水研センター研報，第19号，89－96，平成19年
Bull. Fish. Res. Agen. No. 19, 89-96, 2007

Macrobenthos, current velocity and topographic factors as indicators to assess the assimilative capacity of fish farms: Proposal of two indices

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Abstract In order to provide site selection guidelines for fish farming, two indices have been previously proposed based on surveys of the macrobenthos and bottom environments conducted at fish farms in Kumano-nada, central Japan. In this review, these results are summarized, and requisites for determining the limit of maximum fish production are discussed from a standpoint of assimilative capacity of fish-farm environments. An index 'ED' (Embayment Degree) is calculated from the distance from a bay mouth to a fish-farm site, the width of the bay, the water depth of the site and the maximum depth at the bay mouth. Another index, 'ISL' (Index of Suitable Location) is calculated from the water depth and current velocity under a fish cage. Current velocities can be estimated by plaster balls readily and simultaneously at many stations. Biotic and abiotic factors at the fish farms were found to be changed along gradients of fish production and ED or ISL, suggesting that these indices are effective for estimating the assimilative capacity. ED can be used as a simple indicator for the site selection. ISL has a wider potential application to assess the assimilative capacity under a variety of topographical conditions.

KEY WORDS: Fish farm, Assimilative capacity, Current velocity, Environmental criteria, Plaster ball

Introduction

Intensive net-pen fish farming generates large amounts of uneaten food and fish feces. These particulate organic wastes generally settle on the seabed near to the cages. When the accumulation of wastes exceeds the assimilative capacity of the water body, negative effects on the benthic ecosystem such as impoverished infauna and outgassing of hydrogen sulfide often occur (reviewed by Gowen *et al*., 1991; Pearson and Black, 2001). To maintain sustainable aquaculture, it is necessary to assess farm environments objectively, and to conduct cultivation within the range of the assimilative capacity, which is defined as the ability of an area to maintain a "healthy" environment and "accommodate" wastes (Fernandes *et al*., 2001).

The macrobenthos community has often been used as a sensitive indicator for environmental monitoring of organically polluted areas (reviewed by Pearson and Rosenberg, 1978). Assessments of fish-farm environments using the macrobenthos have also been conducted in many countries of the world. These studies have shown that a reduction in species richness and/or species diversity; a decrease in the number of large-sized species; the disappearance of echinoderms; and the appearance of dense populations of the opportunistic polychaete Capitella species (especially species Ⅰ), which often result in an increase in the total macrofaunal abundance, are typical effects of mariculture farming on the macrobenthos (reviewed by Gowen *et al*., 1991; Pearson and Black, 2001).

In Japan, the "Law to Ensure Sustainable Aquaculture Production" (hereinafter referred

2006年 6 月26日受理（Received. June 26, 2006）
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to as "the Law") was established in 1999 to promote the improvement of aquaculture grounds. Based on the Law, environmental criteria for indicating practical goals for the improvement of aquacultural environments were established. In one of these criteria, the macrobenthos was used as a bio-indicator for identifying healthy and critical environments of mariculture farms. This criterion, however, only specifies that the macrobenthos should be alive. A healthy environment is identified in terms of the existence of live macrofauna throughout the year, while a critical environment is identified from azoic conditions during half a year or more. This criterion has limited ecological relevance, however it was pushed through as the criterion is considered convenient in terms of the ease of monitoring by farmers themselves. For the future, a more detailed criterion should be established based on scientific data.

Under aerobic conditions, organic wastes from aquaculture are liable to be incorporated by benthic animals directly or indirectly through the microbial food chain. Increased benthic animals accelerate the oxygenation process of the sediment by their bioturbation activities. Benthic animals may be fed on by predators, resulting in increase of consumer populations in higher trophic levels.

