to reduce both organic loading and the accumulation of sediments in marine farms. It could increase the efficiency of the feed and reduce the production cost. In addition to the research program for developing new feed, the Fisheries Agency has organized another research program to review feeding technology along with other aquaculture practices.

## 3. FUTURE DEVELOPMENT AND OPERATION PLANNING

With expansion of aquaculture operations in coastal waters,the need for development planning is critical. In 1992, the Fisheries Agency issued guidelines to the prefectural governors regarding fishing ground utilization plans. Under these guidelines, prefectural governors are instructed to take environmental problems into consideration in planning aquaculture utilization of the area. The prefectural governors are asked to consider imposing strict controls on the number of cages being used and on the stocking density according to regional conditions for maintaining environmental quality and sustainable operations. From 1988, the Fisheries Agency has conducted a research program to develop models to quantify a water body's carrying capacity or loading capacity for cultured species.

The Fisheries Agency has also organized a research committee to consider and develop guidelines for marine aquaculture practices and techniques taking into account environmental aspects. The classification of the aquaculture grounds, appropriate scale or layout of aquaculture establishments, appropriate index of the environmental quality, and feeding practices have been considered. New research programs are being planned on integrated aquaculture systems. For example, if various organisms of different trophic levels such as seaweeds, mollusks, and crustaceans are cultured together with fish in the same area, various forms of nutrients can be efficiently utilized and productivity can be improved.

## CONCLUSION

Marine aquaculture provides various nutritional, social, and economic benefits to society. Aquaculture is and will continue to be an increasingly important food production industry for Japan. The Japanese experience of the 1960's evidenced how uncontrolled industrial growth can pollute coastal zone waters and destroy valuable aquaculture food resources. Expanding and intense marine aquaculture in Japan has also been shown to generate pollution leading to environmental problems. This experience has demonstrated the critical need for continued research to improve conservation and protect the marine environment for aquaculture production.

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# NUMERICAL SIMULATION MODEL FOR QUANTITATIVE MANAGEMENT OF AQUACULTURE-CASE STUDY IN KUSU-URA BAY

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## ABSTRACT

A numerical model is developed for aquaculture management, that consists of the following three parts: (1) Chemical Oxygen Demand (COD) diffusion model that calculates spatial distribution of COD using simulated current, (2) Dissolved Oxygen (DO) diffusion model that calculates spatial distribution of dissolved oxygen, and (3) accumulation model that calculates distribution of deposits from aquaculture of fish. Our model is capable of calculating the detailed spatial distribution of COD and DO by dividing the bay into many grid points. It also takes into consideration the effects of feed and fish in each raft and the loading of COD from rivers. The model is applied to Kusu-ura Bay in the Kumamoto Pref., western part of Japan, as a case study.

## 1. MODEL CONCEPTION

In order to calculate this model, current fields around mariculture projects are needed. Usually tidal, wind induced and/or density currents are calculated using three dimensional primitive equations and equation of state, e.g., after Nakata et al. (1983). The spatial concentrations of Chemical Oxygen Demand (COD) are calculated using a diffusion equation based on the calculated currents including sinking velocity of organic matter, attenuation velocity of COD, and COD loadings from rafts and rivers. The detailed descriptions are shown in Kishi et al. (1993). The spatial concentrations of Dissolved Oxygen (DO) also are calculated using a diffusion equation including dissolution of oxygen from air, consumption of oxygen by the respiration of fish, consumption of oxygen due to decomposition of organic matter by bacteria, and supply of oxygen through photosynthesis. The spatial concentrations of deposits from aquaculture are also calculated using a diffusion equation in the same way as the COD model by adding the sinking term. A schematic view of the flow chart of calculations in the model and detailed discussions about physiological parameters are shown in Kishi et al. (1993).

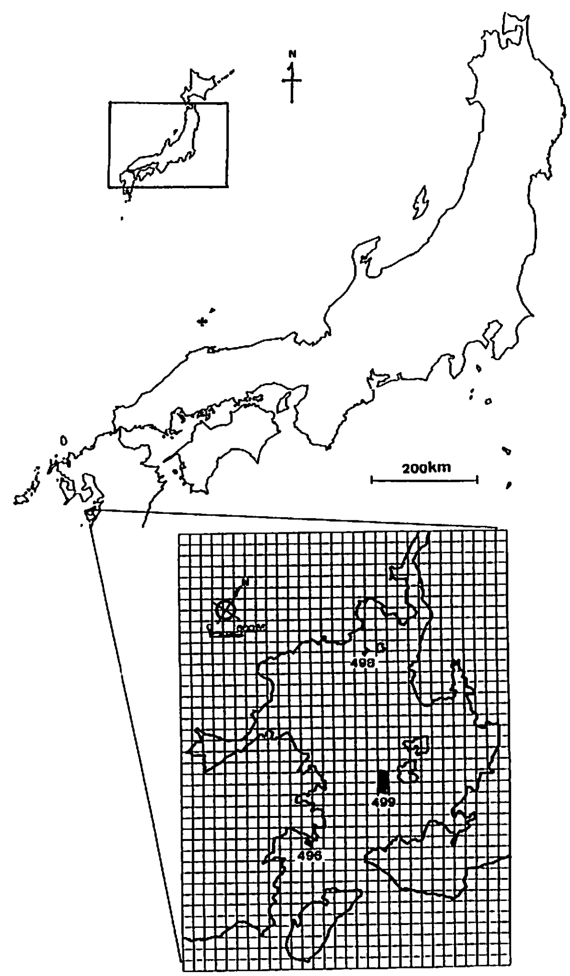


Figure 1. Schematic view of Kusu-ura Bay, Kumamoto Pref. Japan, and horizontal distribution of preserve of aquaculture and grids for numerical simulation in Kusu-ura Bay.

## 2. SIMULATION RESULTS-CASE STUDY IN KUSU-URA BAY

The case study is carried out at Kusu-ura Bay, Kumamoto Pref. shown in Figure 1. The horizontal distribution of the aquaculture preserve is also shown in Figure 1. Yellowtail and sea bream are mainly cultured in this bay. Monthly mean number of fish, body weight (e.g., shown in Table 1), amount of feed and river loading as well as horizontal distributions of COD, DO, water temperature, and salinity are collected by the fisheries experimental station. Based on these data, we calculated COD and DO distributions at different levels and the accumulated organic matter on the bottom. Figure 2 shows tidal residual currents. Notice that the tidal residual current is very slow at the inner region of the bay. Figure 3 shows the horizontal distribution of COD. The highest concentration area of COD is found around aquaculture rafts. Figure 4 shows the horizontal distribution of DO. The value is generally larger in upper layer than in lower layer because of photosynthesis. Although DO around the preserve shows a lower value compared with other areas, the value itself (more than 4.0 ml $l^{-1}$) is not so low that yellowtail or sea bream die within a day. Figure 5 shows the horizontal distribution of accumulated organic matter. Of course, the bottom just under the preserves gets maximum deposits because the effect of advection by currents is very low.

Table 1. Biomass of yellowtail and loading of COD in Kusu-ura Bay; the preserve number corresponds to Figure 1.

| preserve number | | 498 | 499 | 496 |
|---|---|---|---|---|
| number of yellow tail | 1 yr. old | | 306500( 454) | 57500( 454) |
| | 2 yd. old | | 176900(1604) | 144000(1604) |
| | 3 yr. old | | | |
| number of *sparidae* | 1 yr. old | 80000( 47) | 98000( 47) | 128000( 47) |
| | 2 yr. old | 79200(181) | 216000( 181) | 100000( 181) |
| | 3 yr. old | 56000(291) | 157500( 343) | 63000( 343) |
| | 4 yr. old | | 63000( 415) | 68500( 415) |
| amount of feed (kg $d^{-1}$) | | 3730 | 54745 | 33123 |
| COD loading | leftover | 136 | 2006 | 1214 |
| | pellet | 83 | 1221 | 738 |

* mainly moist pellet is feeded
* numbers in ( ) indicate the amount of feed (kg/10000 indvs.)

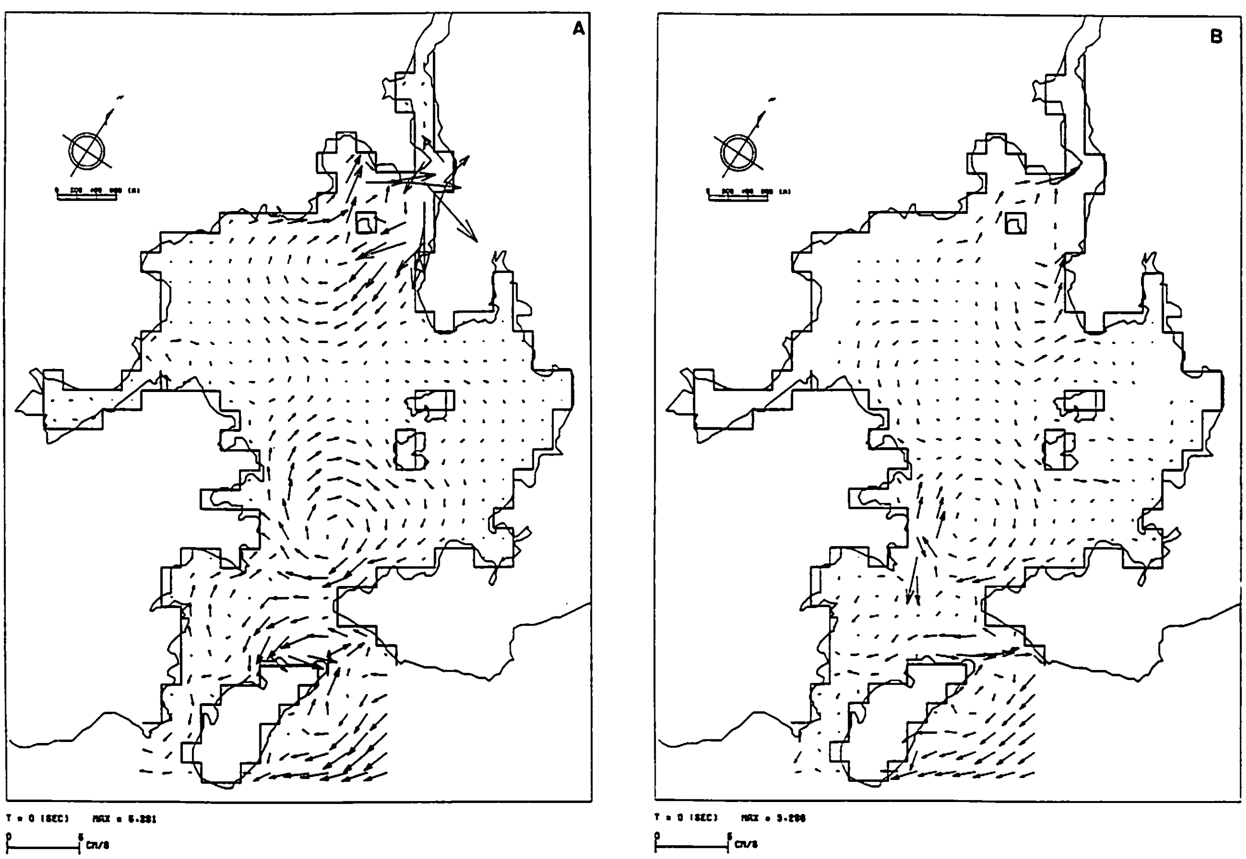


Figure 2. Calculated tidal residual currents in Kusu-ura Bay ; (a) upper 1st layer (0 m–5 m) (b) bottom layer (below 5 m).

