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Assimilative capacity of fish farm environments as determined by the benthic oxygen uptake rate: Studies using a numerical model

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Abstract : In order to promote improvements in the environmental quality of aquaculture grounds, the Japanese government enacted the "Law to Ensure Sustainable Aquaculture Production" in 1999. In the Basic Guidelines for this law, an environmental criterion based on the benthic oxygen uptake (BOU) rate was adopted to assess the quality of aquaculture environments. Biological mineralization is considered to peak when the BOU rate reaches its maximum, which is an indicator of the maximum desirable level of organic matter loading. The acid volatile sulfide (AVS-S) content of the sediment increases in direct correlation to the organic matter loading, and is used as an indicator of the assimilative capacity of bottom sediments. The AVS-S value corresponding to organic matter loading when the BOU rate is at its maximum is defined as the standard value. Recent studies, however, have suggested that it is difficult to detect the maximum (peak) BOU and to determine the standard value through in situ investigations. The practical applicability of this criterion therefore needs to be re-examined scientifically. To do this, we developed a three-dimensional numerical model that takes into account advection, dispersion, sedimentation, and decomposition of organic matter from fish farming systems. The numerical model should be used instead of in situ investigations for the practical application of the criterion. We also used this model to assess the assimilative capacity of an existing fish farm on the basis of the criterion. The model proved to be an effective tool for evaluating the assimilative capacity of the environment of fish farms.

Keywords: environmental criteria, fish farm, numerical simulation, Law to Ensure Sustainable Aquaculture Production

Introduction

Supported by the development of production techniques and by economic growth, Japan has succeeded in increasing its aquaculture production, while the total amount of fishery products has been decreasing for the last 10 consecutive years. Aquaculture, however, has had a large impact on the environment. In particular, overstocking of aquaculture pens has caused environmental deterioration such as eutrophication, hypoxia, and occurrences of noxious red tide.

The Japanese government enacted the "Law to Ensure Sustainable Aquaculture Production" in 1999 in order to promote improvements in the

environmental quality of aquaculture grounds. In the so-called Basic Guidelines for this law, environmental criteria and indicators were adopted to identify healthy farms and "critical" farms (those not being managed sustainably). These criteria and indicators should now be revised, however, on the basis of more recent data (Yokoyama, 2003). Specifically, sediment sulfide content, which was adopted as an indicator of the benthic oxygen uptake (BOU) rate, is difficult to apply (Yokoyama, 2000; Yokoyama and Sakami, 2002). The practical applicability of this criterion needs to be re-examined. We therefore developed a numerical model to examine the practical application of the criterion and studied the

assimilative capacity of fish farms.

Environmental impact of fish farms

Fish farms discharge large amounts of organic matter into the environment. Comparison of the ratio of the distribution of feed to wastage, fish growth, and excretion and feces shows consistently high discharge rates for different species and feed types and varying assessment measures (Table 1). Based on an assessment of nitrogen content, it has been estimated that 80% of the feed inputs to fish farms is discharged out of the culture cages: 20% in the form of feed wastage, and 60% in the form of fish excretion and feces production (Itoh, 1994). On the basis of protein content, Yamaguchi (1978) estimated the ratio in fish farms that rear red sea breams. He estimated that 20% of the feed is discharged into the environment directly as feed wastage and that 60% of the feed is discharged as excretion and feces. Watanabe (1991) studied the distribution of feed in fish farms that rear yellowtails based on dry matter content. He showed that in fish farms that feed moist pellets a total of 74% of the feed is discharged into the environment, 19% as feed wastage and 55% as excretion and feces, while in fish farms that use raw fish, 85% of the feed is discharged, with feed wastage accounting for 72% and excretion and feces for 13%. Bergheim et al. (1991) estimated that in salmonid farms that feed dry pellets, 75% of the feed is discharged: 10% as feed wastage and 65% as excretion and feces. According to Wu (1995), eventually some 80-84% C, 52-95% N, and 82% P

in the feed may be lost to the environment in a salmonid farm using artificial feed.

The Law to Ensure Sustainable Aquaculture Production

To improve the environmental quality of aquaculture grounds and maintain suitable conditions for stable aquaculture production, the Law to Ensure Sustainable Aquaculture Production (hereinafter referred to as the Law) was enacted in 1999. As a fundamental guide for putting the Law into practice, the Minister of Agriculture, Forestry, and Fisheries produced the "Basic Guidelines to Ensure Sustainable Aquaculture Production", which detailed matters relevant to the goal of improving aquacultural practices. The Law stipulates that fisheries cooperative associations should enact an "Aquaculture Ground Improvement Program" so as to ensure sustainable aquaculture, and also secure the approval of the prefectural governor. The Basic Guidelines contain environmental criteria to measure the environmental condition of aquaculture grounds. The criteria utilize three indicators: the dissolved oxygen content of the water within fish cages, the condition of macrofauna beneath the fish cages, and the sulfide content (acid volatile sulfide, AVS-S) of the sediment beneath the cages (Table 2). The criteria serve to identify healthy and critical farms; farm environments are identified as healthy or critical based on the values measured for these indicators, relative to established thresholds.

Dissolved oxygen is an important factor for

Table 1. Comparison of the ratios of the distribution of feed to wastage, fish growth, and excretion and feces in fish farms, for different species and feed types and varying assessment methods.