The remineralization of loaded organic wastes by benthic animals begins originally from supply of oxygen, which is controlled by the water flow and/or water exchange between the fish-farm grounds and the surrounding water. Increased current velocities not only increase the oxygen supply (Jørgensen and Revsbech, 1985; Findlay and Watling, 1997) but also reduce the loading of particulate organic wastes per unit area of the seabed due to waste dispersion (Gowen and Bradbury, 1987; Chamberlain *et al*., 2001). Lumb (1989) demonstrated the importance of avoiding sites with low water movement for reducing the risk of environmental deterioration. Water depth under fish cages also potentially has a great effect on the waste dispersion (Gowen and Bradbury, 1987; Hevia *et al*., 1996).

As the assimilative capacity is different from farm to farm depending on the physical components such as the topography and the current velocity, the maximum limit of fish production should be determined for each individual farm. From this point of view, the Law determined another environmental criterion as "acid-volatile sulfide (AVS) should be less than the maximum value of benthic oxygen uptake (BOU) at each fish farm". However, it is difficult to specify the maximum BOU value from the field survey (see Abo and Yokoyama, 2006 in this volume).

In order to assess the assimilative capacity of fish-farm environments, and to provide site selection guidelines, surveys of the bottom environments and macrobenthos were conducted in fish farms in Kumano-nada, Pacific coast of central Japan (Yokoyama *et al*. 2002a, b, 2004). In this review, these results are summarized, and requisites for determining the limit of the maximum fish production are discussed from a standpoint of the assimilative capacity.

Index incorporating topographic factors

Yokoyama *et al*. (2002a, b) conducted a quantitative survey of the macrobenthos in August and September 1998 at 22 fish farms distributed in ten small bays along the coast of Kumano-nada, central Japan, in order to assess the environmental impacts of fish-farm wastes under a variety of topographic conditions and to suggest site selection guidelines for sustainable fish farms. In this area, fish farming has developed steadily since the introduction of yellowtail (*Seriola quinqueradiata*) culture in the early 1960's. Since the middle of the 1970's, a total of 15,000–20,000 metric tons of fish has been annually produced mainly of red sea bream (*Pagrus major*) and yellowtail. In 1998, annual fish production of each farm in this area ranged from 61 to 1,507 metric tons (Tokai Regional Agricultural Administration Office, 1999).

Yokoyama *et al*. (2002a) devised an index "ED" (Embayment Degree) of the topographic situation of a sampling site. When a fish farm is located in a secondary bay whose axis crosses the axis of the main bay at an angle of <90° (Fig. 1), ED is expressed by $ED = (L_1/W_1 + L_2/W_2)(a/Ds)(b/Dm)$, where L_1 is the distance from the mouth of the main bay to the mouth of the secondary bay, L_2 is the distance from the mouth of the secondary bay to the

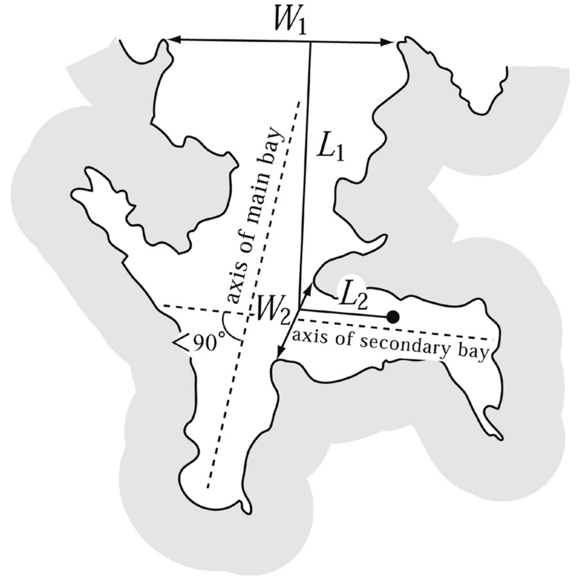

Fig. 1. Parameters for the calculation of ED (after Yokoyama *et al.,* 2002a).

fish-farm site, W_1 is the width of the main bay, W_2 is the width of the secondary bay, *Ds* is the water depth at a sampling site or, if present, the depth of any sill which exists between the site and the bay mouth, *Dm* is the maximum depth at the bay mouth, *a* is the mean depth of all the sampling sites, and *b* is the mean depth of the bay mouths in the study area. Yokoyama *et al.* (2002a) adopted $a = 20$, and $b = 45$ in their case study conducted in Kumano-nada. When a fish farm is located in a secondary bay whose axis crosses the axis of the main bay at an angle of >90°, ED is expressed simply by $ED = (L/W)(a/Ds)(b/Dm)$, where L is the distance from the mouth of the main bay to the fish-farm site, and W is the width of the main bay.