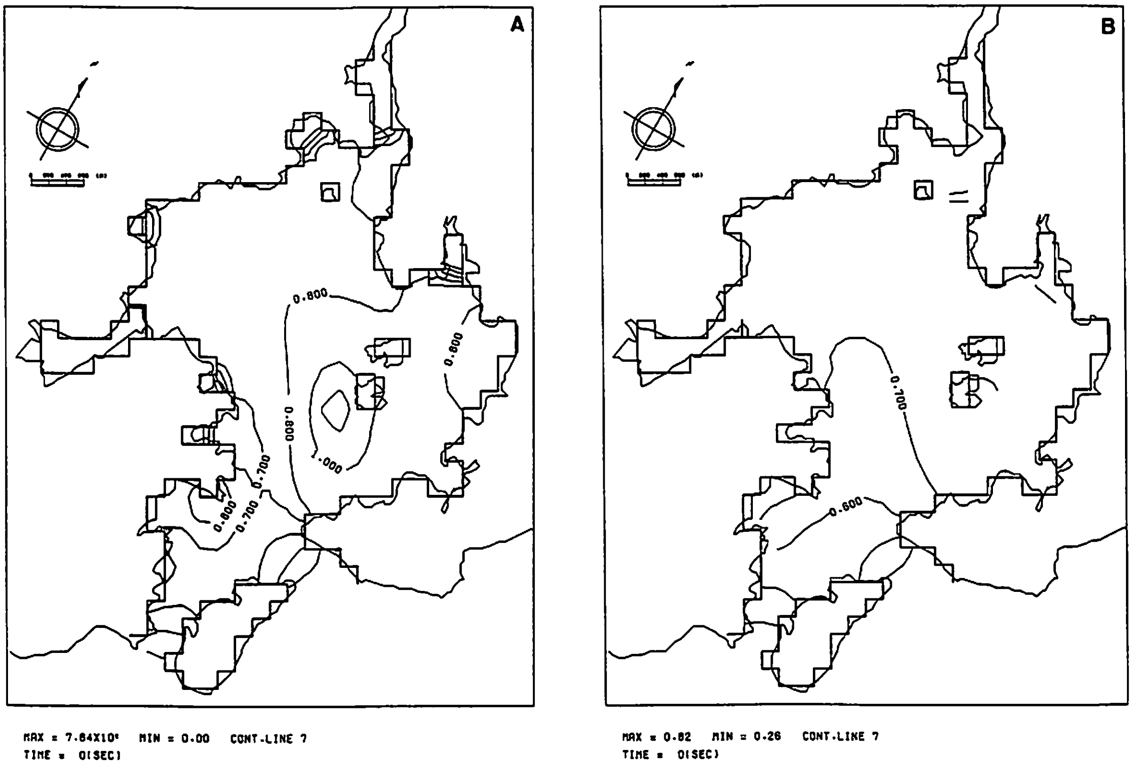


Figure 3. Horizontal distribution of COD (unit in ppm); (a) upper 1st layer (b) bottom layer.

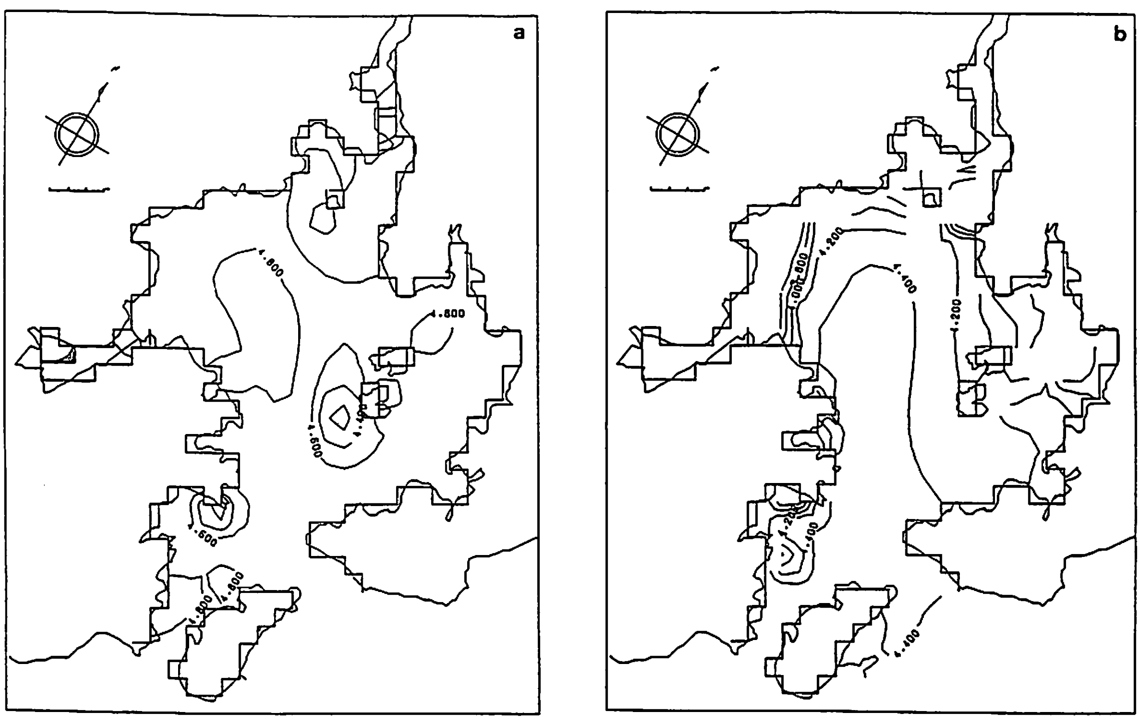


Figure 4. Horizontal distribution of DO (unit in ml $l^{-1}$); (a) upper 1st layer (b) bottom layer.

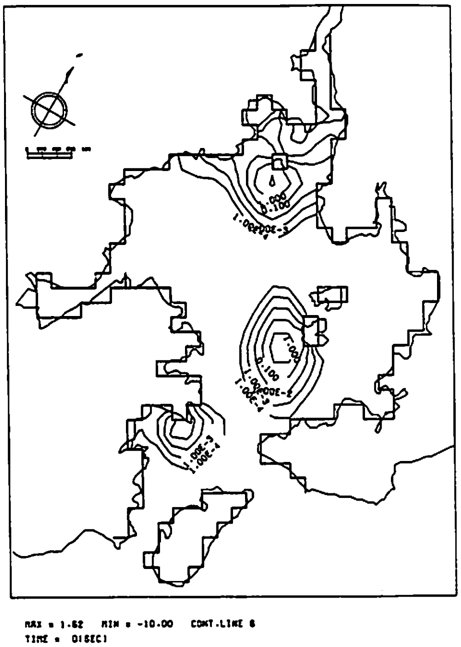

Figure 5. Horizontal distribution of accumulated organic matter (unit in g $m^{-2}day^{-1}$).

## DISCUSSION

According to Kishi et al. (1993) there is not a conspicuous diurnal fluctuation of the observed value of DO in spite of photosynthesis by phytoplankton and/or diurnal variation of respiration of fish. Our model is capable of calculating the detailed spatial distribution of COD and DO, although our model calculates daily averaged values. Using this model, we can assess the influence of the location or the area of the aquaculture preserves on the ecological and/or environmental system. It is also of practical use in obtaining the basic data for the renewal of aquaculture industry licenses.

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# CURRENT TRENDS IN DESIGN AND OPERATION OF ANADROMOUS FISH HATCHERIES IN THE WESTERN UNITED STATES FOR IMPROVED FITNESS

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## ABSTRACT

Anadromous fish hatcheries in the Western United States are coming under increased criticism from wild fish advocates and other groups. Some of the criticism leveled against the hatcheries is valid, others border on a holy crusade against the non-believers and unclean. Changes in the operation of hatcheries also may be driven by legislative measures and by a broadening of the composition of the natural resource managers and users. This paper is a summary of the research being conducted by many people and agencies. Emphasis will be placed on current trends and the potential impact of these changes on the design and operation of anadromous fish hatcheries in the Western United States.

## TYPICAL HATCHERY CHARACTERISTICS

Anadromous fish hatcheries in the Western United States have evolved over a period of 40 to 50 years and therefore may have been built for quite different reasons. Many hatcheries were built to mitigate for the construction of large dams and reservoirs, especially on the Columbia and Snake Rivers. Some of the major characteristics of these hatcheries are presented below:

- Hatchery performance criteria based on release number or weight of fish
- Limited resources for experimentation or research
- Personnel isolated from other fisheries professionals (public and private)
- Limited budgets for upgrading, maintenance, and repair
- Many based on non-biological mitigation settlements ($/year rather than number of returning adult fish)
- Inability to move monies between hatcheries to improve cost-effectiveness of the overall system
- Divided responsibility for funding, operation, and evaluation; hatcheries are not operated on a system-wide basis.
- Very limited coordination between different hatchery operators and hatchery managers
- The absence of an agency champion

## CURRENT OPERATING STRATEGIES AND PROCEDURES

Current operating strategies involve the production of large numbers of fish using high density and high feeding levels. The duration of hatchery rearing is commonly reduced compared to wild fish. This may be accomplished by use of groundwater or reuse systems that allow heating of the water. The carrying capacity of the hatchery may be increased by aeration with air or pure oxygen (Colt and Watten 1988; Colt and Orwicz 1991). These strategies commonly result in the production of smolts that are larger than wild fish.

## ACTORS IMPACTING THE FUTURE OPERATION OF HATCHERIES

There is significant pressure being applied to change hatchery operations or have them shut down completely (Hilborn 1992). This includes the following legislation or concerns:

- ESA (Endangered Species Act)
- Supplementation of wild stocks
- "Green" movement
- "Wild" fish advocates
- State and Federal wild fish or fish health policies
- Potential biotechnology regulations

Several species have been listed under ESA in the Western United States. A much larger number of species could be listed in the future. The ESA can be applied to species as well as sub-stocks of given species. Therefore, the ESA could be applied to Spring Chinook returning to a specific river reach or stream segment. Once a species is listed, its recovery plan may have a significant impact on fisheries management, fishing, and hatchery operations that could potentially impact the listed species.

Hatchery supplementation of wild stock is a relatively new concept in anadromous fish. The hatchery is used to incubate and rear fish for some period of time before the fish are released back into the wild. The period of time the fish may live in the stream before starting their downstream migration may range from 3 days to 12 months or longer. Fish from different reaches of the same river are not mixed in the hatchery. The performance of hatchery supplementation is currently being evaluated in a number of large programs. This method is also being used to try to re-introduce fish into basins where they have been extirpated.

## CHANGES TO HATCHERY DESIGN AND OPERATION-GENETICS CONSIDERATIONS

Selection of broodstock, mating practices, and culling during rearing are the major hatchery operations that can reduce genetic diversity (Kapuscinski and Philipp 1988). Key practices to maintain or increase genetic diversity include:

- Using of a large number of broodstock
- Mating of equal number of males and females
- Producing approximately equal number of progeny from each parent
- Selecting of broodstock over the full run
- Changes in culling procedures
- Separating of different stocks
- Locating of hatcheries on specific streams or reaches of rivers

Successful implementation of these changes may require a significant increase in hatchery staffing and funding.

## CHANGES TO HATCHERY DESIGN AND OPERATION-PHYSIOLOGICAL AND NUTRITIONAL CONSIDERATIONS

Current hatchery rearing units provide a very uniform and low water velocity. The main design consideration for water velocity is soluble metabolite and fecal solid removal. These conditions may result in a fish that is not fit and does not know to conserve energy when feeding in streams. Increases in water velocity can be used to improve the musculatures of salmonids (Josse et al. 1989). Consideration is being given to the design of rearing units that have a wide variation in water velocity. The nutrition of salmon may also be improved by use of rearing units that provide some amount of natural food items either from drift or from leaf litter (Parker et al. 1990). Rearing units designed to provide more natural conditions will have to be constructed quite differently from traditional raceways or ponds.

The rapid growth of hatchery fish may result in a large increase in precocious males (Mullan 1992). Slower growth as well as careful control of release size and timing may result in significant improvements in adult return. Emphasis is being placed on physiological condition, acclimation and imprinting, coloration, and straying control.

## CHANGES TO HATCHERY DESIGN AND OPERATION-PATHOLOGY CONSIDERATIONS

Bacterial and viral pathogens such as IHN, VHS, and bacterial kidney disease can result in major moralities under hatchery conditions. While vaccination and drug treatment may offer some potential for control, the use of disease-free water and basic sanitation procedures may have more promise. For example, Alaska Fish and Game has been able to reduce its IHN losses in sockeye eggs to less than 3% even when the majority of the broodstock are IHN positive (ADFG 1987).