Environmental deterioration does not occur in the deeper offshore areas in Kumano-nada with ED values <2, even if a high production (>1,000 t/yr) of fish is maintained. In fact, within the deeper offshore areas, DO (dissolved oxygen) was usually more than 5 mg/l, and AVS (acid-volatile sulfide) was usually less than 0.6 mg S/g, even for medium- and large-scale farms (fish production, >500 t/yr). Such an undisturbed condition and an enhanced food supply from the fish cages resulted in large macrofaunal biomasses, high densities and high species richness, which were generally encountered >10 g/m^2, >2,000 individuals/m^2 and >30 species/0.04 m^2, respectively. On the other hand, deterioration of the sediment quality (AVS, >1 mg S/g dry), deoxygenation of the bottom water (DO, <2 mg/l) and decreases in biomass (<1 g/m^2), density (<500 individuals/m^2) and species richness (<5 species/0.04m^2) were often found in the inner and shallower parts of the bay (ED, >5). This tendency was more conspicuous in large-scale farms (fish production, >1,000 t/yr) than in small-scale farms (<500 t/yr). These findings suggest that variability of the macrobenthos and environmental factors are attributable to the topography as well as to the aquacultural activities, and that topography is the important factor in the location of environmentally efficient fish farms.

Yokoyama *et al.* (2002b) also examined the species composition of the macrobenthos as an indicator of fish farm environments. They found six assemblages (A–F) in August–September 1998 at the fish farms in Kumano-nada by the cluster analysis. These assemblages could be classified into three groups, i.e., a group characteristic of a healthy zone (A–D), a group characteristic of a cautionary zone (E), and an azoic group characteristic of a critical zone (F), based on the macrofauna and chemical factors of the bottom water and the sediment. These assemblages were placed in a gradient of ED versus fish production (Fig. 2). Fig. 2 suggests that all levels of fish production (<1,500 t/yr) could be sustained in areas where ED is <3

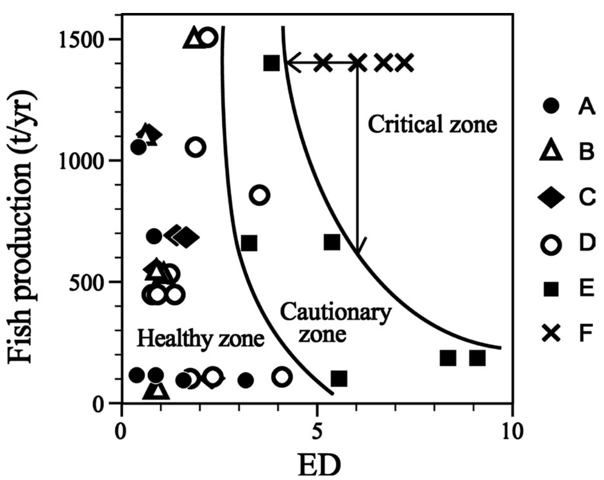

Fig. 2. Distribution of the six assemblages (A–F) in a gradient of ED versus fish production (after Yokoyama et al., 2002b).

and smallest-scale fish production (<200 t/yr) could possibly be conducted in areas where ED is <10, but medium- and large-scale production should be limited to areas where ED is <5. A fish farm with large-scale production (e.g., 1,400 t/yr) and located in the critical zone (e.g., ED = 6) should be shifted to an area with ED values <4 or annual production should be reduced to <600 t to alleviate the critical conditions.