When serious diseases are endemic in the water supply, disinfection of influent waters with ozone or UV has proved successful but expensive. In some cases, disinfection of effluent water may be needed to protect wild fish, especially for hatcheries that receive broodstock and fingerlings from other basins. For critical species it may be necessary to locate hatcheries on specific streams or reaches of rivers to reduce the possibility of disease transmission between different species or stocks.

Stricter enforcement of drug registration requirements and concerns about the potential impacts of the discharge of therapeutic chemicals have significantly restricted the number of legal therapeutic chemicals. This is especially critical for the treatment of broodstock and eggs. Malachite green can only be used with a special permit. Removal of the malachite green using activated carbon may be required prior to discharge. The use and discharge of formalin is still permitted but will likely be restricted in the future.

## CHANGES TO HATCHERY DESIGN AND OPERATION-BEHAVIORAL CONSIDERATIONS

Density and husbandry practices commonly cause abnormal behavior in hatchery fish. Key behavioral improvements that are being considered include the following:

- Reduction in density to reduce the aggressive characteristics of hatchery fish
- Introduction of feed under the water surface to break man/food linkage
- Design of rearing units to provide fish with experience in foraging for natural food items
- Behavioral conditioning to improve predator avoidance reactions

## CHANGES TO HATCHERY DESIGN AND OPERATION-HATCHERY MANAGEMENT CONSIDERATIONS

There are a number of salmon hatcheries in the Pacific Northwest that do not produce enough returning adults to supply the hatchery with eggs. Rationally, these hatcheries should be shut down; however, institutional pressures have kept them open. In addition to producing fish, hatcheries are a very visible facility that represent a commitment to the fisheries resources even if it is not productive (Hilborn 1992). The ability to rationally change hatchery operations and practices must be based on hard data. In the past, certain agencies have reduced data collection and analysis to allow management of the resources on purely political grounds. Improved hatchery design and operation will depend on some the following issues:

- Improved and valid evaluation of performance
- Flexible operation of hatchery systems to allow improved performance
- Improved communication between hatchery and harvest managers
- Improved status of hatchery workers and managers

## POTENTIAL IMPACT ON HATCHERY DESIGN AND OPERATION

While it is hoped that many of the changes discussed in this paper will improve adult return, most must be experimentally verified. For some endangered stocks, improved adult return will be the best measure of success. For other species and stocks, the utility of the techniques used will also depend on costs. Key impacts of the techniques may have the following impact on overall hatchery operations:

- Use of smaller hatcheries, acclimation ponds, and adult capture facilities
- Emphasis on construction of more natural looking rearing facilities
- Decreased rearing density
- Increased costs for monitoring and evaluation
- Increased labor costs resulting from genetic and feeding considerations
- Increased capital costs resulting from lower rearing density, smaller facilities, and operation in more remote locations
- Increased potential for flooding, ice, and snow damage (increased variability in production)
- Increased use of heating and chilling to adjust development times
- Production of smaller numbers of higher quality fish
- Increased adult return

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Bull. Natl. Res. Inst. Aquaculture, Suppl. 1: 139–144 (1994)

# THE CHANGE OF BEACH PROFILE AND THE DISTRIBUTION OF SANDY BEACH BIVALVES

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## ABSTRACT

In the surf zone, most of the organisms are influenced by sediment movement. The change of beach profile and distribution of bivalves on a sandy beach were studied at the Hasaki Oceanographical Research Facility belonging to the Port and Harbor Research Institute. Since December 1986, the beach profile has measured by lead soundings diurnally, and the sediment has been sampled with the Smith-McIntyre grab along the beach platform at monthly intervals. These samples were analyzed for particle size and the macrofauna. The number and shell length of bivalves at each station were then recorded. Five main species were collected there. *Chion dysoni semigranosus* were distributed near the shore line. *Meretrix lamarckii* and *Gomphina melanaegis* tended to distribute on the bar and the trough, respectively. *Tentidonax kiusiuensis* were distributed in both the bar and the trough. *Mactra crossei* distributed in the farthest offshore zone. They divided into three zonated groups. *M. lamarckii* and *G.melanaegis* seem to migrate offshore to onshore and then back to offshore according to their growth. While most of bivalves were collected in fine sediment, *G.melanaegis* was often collected in coarse sediment.

## INTRODUCTION

The length of coastline in Japan is about 34,000 kilometers, and natural exposed sandy beaches form along 12 percent of them. Recently, it was recognized that sandy beaches are more productive and their ecological functions are more significant than we previously imagined (Brown and McLachlan 1990). It is important to consider how we conserve the environment of sandy beaches and their aquatic resources, and we manage their fisheries and other developments (industry, recreation, etc.).

Along the Kashima coast in Japan, there are various bivalve species on exposed high-energy sandy beaches, and they include commercially important species. In the surf zone, much sediment movement takes place. Most of the organisms including bivalves are influenced by sediment movement. However, it is difficult to investigate the ecology of a sandy beach, because severe sea conditions prevent us from measuring the physical environment and sampling the organisms. For this reason, only a few studies about the distribution of sandy beach bivalves have been performed in Japan.

The Port and Harbor Research Institute, Ministry of Transport constructed a research pier, also known as the Hasaki Oceanographical Research Facility (HORF). A collaborative study about the relationship between the physical environment and the ecology of sandy beach was started in 1986 by the National Research Institute of Fisheries Engineering and the Port and Harbor Research Institute. Sediment sampling and the measurement of physical environment were carried out at the HORF. The purpose of this study is to clarify the relationship between sand movement and the distribution of bivalves. We will consider if there is a way to control the environment of sandy beaches and increase bivalve resources.

## MATERIALS AND METHODS

From December 23, 1986, to December 16, 1987, the sediment sampling was performed 12 times at the HORF at approximately monthly intervals. The research site, the HORF, is located in sandy shores facing the Pacific Ocean (Figure 1), where the warm and cold currents clash. Most of the coast is a sandy beach, except the Kashima Port.

Total length of the HORF is 427 m, and the 392 m pier juts out into the surf zone (Figure 2). The pier

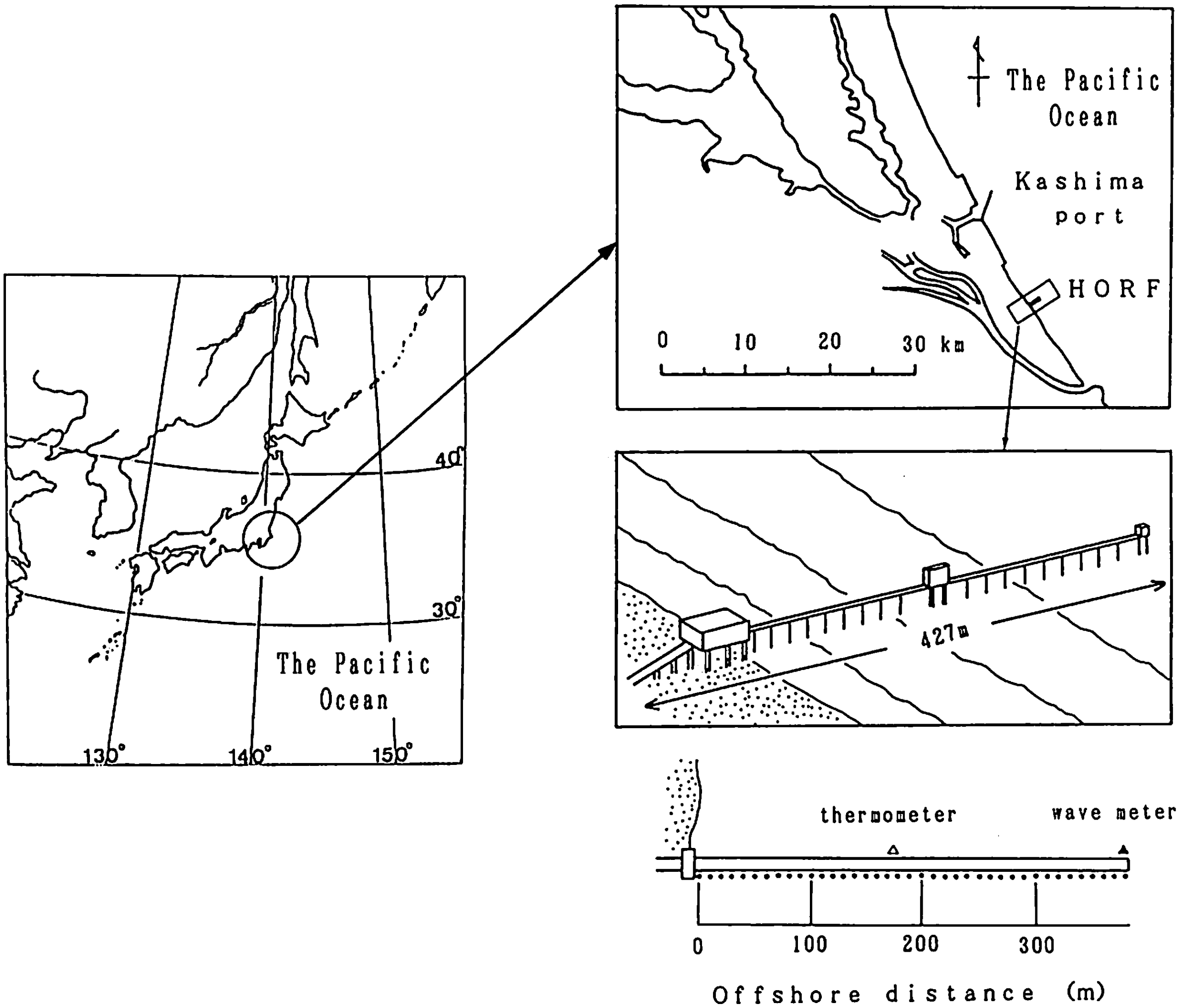


Figure 1. Study site along the Hasaki coast, Japan. The coast consists of exposed sandy shores facing the Pacific Ocean. Location of Hasaki Oceanographical Research Facility (HORF), water temperature meter and wave gages, and sampling stations of bottom sediments ( • ) are shown.

deck is 2.5 m wide and 7 m above the low water level. Average water depth at the tip of the pier is about 5 m. So, it is safe enough to work there without overtopping waves even in severe conditions.

On the pier deck, the stations are marked with paint at a space of 5 m. Thus the stations 0 m and 385 m mean the base and the tip of the pier, respectively.Beach profiles were measured at intervals of 5 m once a day by casting a lead line. The measurements were performed by the staff of the Port and Harbor Research Institute, and they provided these data. The levels were represented by D.L.m (D.L. 0 m means nearly low water level).

Bottom sediments along the pier were sampled at intervals of 10 m once a month using a Smith-McIntyre grab covering an area of 0.05 $m^2$ (Figure 3). The samples were picked up singly at each station. Dry sieving was adopted as particle size analysis, and the median particle diameter of every station was calculated. After initial sieving with a 0.5 mm mesh stainless screen, the samples of benthic organisms were preserved in 5% solution of formalin and they were separated from the sand particles. Then the bivalves were identified and the shell length was measured.

## RESULTS AND DISCUSSION

Five main bivalve species were collected at HORF. *Chion dysoni semigranosus* (Donacidae) is a very rapid burrower and inhabits near the shore line; the maximum shell length is about 20 mm. *Tentidonax kiusiuensis* is taxonomically similar to the genera *Chion* and *Donax* and maximum shell length is about 10 mm. *Gomphina melanaegis* and *Meretrix lamarckii* (Veneridae) are commercially important for food and reach a shell length of 80 mm and 100 mm, respectively. *Mactra crossei* (Mactridae) is abundant and inhabits the offshore region. The max-

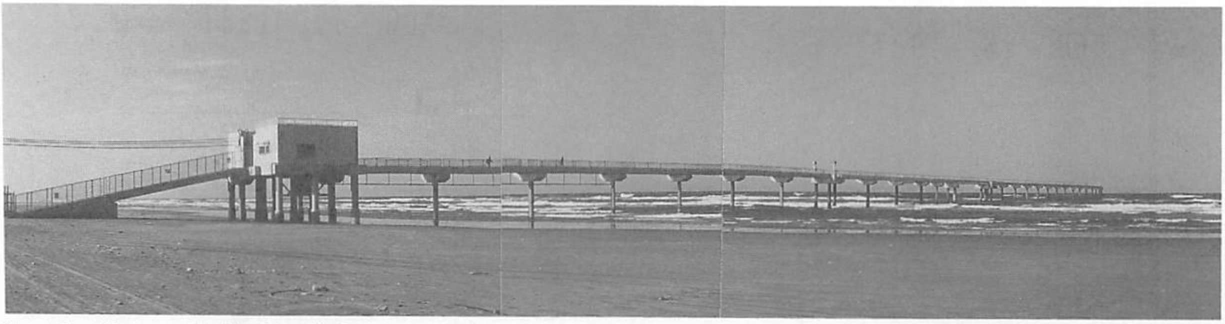

Figure 2. Photograph of the Hasaki Oceanographical Research Facility. The beach slope is flat, and the width of the surf zone is more than 200 m. This is the typical dissipative sandy beach.