Many mathematical models have been developed to predict benthic impacts and responses to organic enrichment associated with fish farming (reviewed by Henderson *et al*., 2001). Most of them recognized that the current flow is a key factor in predicting the dispersion and input of organic wastes to the seabed (e.g. Hevia *et al.*, 1996; Findlay and Watling, 1997). ED is an index based on the same concept as those adopted in the previous modeling studies, which demonstrated that dispersive environments are less susceptible to environmental degradation than semi-enclosed systems, but a novel aspect is that the index is readily applicable for use in decisions about the siting of fish farms. Factors such as the inflow of freshwater into the bay, the current outside the bay, and wind velocity and direction, which may vary in different localities might also control flushing. In neighboring localities under similar oceanographic conditions, however, benthic impacts from fish farming might depend largely on the topographic conditions. Results obtained from these surveys demonstrated the importance of topographic factors for assessing the impact of organic wastes and for developing site selection guidelines.

Index incorporating the current velocity and water depth

ED is an index based on topographic factors only, and has proved helpful to develop guidelines for siting fish farms within the Kumano-nada area, however, it is unknown whether this index is applicable to other localities exhibiting different tidal ranges or different bay sizes. The current flow and water depth are the most important factors that control directly the waste dispersal and loading. These factors are essential to assess the assimilative capacity of fish-farm environments.

Yokoyama *et al.* (2004) conducted a survey of the water flow to examine whether the current velocity and water depth in fish farms can be used as indicators for site selection guidelines. They proved that plaster balls (plaster of Paris : water = 100 g : 70 ml) can be used as a convenient and effective tool for measuring the time-averaged current velocity. They revised the method for the calculation of the time-averaged intensity of water motion that was presented by Komatsu and Kawai (1992) and Komatsu (1992). Yokoyama *et al.* (2004) showed the equation,

$$v = \frac{\left(\sqrt{W_0 - W_S} - \sqrt{W - W_S}\right)(284 - 4.03T)}{h} - 0.048T - 0.27$$

where v is the time averaged current velocity (cm/s), W_0 is the wet weight (g) of a plaster ball including an iron bolt before setting on the seabed, W is the wet weight (g) of the plaster ball including the iron bolt after being retrieved from the seabed, Ws is the weight (g) of the iron bolt, T is the average water temperature (℃) during the immersion period, and h is the immersion period

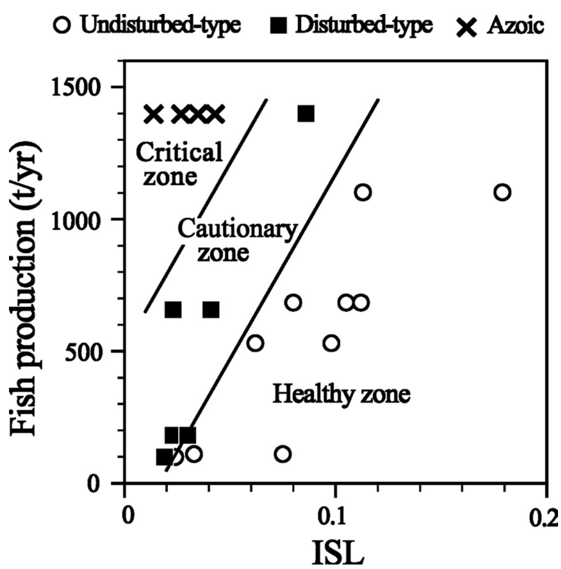

Fig. 3. Distribution of the three assemblage groups in a gradient of ISL versus fish production (adapted from Yokoyama *et al.,* 2004). Symbols represent the group characteristic of the healthy zone (○), the group characteristic of the cautionary zone (■), and the group characteristic of the critical zone (×), respectively.

(hours). Plaster balls (diameter = 48 mm), which were fixed on a stand using a bolt and nuts, were put 1.0 m above the seabed at 20 stations in 8 fish farms in Gokasho Bay and Owase Bay for about 50 hours at the same time during neap- and spring-tide periods in September 2003.

Yokoyama *et al.* (2004) devised an index 'ISL' (Index of Suitable Location). ISL is expressed as ISL = DV^2, where D is the water depth (m) at a fish-farm site and V is the time-averaged current velocity (m/s). The mathematical derivation of the index is as follows: the loading rate of organic wastes to the seabed has an inverse relationship to DV; as the current velocity maintains the oxygen supply that serves to remineralize the loaded organic wastes, the value obtained by multiplying DV by V, i.e., DV^2 will represent the assimilative capacity of the water body.

Three zones of fish-farm environments, i.e., healthy, cautionary and critical zones, which had been defined on the basis of the macrofauna and chemical factors (Yokoyama *et al.*, 2002b), were also arranged in a grid of ISL versus fish production (Fig. 3). The healthy zone was located at areas having large ISL values, whereas the critical zone was located at areas having small ISL values and high levels of fish production.

Field data on biotic and abiotic factors that have been obtained from the same stations (Yokoyama *et al.*, 2002a) were used to validate ISL (Fig. 4). Values

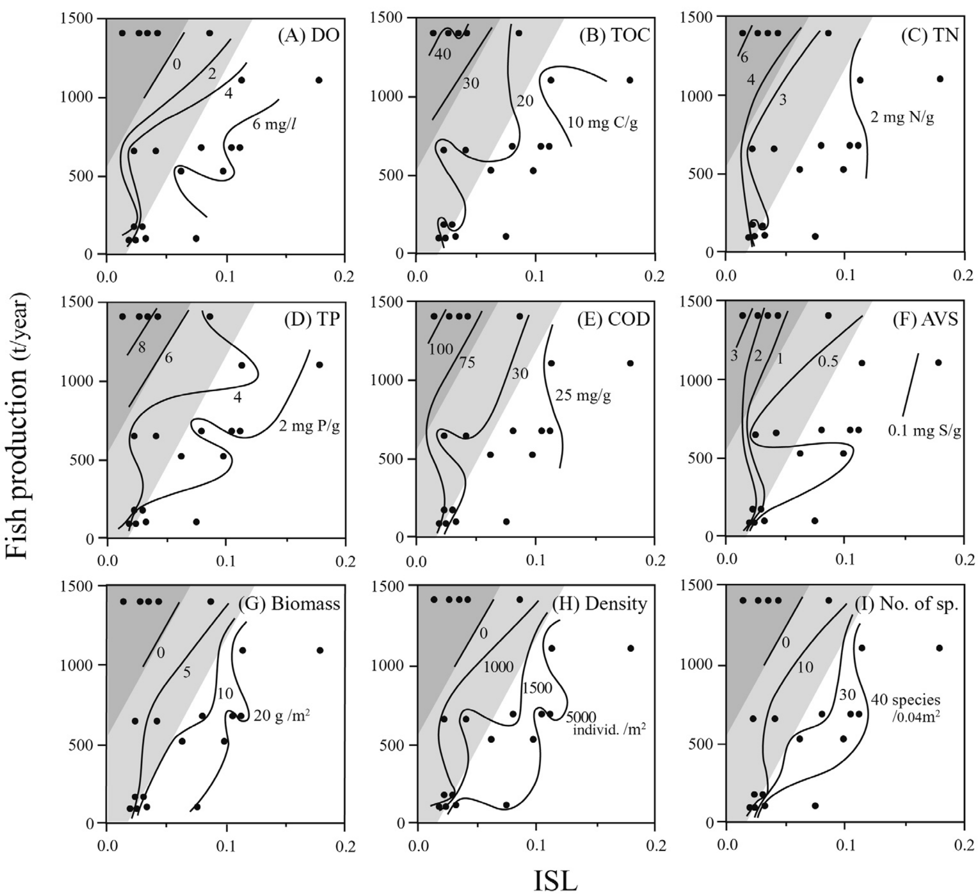

Fig. 4. Distribution of values of six abiotic (A–F) and three biotic (G–I) factors in a gradient of ISL versus fish production (after Yokoyama *et al.*, 2004). Dark, gray, and white areas show critical, cautionary, and healthy zones, respectively (defined in Fig. 3). (A) Dissolved oxygen of the bottom water, (B) total organic carbon in the sediment, (C) total nitrogen in the sediment, (D) total phosphorus in the sediment, (E) chemical oxygen demand of the sediment, (F) acid-volatile sulfides in the sediment, (G) biomass of the macrobenthos, (H) density of the macrobenthos, and (I) number of species of the macrobenthos.