Figure 3. Sampling of bottom sediment using the Smith-McIntyre grab hoisted by a crane.

imum shell length is about 25 mm.

Figure 4 shows the distribution of each bivalve in winter as of February 26, 1987. *C. dysoni semigranosus* was distributed near the shore line, *M. crossei* was distributed in the offshore zone, and the others were intermediate. The beach profile has a bar-trough configuration that shows the typical beach type of exposed sandy shores. Most of median particle diameters of bottom sediments ranged from 150 to 200 $\mu$m, but the sediment tended to be coarse in the trough area. *M. lamarckii* tended to be distributed in the fine sand area on the offshore side of the bar. *G. melanaegis* tended to distribute in the coarse sand of the trough. The example in summer, August 11, 1987, shows a similar distribution pattern as in winter (Figure 5). From these results, there seems to be a correlation between the zonation of these bivalves for each species and the relationship between distribution and topography.

In order to understand the zonation of the bivalves numerically, complete data from 468 samples were provided for statistical examination. The averages and standard deviations were calculated for offshore distances, bottom levels, and median diameters of sand particles for each of the five species. Each section was divided every 10 mm in shell length for *M. lamarckii* and *G. melanaegis*. The formulas are shown as follows.

Average distribution distance $= \sum n_i d_i / \sum n_i$
Average distribution level $= \sum n_i l_i / \sum n_i$
Average distribution diameter $= \sum n_i D_i / \sum n_i$

$n_i$ = iindividuals/0.05 m$^2$ at each station, $d_i$ = offshore distance(m) at each station, $l_i$ = bottom level(m) at each station, and $D_i$ = median diameter ($\mu$m) of sand particles at each station. Additionally, the 95% confidence intervals were calculated from the standard deviations based on $t$-distribution.

The plots of the average distribution distances and 95% confidence interval of each species are illustrated in Figure 6. *C. dysoni semigranosus* was 53 m from the shore line, *T. kiusiuensis, G. melanaegis,* and *M. lamarckii* was 216, 224, 248 m, respectively. The difference between the distribution distances of *T. kiusiuensis* and *G. melanaegis* was not significant at the 5% level. *M. crossei* was 337 m offshore.

The offshore distance for *M. lamarckii* for those less than 10 mm in shell length was 250 m; those from 10 mm to 20 mm were distributed onshore (200 m); and they went back offshore at larger sizes. *G. melanaegis* showed the same regime as *M. lamarckii* except for those in the 20–40 mm range.

The average distribution levels were similar in distribution to those for distance (Figure 7). *C. dysoni*

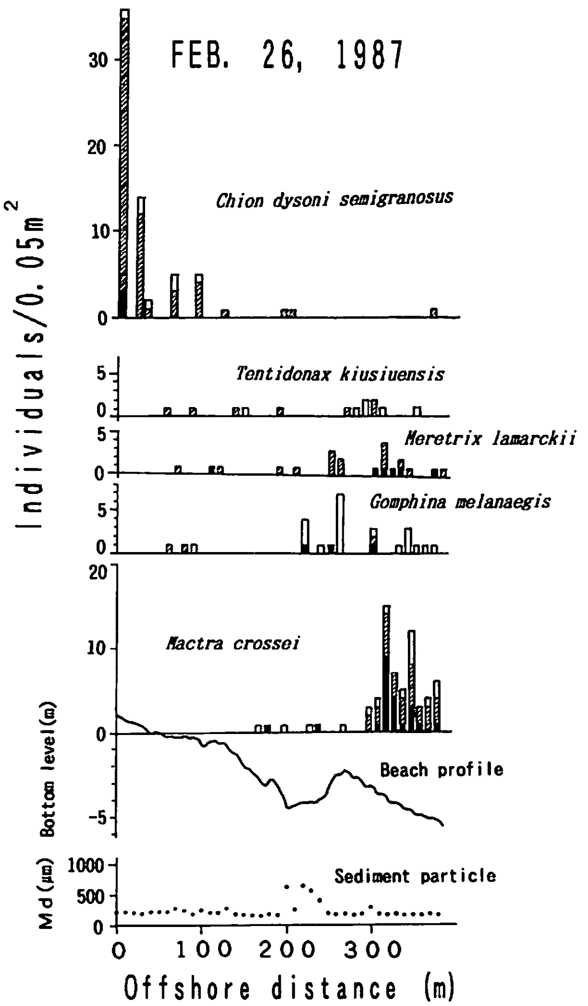


Figure 4. Beach profile (solid line), median particle diameter of sediments (points), and distribution density of bivalves (columns) at HORF on February 26, 1987.
*Chion dysoni semigranosus, Tentidonax kiusiuensis*;
☐ represents shell length≦5 mm; ▨, 5 mm<s.l.≦10 mm; ■, 10 mm<s.l.,
*Meretrix lamarckii, Gomphina melanaegis*;
☐ represents shell length≦10 mm; ▨, 10 mm<s.l.≦30 mm; ■, 30 mm<s.l.,
*Mactra crossei*;
☐ represents shell length≦10 mm; ▨, 10 mm<s.l.≦20 mm; ■, 20 mm<s.l.,

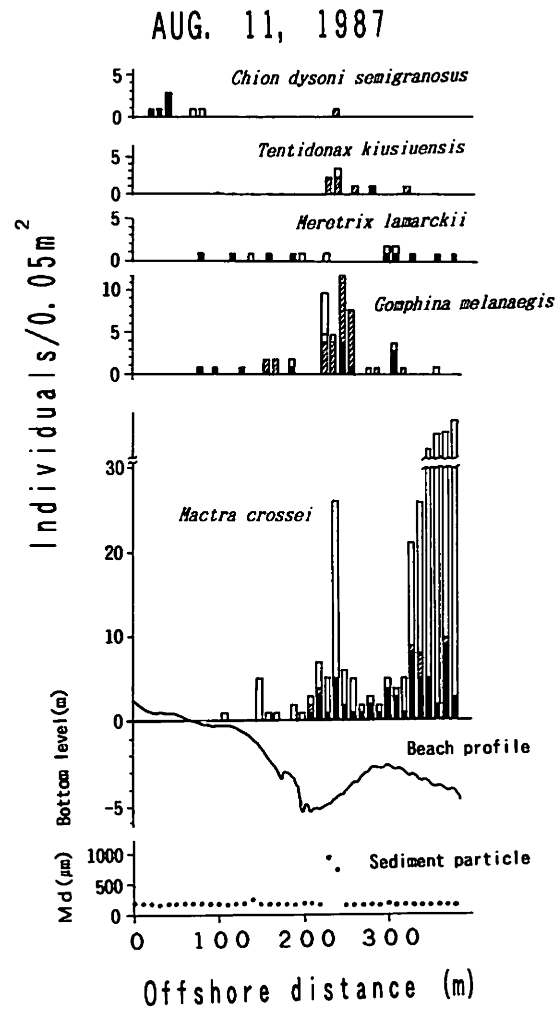


Figure 5. Beach profile (solid line), median particle diameter of sediments (points), and distribution density of bivalves (columns) at HORF on August 11, 1987.
*Chion dysoni semigranosus, Tentidonax kiusiuensis*;
☐ represents shell length≦5 mm; ▨, 5 mm<s.l.≦10 mm; ■, 10 mm<s.l.,
*Meretrix lamarckii, Gomphina melanaegis*;
☐ represents shell length≦10 mm; ▨, 10 mm<s.l.≦30 mm; ■, 30 mm<s.l.,
*Mactra crossei*;
☐ represents shell length≦10 mm; ▨, 10 mm<s.l.≦20 mm; ■, 20 mm<s.l.,

*semigranosus* were distributed in the upper level (−0.12 m D.L.); *T. kiusiuensis* (−2.63 m D.L.), *M. lamarckii* (−3.08 m D.L.), and *G. melanaegis* (−3.30 m D.L.) were in the medium level; and *M. crossei* distributed lower (−4.27 m D.L.). The only difference between the level of *M. lamarckii* and *G. melanaegis* was not significant at the 5% level.

Changes in the average distribution level of *M. lamarckii* and *G. melanaegis* showed very similar patterns to the average distribution distance. But the range of level difference of *G. melanaegis* was about three times greater than that of *M. lamarckii.*

Figure 8 showed the plots of the average distribution diameters of the sediments. *C. dysoni semigranosus, M. lamarckii,* and *M. crossei* were found in sediments less than 200 µm, and *G. melanaegis* was found in sediments larger than 300 µm. Sediment diameters are depending on offshore distances and water depth. Whereas young M. lamarckii of less than 10 mm in shell length tend to distribute in slightly coarser sediments (270 µm), *G. melanaegis* of less than 20 mm distribute remarkably in much coarser sediments (400–570 µm). Larger *M. lamarckii* and *G. melanaegis* are found in fine sand.

From the calculations of average distances and aver-

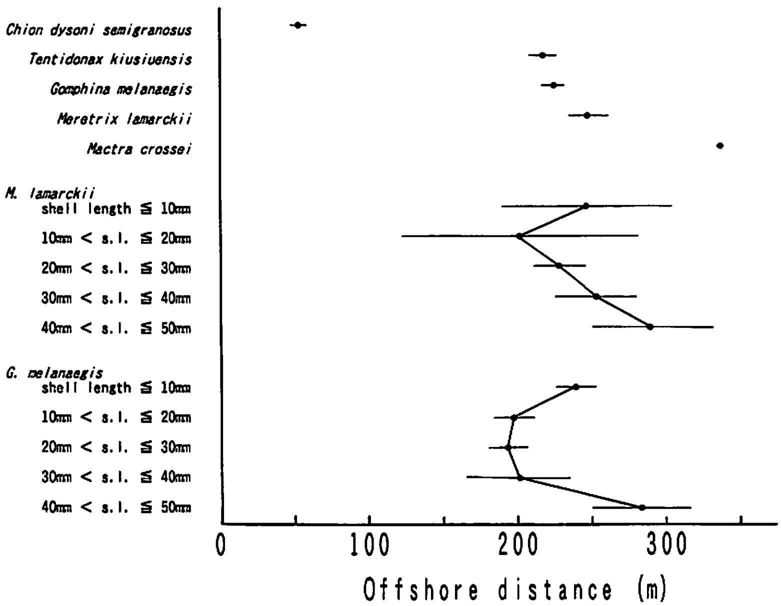


Figure 6. Average distribution distances for each bivalve species and each section (divided every 10 mm in shell length) of both *M. lamarckii* and *G. melanaegis*. Horizontal bars represent 95% confidence intervals based on the *t*-distribution. The difference between *T. kiusiuensis* and *G. melanaegis* is not significant at the 5% level in Welch's *t*-test.

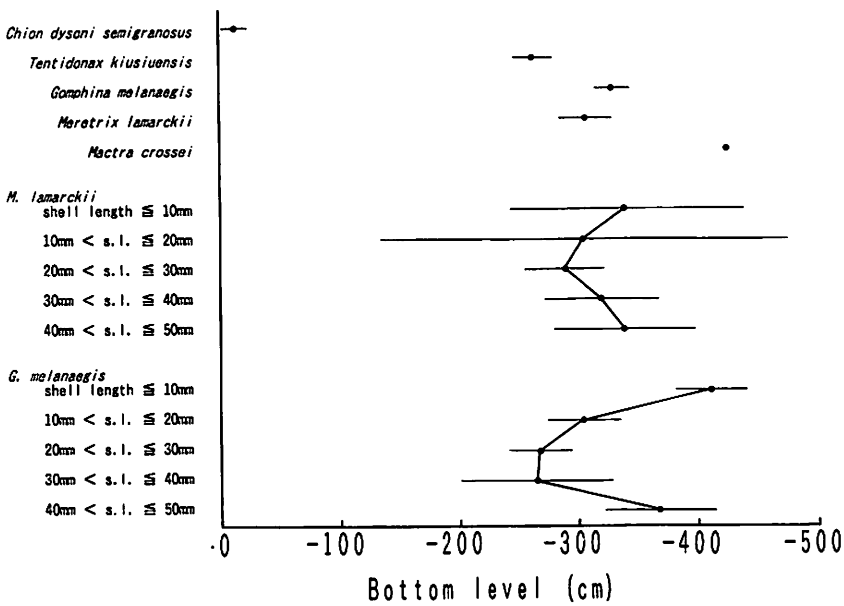


Figure 7. Average distribution bottom levels for each bivalve species and each section (divided every 10 mm in shell length) of both *M. lamarckii* and *G. melanaegis*. Horizontal bars represent 95% confidence intervals based on the *t*-distribution. The difference between *M. lamarckii* and *G. melanaegis* is not significant at the 5% level in Welch's *t*-test.

age water depth, five bivalve species were divided into three zonated groups: onshore group, intermediate group, and offshore group. This may correspond to three faunal assemblages in swash, breaker, nearshore zones (Freischack and de Freitas 1989).

However, regarding the distribution diameter, each species of the intermediate group was quite different. I believe that the difference was caused by the relationship between characteristics of bivalves (shapes, specific gravities, burrowing speeds, etc.) and the physical environment of beaches (wave, sediments, water temperature, etc.) (Higano et al. 1993a, b).

The changes in distribution of *M. lamarckii* and *G. melanaegis* seem to be onshore-offshore and vertical. This migration may not be active; if anything, it might be passive migration as the result of movement by wave. Moreover, while the distances and the levels of larger shells were close to the younger shells, the results of median diameter of sediments didn't correspond with them. So, in the future, it is necessary to investigate the mechanism of their migration.

On the other hand, the tidal migration of *C. dysoni*

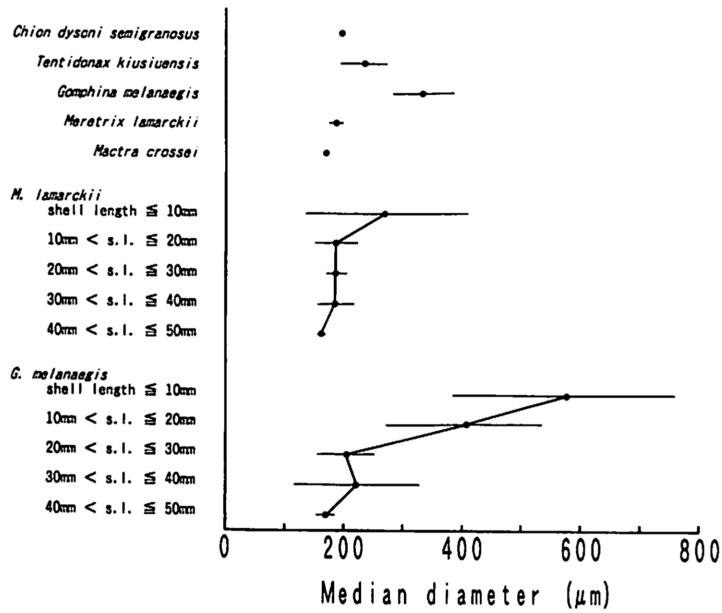


Figure 8. Average distribution median particle diameter for each bivalve species and each section (divided every 10 mm in shell length) of both *M. lamarckii* and *G. melanaegis*. Horizontal bars represent 95% confidence intervals based on the *t*-distribution. The differences between *M. lamarckii* and *C. dysoni semigranosus* and between *T. kiusiuensis* and *C. dysoni semigranosus* aren't significant at the 5% level in Welch's *t*-test.

*semigranosus* is known, as well as that of *Donax* spp. (Mori 1938; Mori 1950; Turner and Belding 1957), and the burrowing speed of them is superior to their movement by wave action. The mechanism of forming zonation in this species is different from other species.

## SUMMARY

The results of this study are as follows:

1. The zonation of sandy beach bivalves was observed, and it was concluded that three zonated groups were formed by wave action and physical characteristics of shells and their behavior.
2. Young *M. lamarckii* and *G. melanaegis*, less than 10 mm in shell length, distributed offshore at a deeper level in coarse sands. According to growth, they migrate to onshore and then to offshore later.

## ACKNOWLEDGMENTS

This study was a result of the collaboration with the Port and Harbor Research Institute, and I greatly appreciate their staffs who helped us with sampling and provided the data for the physical environments. I think it is very important for engineers and biologists to cooperate for an interdisciplinary approach.

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# WATER QUALITY IN A NURSERY POND CONSTRUCTED ON A SANDY BEACH

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## ABSTRACT

A nursery pond(1200 $m^2 \times 1$ m) for Japanese flounders, *Paralichtys olivaceus*, was constructed on a sandy beach. The pond utilizes wave energy for sea water exchange through an inlet with a submerged dike and an outlet opening to the sea. The water qualities in it are changeable, according to hydrographic and atmospheric conditions. Therefore, forecasting the water quality changes is most important in designing this type of nursery pond.

A field investigation to clarify the water quality changes and make some calculations about dissolved oxygen (DO) budget were carried out. The inflow rate varied from 130 to 340 $m^3$/hr with the sea level and wave height during the measurement. The DO level fluctuation in the pond was wider than that in coastal waters. The DO level fell to 60% saturation at around 6 a.m. under the closed condition of the inlet. The total DO consumption rate was estimated to be 0.162 mg/l/hr from the DO budget equation. About 60% of that was due to the organisms and chemicals suspended in the water, about 20% was due to the flounders, and the remainder was due to the sediment.

## INTRODUCTION

At present, the seed production system of the flounders has been established in many hatcheries. In 1990, 14 millions juvenile flounders were released in order to increase the natural population (Fisheries Agency and Japan Sea-Farming Association 1992). Nevertheless, the amount of catches are still small. Thus various field experiments have been done to raise the survival rate. They proved that making the release size larger is more efficient to increasing the rate in their early life histories. Several years ago, the flounders that had grown up to 30 mm in body length had been released. Now the sizes are 50 or 60 mm. Still the rate of recovery is not sufficient.

Just after being released, juveniles that had been reared generally couldnot acquire enough ability in motion to survive. Hence they are easily caught by predators or often starve to death because they couldnot catch mysids (Aomori Prefectual Aquaculture Center and Aomori Prefectual Fisheries Experimental Station 1984). From these facts, not only the size of juveniles but also the quality has become regarded as important in the last few years.

Recently it was made clear by experiments that rearing juveniles under natural-like conditions with low rearing density for a period of time is efficient to improving their qualities (Shizuoka Prefectual Fish Farming Center and Shizuoka Prefectual Fish Experimental Station 1990; Miki et al. 1992). The low rearing density is that the bottom area that flounders occupy is under 10%, the period is about 1 week long, and natural condition include hydraulic, bottom material, and feed condition. During this period it is possible for them to become acclimated to the natural conditions.

Generally, retention nets or fish tanks are used during this period, which have some disadvantages. For example, the former are easily broken by tidal current and waves and are difficult to set up and manage. With the latter, flounders have to be reared under high density because of the limited bottom area, and moreover maintenance expenses are high.

Being confronted with such disadvantages, a new facility was proposed. This was a pond (1200 $m^2 \times 1$ m) that utilizes wave energy for water exchange. It was constructed on the sandy beach in Udani district, Tomari village, Tottori prefecture. In this project, 150,000 juvenile flounders with a body length of 30 mm were released into the pond. After acclimation, 100,000 individuals at 50 mm length were expected to be released to the sea. It is assumed to take about 1 month and planned to be completed in two cycles by early summer. For the first 20 days of a month, juveniles are reared in a net-surrounded portion in the pond. The main purpose is to raise juveniles with controlled feeding. The last 10 days they are acclimated to the natural conditions. The net is removed on the first day of this period, and the juveniles scatter all over the pond, which decreased the density, and allowed them to feed on mysids. Gradually they acquire the ability to survive.

Water qualities in the pond constructed on a sandy beach are more changeable than those in a retention net because of hydrographic and atmospheric conditions. Therefore, forecasting the water qualities is important to designing this type of nursery pond. The water temperature, salinity, and dissolved oxygen (DO) are especially important features to monitor. We are presently working on a numerical model for forecasting the water quality changes in a nursery pond.

In this paper, the authors focus on DO as the water quality, and will describe our field experiments and some calculations about DO budget in the pond.

General Characteristics of the Pond Constructed on a Sandy Beach

For constructing a nursery pond on a sandy beach, its location depends on the conditions. General characteristics are itemized as follows (also see Figure 1).

In the case of constructing it in the sea:

- Sea water easily flows in.
- It is difficult to remove predators completely.
- It is affected by sand drift.
- The breakwater costs are high.

On the other hand, in the case of constructing it on the shore:

- Sea water has difficulty flowing in.
- Coastal underground water may ooze.
- It is affected by wind-drift sand.
- The pond size is restricted by the shore configuration.

Moreover, characteristics also depend on the pond configuration. For example, if the pond is long along the shore line, the cost of the breakwater become expensive. If the pond is long across the shore line, dead water regions appears.

Configuration of the Pond

To decrease the maintenance expense, we should consider the use of natural energy to exchange sea water in the pond. Generally, tide, tidal currents, nearshore currents, and waves are the main natural energies we could use. The field study made clear that wave energy is outstanding from the standpoint of quantity. Therefore, wave energy was selected for this project.

The schematic diagram of the pond is shown in Figure 2. It is surrounded by sheet piles. It was designed with other considerations. In the first place, we attached importance to the ease of getting sea water inflow. But constructing it in the sea is much more expensive. Therefore, it was decided that half of the pond would be constructed in the sea and the other half would be on the shore. A depth of 1m accommodates the natural habitat of flounder juveniles and prevent birds from preying on them.

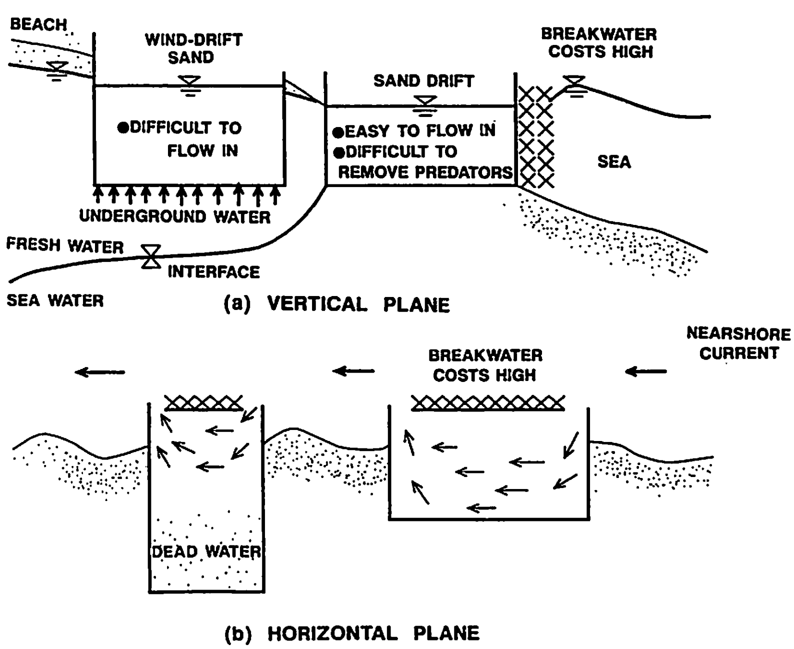


Figure 1. Schematic diagrams of the characteristics of a pond on a sandy beach. (a) shows the differences caused by the pond location against the shoreline. (b) shows the differences caused by the configuration of the pond.