Table 1. Values of benthic components for identifying cautionary and critical conditions of fish-farm environments (adapted from Yokoyama *et al.* 2004)

Benthic components	Cautionary condition	Critical condition
Sediment		
Total organic carbon (mg C/g dry)	20 – 30	> 30
Total nitrogen (mg N/g dry)	2.5 – 4.0	> 4.0
Total phosphorus (mg P/g dry)	4 – 6	> 6
Chemical oxygen demand (mg/g dry)	30 – 75	> 75
Acid-volatile sulfide (mg S/g dry)	0.5 – 1.5	> 1.5
Macrobenthos		
Biomass * (g/m^2)	< 10	0
Density (individuals/m^2)	< 1500	0
Number of species (/0.04 m^2)	< 20	0

* Wet weight of animals excluding the shell of mollusks.

of biotic and abiotic factors changed along a gradient of ISL versus annual fish production. As ISL values decreased and fish-production levels increased, values of DO of the bottom water decreased, values of sediment total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD) and AVS increased, and values of biomass, density and number of species of the macrobenthos decreased. These findings suggest that environmental conditions are predictable in gradients of ISL and fish production, and that ISL is an effective indicator in the assessments of the assimilative capacity and the upper limit of fish production. For instance, at farms showing ISL of 0.05, it is recommended to restrict fish production within 500 t/yr, while at farms having ISL of 0.1, allowable production may increase to 1,000 t/yr (Fig. 3).

Since benthic impacts are integrated over time, chemical factors of the sediment and community parameters of the macrobenthos are convenient for environmental monitoring. Threshold values of these factors and parameters that classify fish-farm environments into healthy, cautionary and critical conditions can be roughly estimated from a comparison of Fig. 3 with Fig. 4. These values of sediment and community parameters (Table 1) are useable as environmental quality standards, however further verification in other localities is necessary.

Comparison between ED and ISL

ED and ISL were proposed based on the concept that assimilative capacity of fish-farm environments is determined by waste dispersal and oxygen supply. It was hypothesized that waste dispersal and oxygen supply are influenced by topographic conditions (ED) and by water depth and current velocity (ISL). Surveys of the macrobenthos and environmental factors conducted at the fish farms in Kumano-nada indicate that both indices are indicative of the assimilative capacity of environments. ED is easy to calculate from a nautical chart, and is effective for comparison of the suitability for fish farming between neighboring areas that are located under similar oceanographic conditions. However, to compare fish farms in a variety of topographic situations under different oceanographic and/or geographic conditions this index may be less suitable. ISL incorporates factors of the water depth and current velocity, which are more direct variables that control waste dispersal and loading

(Gowen and Bradbury, 1987; Chamberlain *et al.*, 2001) and oxygen supply (Jørgensen and Revsbech, 1985; Findlay and Watling, 1997). ISL has a wider potential application to assess the suitability of fish farms under a variety of topographical conditions as a simple and effective tool for locating suitable culture sites in coastal areas.

The plaster-ball technique was successfully used to estimate the current velocity at the fish farms in Kumano-nada (Yokoyama *et al.*, 2004). However, a series of checks and calibrations by a current meter may be necessary before use in other localities, because this method needs to be used with caution in different flow environments (Porter *et al.*, 2000). Advantages of using plaster balls are that the device is easy to construct with readily available materials at a low price and that fish farmers can measure the current velocity readily and simultaneously at many stations. The use of plaster balls will be an effective and pragmatic approach to estimate the assimilative capacity of the water body, and to decide the suitable location for fish farming.

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