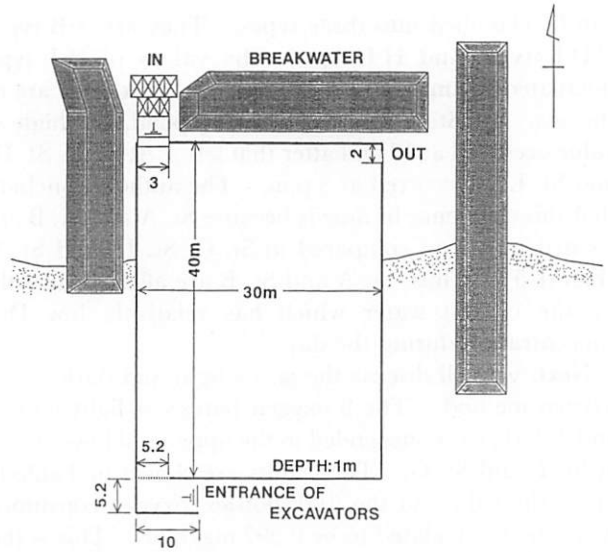


Figure 2. Schematic diagram of the nursery pond (1200 $m^2 \times 1$ m) on a sandy beach, Udani area, Tottori prefecture. Half of the pond was constructed in the sea and other half on the shore. The pond is surrounded by sheet piles.

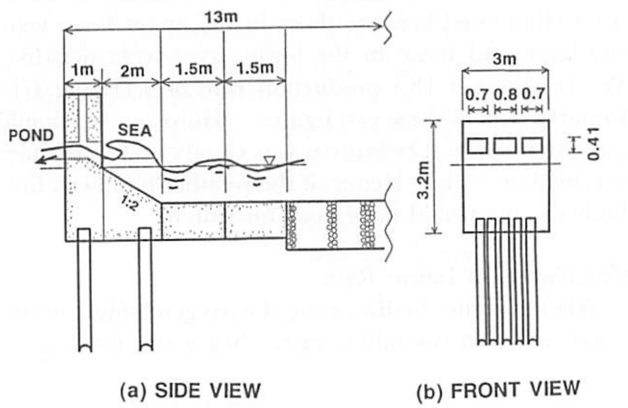


Figure 3. Schematic diagrams of the inlet. Waves break on the submerged dike and flow into the pond through three holes.

The schematic diagram of the inlet is shown in Figure 3. It is composed of a submerged dike with 1 : 2 slope and three holes with a gate. Waves approach from the right and break on the submerged dike. Then, sea water is transported toward the traveling direction of the wave and flows in through three holes.

Results of the Field Experiment

A field experiment was carried out June 8–11, 1992. Figure 4 shows the measured points. Water level was measured at St. A. The flow speed was measured at St. F and St. G, salinity was measured at St. A, St. B, St. C, St. D, St. E, and St. I. Water temperature and DO were measured at St. A, St. B, St. C, St. D, St. E, St. H, and St. I. At St. A, St. B, St. C, St. D, and St. E, the water qualities (i.e. salinity, water temperature, and DO) were measured at two depths, 10 cm below the surface and 10 cm above the bottom. The pond was not stratified during the measurement; therefore, the values obtained at the two depths were averaged. *In situ* light and dark bottle oxygen methods were done at St. J and St. K. The mesh region is the rearing area which is surrounded by nets for the first 20 days.

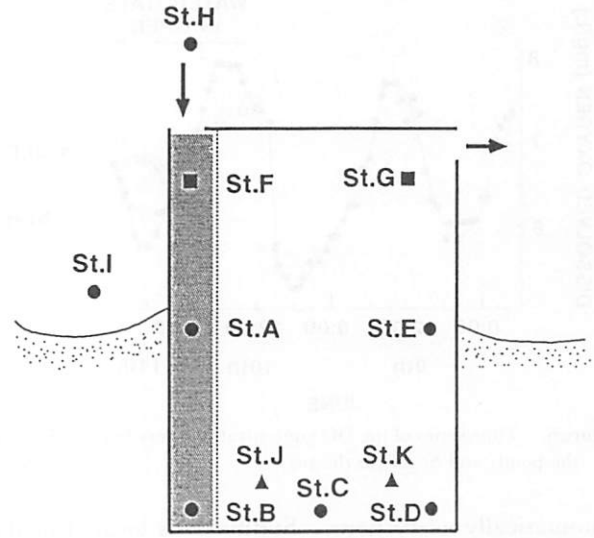


Figure 4. Map of the measured points: water temperature, salinity, DO, current velocity, and *in situ* light and dark bottle oxygen method.

Figure 5 shows the result of the dye diffusion study. The dotted lines represent time series of the edge of the dye diffusion region. The arrows denote flow direction. Sea water coming from the inlet to outlet generally creates a recirculating flow pattern in the pond. At the center of the circulation, the mesh region in Figure 5, carcasses of flounders and algal drift were accumulated.

Figure 6 shows the DO changes being measured

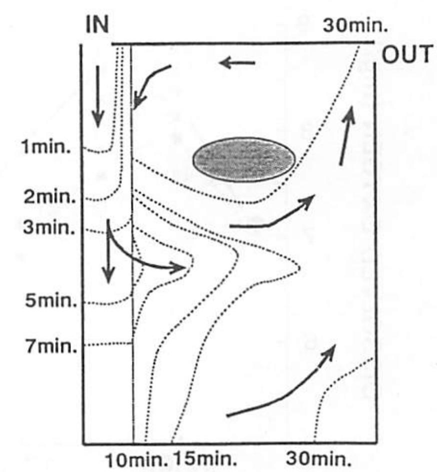


Figure 5. Results of dye diffusion study. The dotted lines represent the time series of the edge of dye diffusion regions. Arrows mean flow direction. Mesh region is the center of the vortex where carcasses of flounders and algal drift accumulated.

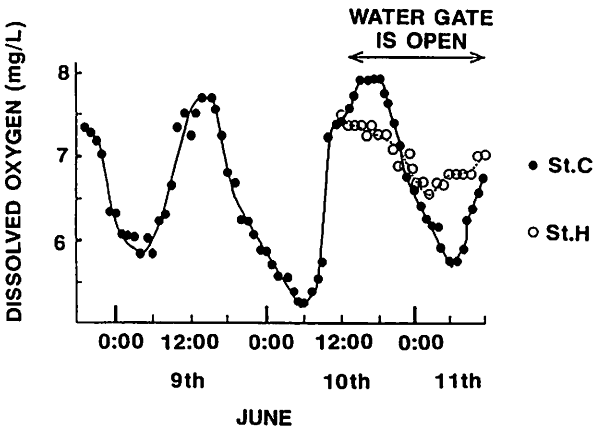


Figure 6. Time series of the DO concentration every hour at St. C (in the pond) and St. H (in the sea).

automatically every hour. Station C is located in the pond, and St. H is in the sea (Figure 4). For 24 hours from midday on 10th, one of the three holes of the inlet was opened. During other times, they were shut, because too much sea water flowed into the pond when the wave height was over 50 cm. The lowest value occurred around 6 a.m. each day, and the DO level fell to 60% saturation at 6 a.m. on 10th. Flounders may be in danger in this situation. On the other hand, the DO level rose to about 110% saturation at 3 p.m. on the same day. The range of fluctuation at St. C is wider compared to that at St. H. This presumably is caused by the difference in phytoplankton density. The density in the pond is considered to be higher than that in the coastal water.

Figure 7 shows the changes of DO at St. A, St. B, St. C, St. D, St. E, St. H, and St. I. The pattern changes can be classified into three types. They are A·B type, C·D·E type, and H·I type. The values of H·I type fluctuated around 7 mg/l, because St. H and St. I are in the sea. At St. A and St. B in the pond, the highest value occurred at 12 and after that fell. At St. C, St. D, and St. E, it occurred at 3 p.m. The authors conclude that this difference in time is because St. A and St. B are located upstream compared to St. C, St. D, and St. E (Figure 5). Thus, St. A and St. B are affected directly by the coastal water which has relatively low DO concentration during the day.

Next, we will discuss the *in situ* light and dark bottle oxygen method. The 8 oxygen bottles, 4 light bottles and 4 dark, were suspended in the upper and lower layer at St. F and St. G. The results are shown in Table 1. From the values in the dark bottles, oxygen consumption rate is calculated to be 0.097 mg/l/hr. This is the average of three bottles values. The value of the lower layer at St. G was eliminated because this was too small compared to the other values. From the values in the light bottles at St. F, the total oxygen production rate is calculated to be 0.015 mg/l/hr. The values of St. G were eliminated because those in the upper layer were too large and those in the lower layer were negative. We get the net DO production rate of 0.112 mg/l/hr from the sum of these two figures. However, we should pay attention to it because it was cloudy and sometimes it rained on 11th. Hence, if the weather had been fine, higher value would have been measured.

Calculation of Inflow Rate

When it comes to discussing the oxygen budget in this pond, we need the inflow rate. Sea water flows in an

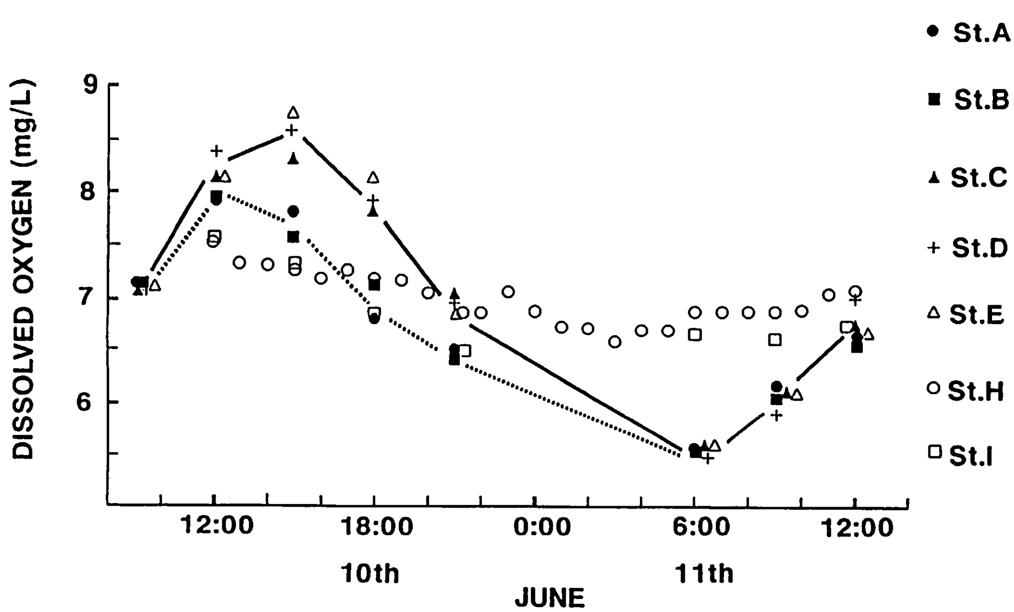


Figure 7. Time series of the DO concentration. Values in the pond are the averaged values of the upper and lower layer.

unsteady jet from the inlet; therefore, it is difficult to measure. This time we applied these expressions to estimate it. They are experimental equations. The derivation process of them was described in detail elsewhere (Yamamoto et al. 1988).

$$\eta = 0.1782\,(h_c + H) \quad (1)$$

and

$$Q = [0.18\sqrt{2g\eta}\,(\eta + h_c) + 0.03h\sqrt{2g\eta}]\,B \quad (2)$$

where

$\eta$: set-up,
$h_c$: water depth above the submerged dike,
$H$: offshore wave height,
$Q$: inflow rate,
$h$: water depth,
$g$: gravity acceleration, and
$B$: length of submerged dike.

From these expressions, the calculated inflow rate varied from 130 to 340 $m^3$/hr during our field experiment.

DO Budget in the Pond

The DO budget equation can be written as follows: where

$$DDO = Q\,(C_{in} - C_{out}) + P_a + P_p - S_f - S_w - S_b, \quad (3)$$

$DDO$: DO change rate in the pond,
$Q$: inflow rate,
$C_{in}$: DO concentration rate of the inflow,
$C_{out}$: DO concentration rate of the outflow,
$P_a$: DO change rate by surface reaeration,
$P_p$: DO production rate by phytoplankton,
$S_f$: DO consumption rate by flounders,
$S_w$: DO consumption rate by organisms and chemicals suspended in the water, and
$S_b$: DO consumption rate by sediment.

Table 1. Result of in situ light and dark bottle oxygen method. Fup, Gup: 10 cm below the surface at St. F, and St. G. Flow, Glow: 10 cm above the bottom at St. F, and St. G.

| | DARK BOTTLES | | | | LIGHT BOTTLES | | | |
|---|---|---|---|---|---|---|---|---|
| St. | Fup | Flow | Gup | Glow | Fup | Flow | Gup | Glow |
| 10th | | | | | | | | |
| 17:40 | 8.16 | 8.24 | | | | | | |
| 18:00 | | | 8.28 | 8.21 | | | | |
| 11th | ↓ | ↓ | | | | | | |
| 5:00 | | | ↓ | ↓ | 5.69 | 5.73 | 5.67 | 5.74 |
| 5:40 | 6.83 | 7.08 | | | ↓ | ↓ | ↓ | ↓ |
| 12:00 | | | 6.76 | 7.73 | 5.78 | 5.85 | 6.01 | 5.64 |
| RATE | −0.11 | −0.097 | −0.084 | −0.004 | 0.013 | 0.017 | 0.049 | −0.014 |
| AVE. | −0.097 mg/l/hr | | | | 0.015 mg/l/hr | | | |

(unit: mg/l, mg/l/hr)

We can estimate these terms from the field data or experimental values, respectively, except the last one ($S_b$). We didn't measure it because the proper method of measurement has not been developed. Its value cannot be estimated theoretically because of the lack of understanding of sediment-water interactions. Therefore, we decided to estimate it with the above expression. We applied it during the period from 9 p.m. on 10th to 6 a.m. on 11th, so the DO production rate by phytoplankton ($P_p$) could be eliminated.

About the term ($DDO$) on the left side of the equation, DO concentration was reduced by 1 mg/l from the field data (Figure 7). Hence, its rate is 0.11 mg/l/hr.

About the first term ($Q(C_{in} - C_{out})$) on the right side, the inflow rate was calculated to be 160 $m^3$/hr. The DO concentration of the inflow was 6.6 mg/l measured at St. H and that of outflow was 6.25 mg/l as the average value of St. E which was near the outlet. Therefore, we calculated 0.039 mg/l/hr.

The second term ($P_a$) is the DO change rate by surface reaeration. This value is calculated by the expression which is in proportion to the oxygen deficit. Its proportion constant, that is the reaeration coefficient, depends on the wind speed, surface roughness, current velocity, and so on. Hence, it has not been formulated definitely. However, some empirical or experimental expressions have been proposed. In this study, the authors used these expressions that were formulated as a function of wind speed by Mackay and Yeun(1983). The equations are as follows:

$$N = K(DO^* - DO) \quad (4)$$

$$K = 1.0\times10^{-6} + 34.1\times10^{-4}U^*\,S_{CL}^{-0.5} \quad (U^* > 0.3) \quad (5)$$

$$= 1.0\times10^{-6} + 144\times10^{-4}U^{*2.2}\,S_{CL}^{-0.5} \quad (U^* < 0.3) \quad (6)$$

and

$$U^* = (6.1 + 0.63\,U_{10})^{0.5}U_{10} + 10^{-2}, \quad (7)$$

where

$N$: rate of transport,
$K$: reaeration coefficient,
$DO^*$: saturated DO concentration,
$DO$: DO concentration,
$S_{CL}$: schmit number(coefficient of viscosity divided by the coefficient of diffusion: nearly equal 500), and
$U_{10}$: wind-speed 10 m above the ground.

During our field experiment, the average wind speed was about 2 m/s. Hence, using the above equations, we calculated 0.013 mg/l/hr of $P_a$.

The fourth term ($S_f$) is the DO consumption by flounders. There have been many publications on the oxygen consumption of various kinds of fish; few reports, however on the juvenile Japanese flounders (Morioka 1985, Higano and Yasunaga 1986, Kikuchi et al. 1990). All of these papers reported the value when flounders were resting. What we want to know is the value during activity. Among the reported data and the experimental data of Tottori Prefectual Fisheries Experimental Station, we selected 500 mg/kg/hr as a proper value. During our field experiment, 120,000 flounders that were 40 mm in body length had been reared. The relation between body weight ($W$:g) and total length ($L$:mm) is expressed as follows (Kato 1985):

$$W=1.35113\times10^{-5}\times L^{2.88984} \qquad (8)$$

The total weight of 120,000 flounders is calculated to be 69.1 kg. Therefore, the DO consumption rate by flounders is calculated to be 0.034 mg/l/hr as a whole.

The fifth term ($S_w$) is the DO consumption by organisms and chemicals suspended in the water. From the values of the dark bottles, we calculated 0.097 mg/l/hr.

We substitute these values into the DO budget equation and solve it for the last term ($S_b$). We get 0.031 mg/l/hr. It is noted that this value may include the error with the estimation of other terms. However, we cannot discuss it in more detail from our field data. Therefore, it is regarded as the DO consumption rate by sediment. It is converted to 37.2 mg/m$^2$/hr in the general expression of unit.

Concerning the DO consumption rate by sediment, some reports have been published. For example in the Nomi Bay, Kouchi prefecture in Japan, where aquaculture is prosperous, it is 10.8 mg/m$^2$/hr at 21°C and 14.2 mg/m$^2$/hr at 27°C. At an aquaculture ground for young yellowtails where water exchange depends on tide, the DO consumption rate by sediment is 53 mg/m$^2$/hr at 19.5°C and 70 mg/m$^2$/hr at 27°C. The value we calculated from the DO budget equation is between those values. Therefore, it is considered that this value is not inadequate. The sea water exchange rate in this pond is greater than that in a pond that depends on tide only. Therefore, the sediment is decomposed more easily and flushed to a certain extent. But as long as feeding is continued, the DO consumption rate is greater in general. Hence, we should recognize that the DO consumption rate by sediment is not the fixed value.

The DO consumption rate by all processes in the pond, "whole pond respiration," is estimated at 0.162 mg/l/hr. This is the sum of those three figures ($S_f$: 0.034 mg/l/hr, $S_w$: 0.097 mg/l/hr, $S_b$: 0.031 mg/l/hr). About 60% of that is due to the organisms and chemicals suspended in the water, about 20% is due to the flounders, and the rest is due to the sediment.

Using the "whole pond respiration," we can calculate easily how much inflow rate is needed. For example, DO concentrations were supposed to permit a decrease of 1 mg/l during the night for 10 hours. From this calculation, we can get the 220 m$^3$/hr inflow rate that is needed.

$$1/10=Q\times(6.6-6.25)/(40\times30\times1)-0.162$$

and

$$Q=220\ \text{m}^3/\text{hr}.$$

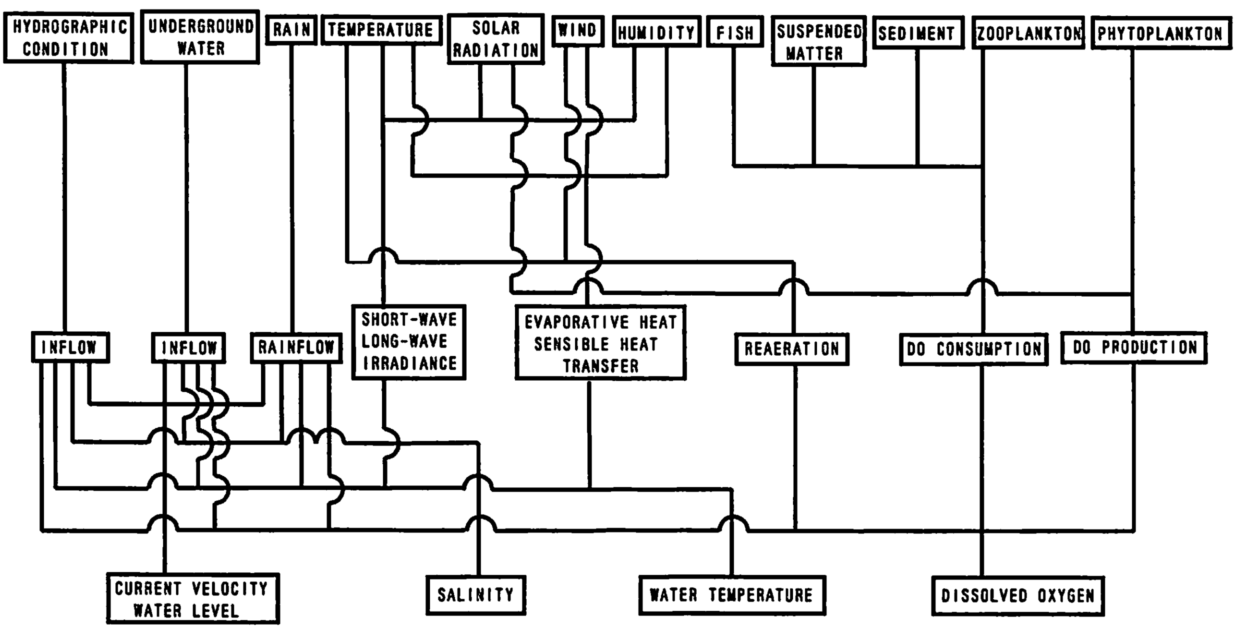


Figure 8. Diagram of the numerical model for forecasting the changes in water qualities in a nursery pond.

This is the primitive method to decide the minimum inflow rate.

Numerical Model for Forecasting Water Qualities in a Nursery Pond

In designing this type of a nursery pond, the inflow rate is the most important factor. To decide it, the changes of the water qualities in the pond should be forecasted. Hence, we made a numerical model for forecasting the change of water qualities in nursery ponds according to hydrographic, atmospheric, and rearing conditions (Fujihara et al. 1991; Fujihara et al. 1992). The diagram of the model is shown in Figure 8. The components in the top line are input parameters, and those in the bottom line are state variables: current velocity, water level, water temperature, salinity, and dissolved oxygen. The details are described elsewhere (Fujihara et al. 1991).

## CONCLUSION

A field study was carried out to make clear the changes of water qualities in a nursery pond for Japanese flounders. From the results, the following conclusions are obtained:

(1) The inflow rate varied according to sea level and wave height. During the measurement, it varied from 130 to 340 $m^3$/hr when one of three holes of the inlet was open.

(2) Sea water coming from the inlet to outlet generally creates a recirculating flow pattern in the pond.

(3) The DO level fluctuation in the pond is wider compared to that in the coastal water. This is caused by the difference between phytoplankton density between in the pond and in the coastal water.

(4) The lowest value occurred at around 6 a.m. every day during the measurement.

(5) The DO level fell to 60% saturation at around 6 a.m. when the inlets were closed.

(6) The DO consumption rate by all processes in the pond, the "whole pond respiration," is calculated at 0.162 mg/l/hr.

(7) About 60% of the "whole pond respiration" is due to the organisms and chemicals suspended in the water, about 20% is due to the flounders, and the rest is due to the sediment.

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# MODELING PRODUCTION CAPACITY OF AQUATIC CULTURE SYSTEMS UNDER FRESHWATER CONDITIONS

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## ABSTRACT

In the design of flow-through systems, it is typically assumed that oxygen is the most limiting parameter. This is correct for single-pass systems without aeration, except for water with alkalinities less than 10 mg/liter (as $CaCO_3$) where metabolic carbon dioxide can reduce the pH below acceptable limits.

As the rearing intensity is increased by the use of pure oxygen or aeration, the build-up of carbon dioxide becomes more important. The build-up of carbon dioxide has three primary effects: (1) increase in dissolved carbon dioxide concentrations, (2) decrease in pH, and (3) reduction in the mole fraction of un-ionized ammonia due to the decrease in pH.

In a closed system with no carbon dioxide removal, the maximum carrying capacity is controlled by pH at low pH's, by carbon dioxide at intermediate pH's, and by un-ionized ammonia at high pH. Under pH's typical of salmonid systems, it is impossible to exceed an un-ionized ammonia criterion. In an open system with 100% carbon dioxide removal, the maximum carrying capacity is limited by un-ionized ammonia computed at the influent pH. Published information on un-ionized ammonia is seriously biased by inappropriate analytical procedures used in the measurement of pH and possible loss of carbon dioxide from the sample. This article is based on Colt and Orwicz (1991).

## INTRODUCTION

Intensification of production increases the concentrations of carbon dioxide, ammonia, fecal solids, and dissolved organic matter. The simultaneous impact of these parameters must also be considered when evaluating the carrying capacity and operation of high intensity production systems. Depending on environmental conditions (which are not well-understood by either biologists or engineers), the addition of oxygen may not increase the carrying capacity.

The purpose of this paper is to develop design procedures for flow-through systems based on water quality criteria, metabolic production rates, and basic water chemistry relationships. Emphasis is placed on fingerling rearing (as opposed to incubation or fry rearing) as this rearing phase requires the most water and space. The relationships developed in this paper should result in the design and operation of more efficient rearing systems.

## MEASUREMENT OF INTENSITY IN FISH CULTURE

Hatchery intensity can be characterized by density (D) or loading (L):

$$D=\frac{M}{V} \qquad (1)$$

$$L=\frac{M}{Q}, \qquad (2)$$

where:

D = density of fish (kg/m$^3$ of rearing unit),

M = mass of fish in rearing unit (kg),

V = volume of rearing unit (m$^3$),

L = loading (kg of fish divided by flow to rearing unit in liters/minute), and

Q = flow to rearing unit (liters / minute).

Cumulative oxygen consumption (COC) is another useful measure of hatchery intensity:

$$COC=\sum_{i=1}^{n} (DO_{in}-DO_{out}), \qquad (3)$$

where

COC = cumulative oxygen consumption (mg/liter),
$DO_{in}$ = influent dissolved oxygen to a rearing unit (mg/liter), and
$DO_{out}$ = effluent dissolved oxygen from a rearing unit (mg/liter).

## HATCHERY DESIGN APPROACHES

As the intensity and complexity of hatcheries have increased, several different design approaches have evolved. Most of the hatcheries built before the 1960's were designed by an empirical approach. Generally, the flow to each rearing unit was held constant, and the hatchery manager moved or planted fish if stress was observed.

Haskell (1955) developed a simple and useful design procedure based on the following assumptions:

(1) Carrying capacity is limited by (a) oxygen consumption and (b) accumulation of metabolic products;

(2) Amount of oxygen consumed and the quantity of metabolic products are proportional to the amount of food fed.

Using these assumptions, Willoughby (1968) developed a design equation for the maximum amount of feed that could be fed based on influent DO, effluent DO, and flow.

Based on experience with multi-pass reuse systems, Westers and Pratt (1977) developed a design procedure based on both oxygen and ammonia limitations. The effects of carbon dioxide on pH and ammonia toxicity was not considered.

## WATER QUALITY CRITERIA

The criteria used in this study:

| Parameter | Value |
|---|---|
| Dissolved Oxygen Criterion (low) | 6.5 mg/liter |
| (high) | 300 mm Hg |
| Dissolved Carbon Dioxide Criterion | 20 mg/liter |
| Un-ionized Ammonia Criterion | 12.5 mg/liter $NH_3$–N |
| pH Criterion (low) | 6.0 |
| (high) | 9.0 |
| Suspended Solids Criterion | 15 mg/liter |

## MATERIALS AND METHODS

The modeling approach used in this work is based on (1) water quality criteria for critical parameters, (2) metabolic characteristics of fish under production conditions, and (3) basic carbonate chemistry. The specific details of the modeling are presented in Colt and Orwicz (1991). The consumption of oxygen and production of metabolic by-products is proportional to feed consumption:

| Parameter | Range | Value Used |
|---|---|---|
| | (kg/kg feed) | (kg/kg feed) |
| Oxygen | −0.20 to −0.28 | −0.25 |
| Carbon Dioxide | 0.26 to 0.39 | 0.34 |
| Total Ammonia Nitrogen | 0.026 to 0.032 | 0.030 |
| Solids | 0.30 to 0.65 | 0.50 |

## PRODUCTION CAPACITY

Because of the dependence of cumulative oxygen consumption on the amount of carbon dioxide retained in the water, the overall production capacity will be presented in terms of the degree of gas transfer across the system boundaries.

## CLOSED SYSTEM (NO TRANSFER OF GASES)

A typical flow-through, single-pass culture system approximates a closed system with no transfer of gases. The maximum cumulative oxygen consumption for a closed system is presented in Figure 1. The available oxygen is assumed to be 90% of saturation. At a given

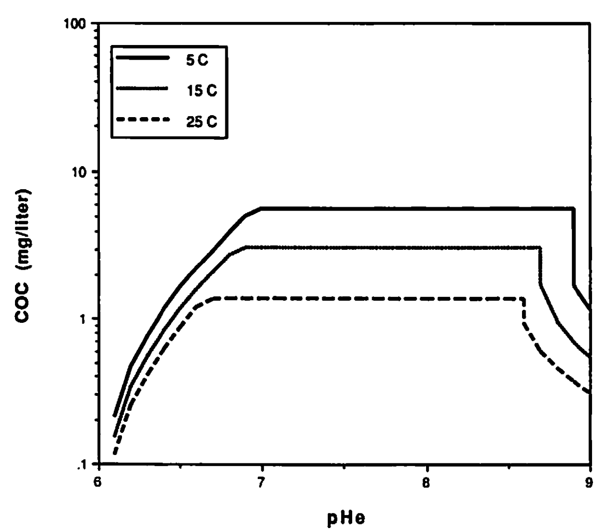


Figure 1. Overall cumulative oxygen consumption for a closed system as a function of equilibrium pH (assumes barometric pressure= 760 mm Hg, influent DO=90% of saturation).

equilibrium pH, the minimum of $COC_{pH}$, $COC_{ammonia}$, $COC_{carbon}$, and $COC_{ss}$ is the limiting COC and therefore controls the amount of oxygen that can be used. This produces the sharp changes in the limiting COC curves at the intersections between different individual COC curves.

The controlling factor depends on equilibrium pH and at 15°C are equal to:

| Equilibrium pH ($pH_e$) | Controlling Factor |
|---|---|
| <6.8 | pH |
| 6.8–8.7 | available oxygen |
| >8.8 | un-ionized ammonia |

Because available oxygen is low, carbon dioxide is not a limiting factor in a closed system. The COC in the three regions increases with decreasing water temperature.

## CLOSED SYSTEM WITH PURE OXYGEN ADDITION

The maximum cumulative oxygen consumption for a closed system with pure oxygen addition is presented in Figure 2. Carbon dioxide removal in pure oxygen aeration systems is minimal due to the low gas-to-liquid ratios used in these systems. The controlling factor depends on equilibrium pH and at 15°C are equal to:

| Equilibrium pH ($pH_e$) | Controlling Factor |
|---|---|
| <7.4 | pH |
| 7.4–8.6 | carbon dioxide |
| >8.6 | un-ionized ammonia |

The COC in the three regions increases with decreasing water temperature.

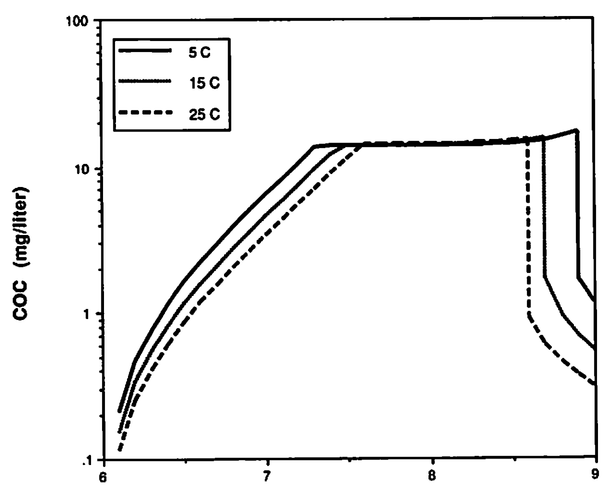


Figure 2. Overall cumulative oxygen consumption for a closed system with pure oxygen addition as a function of equilibrium pH.

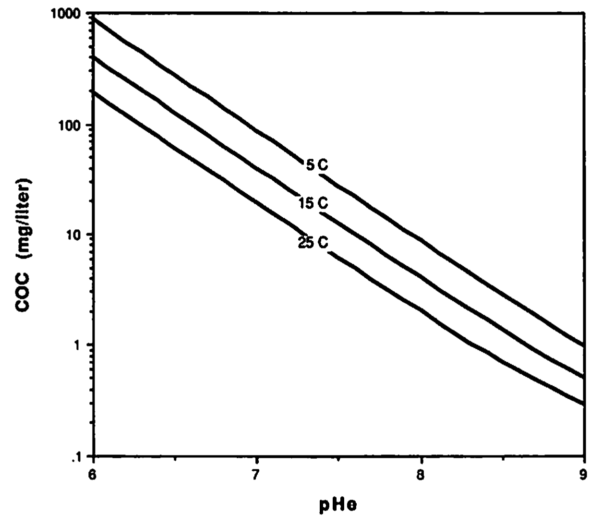


Figure 3. Maximum cumulative oxygen consumption for un-ionized ammonia ($COC_{ammonia}$) as a function of temperature and equilibrium pH (assumes complete removal of excreted carbon dioxide from the water and an un-ionized ammonia criterion equal to 12.5 mg/liter $NH_3$–N).

## OPEN SYSTEM

A serial-reuse culture system with gravity aerators or a transport system with diffused aeration approximates an open system. These types of aeration can effectively remove carbon dioxide, but they will have little impact on ammonia. Because of the removal of carbon dioxide, the pH of the water will not be significantly changed due to metabolic activities. The maximum cumulative oxygen consumption for a open system is presented in Figure 3. The open system is controlled by the un-ionized ammonia criterion computed at the equilibrium pH. The maximum cumulative oxygen consumption is seriously limited at high pH's.

## CLOSED SYSTEM WITH OXYGEN ADDITION AND CARBON DIOXIDE REMOVAL

The use of surface or gravity aerators can greatly increase the amount of carbon dioxide removed from the process water. This system is intermediate between a closed and open system. The overall production capacity is presented in Figure 4 for various degrees of carbon dioxide removal. Increased removal of carbon dioxide increases the maximum COC in the pH and $CO_2$ limited regions but decreases it in the ammonia limited region.

The most limiting water quality parameter in an aquatic production facility will depend on a variety of factors such as equilibrium pH of the water, the degree of carbon dioxide retention, influent DO concentration, and water temperature. Relatively small design and operational factors may have a major impact on the importance of these parameters.

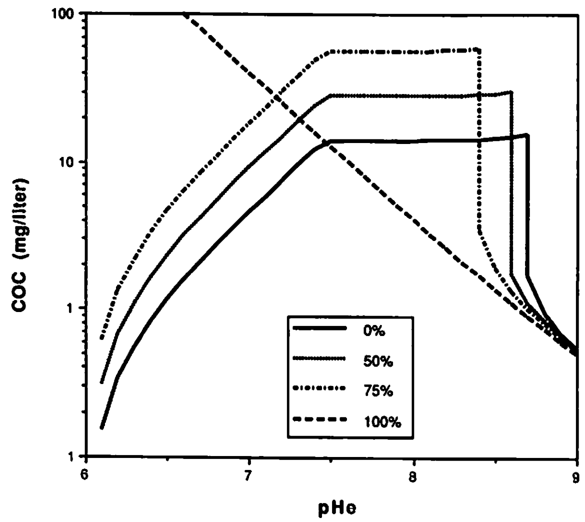


Figure 4. Effect of carbon dioxide removal (%) on overall cumulative oxygen consumption. The solid line is for an open system with 100% carbon dioxide removal (assumes water temperature= 15°C).

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