	Seabreams	Yellowtails	Yellowtails	Salmonids
Feed	100	100	100	100
Feed Wastage	20	19	72	10
Excretion and Feces	60	55	13	65
Growth of Fish	20	26	15	25
	Yamaguchi (1978) Raw Fish Protein Basis	Watanabe (1991) Moist Pellets Dry Matter Basis	Watanabe (1991) Raw Fish Dry Matter Basis	Beregheim (1991) Dry Pellets Nitrogen Basis

Table 2. Environmental criteria adopted in the Basic Guidelines for the Law to Ensure Sustainable Aquaculture Production.

Item	Indicator	Criteria for healthy farms	Criteria for critical farms
Water in cages	Dissolved oxygen	> 4.0 ml/l	< 2.5 ml/l
Bottom environment	Sulfide (AVS-S)	Less than the value at the point where the benthic oxygen uptake rate is maximum	> 2.5 mg/g dry sediment
	Benthos	Occurrence of macrobenthos throughout the year	Azoic conditions for more than 6 months

maintaining the life of cultured organisms. The criteria established 4.0 ml/L and 2.5 ml/L of dissolved oxygen as thresholds for identifying healthy and critical farms, respectively. Macrofauna have often been used as a sensitive indicator to assess fish farms environments (Yokoyama, 2002). The criteria used in the Basic Guidelines only specify that the benthos beneath the culture cages should be alive. The farm environments are identified as healthy when macrobenthos occur throughout the year, and they are identified as critical when azoic conditions occur for more than 6 months in a year. Sulfide content (AVS-S) levels are used as an indicator of the assimilative capacity of bottom sediments. The threshold AVS-S level for healthy farms is determined by reference to the BOU rate; the threshold for critical farms is > 2.5 mg/g dry sediment. Using a simple numerical model, Omori et al. (1994) found a peak in the BOU rate which they took to be an indicator of the level of organic matter loading that would result in the maximum rate of re-mineralization. Takeoka and Omori (1996) proposed a method to determine the assimilative capacity of fish farm environments by using the sulfide content as an indicator, because sulfide content is positively correlated with organic matter loading. In the criteria, farm environments are identified as healthy when AVS-S is less than the AVS-S value at the point where the BOU rate is maximized. The concept of using sulfide content as an indicator to identify healthy farms is unique, but there are problems in its practical application, as described below. In the following section, we examine the practical use of the indicator of sulfide

content to identify healthy farms.

Assimilative capacity based on benthic oxygen uptake rate

The use of sulfide content as an indicator considers the capacity of bottom sediments to assimilate organic wastes, and it is based on the relationship between the organic matter loading and the BOU rate in the bottom water. An increase in the organic matter loading to the sea bottom is accompanied by an increase in the aerobic degradation of organic matter in the sediment. Increases in organic matter loading also lead to a decrease in dissolved oxygen content, however, causing benthic conditions to become anaerobic, at which point the BOU rate begins to decrease. Consequently, organic matter loading should be limited to the level at which the BOU rate is at its maximum, because this corresponds to the point at which the greatest biological re-mineralization of organic matter takes place (Fig. 1). There is a positive correlation between the organic matter loading and sulfide content in the sediment, and thus the AVS-S level that corresponds to the BOU maximum is used as an indicator of the assimilative capacity of fish farms, and to determine which are healthy.

There are problems in applying this criterion to existing aquaculture farms. Recent studies have suggested that it is difficult to detect the maximum (peak) BOU and to determine the standard AVS-S value through in situ investigations (Yokoyama and Sakami, 2002; Yokoyama, 2003; Abo and Yokoyama, 2003). In order to determine the standard AVS-S value of the criterion, it is necessary to detect

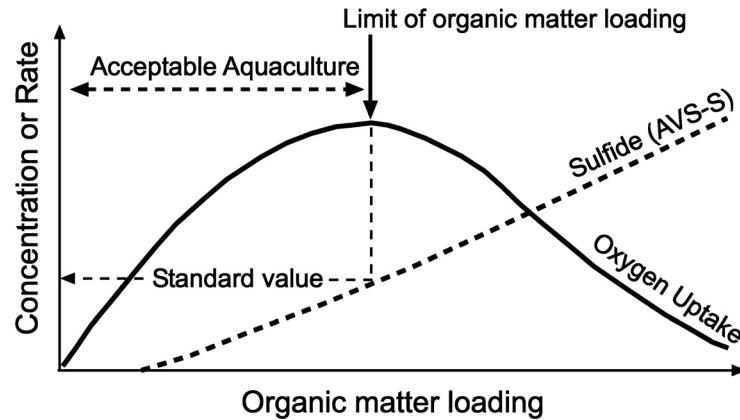


Fig. 1. Acceptable limits for organic matter loading from fish farms, and the relationship to benthic oxygen uptake and sediment sulfide content (adapted from Takeoka and Omori, 1996).

the maximum value of the BOU rate relative to the organic matter loading rate from a farm. Theoretically, we have to investigate the BOU rate when the level of organic matter loading is changed, but this is almost impossible to do in an existing farm. In addition, it takes many years to investigate, even if the organic matter loading is altered. Consequently, it is almost impossible to determine the standard BOU value by this method. Another method involves investigating the BOU rate in several farming areas whose topography and hydrodynamic conditions are very similar, and detecting the maximum among the similar farming areas. Many researchers have carried out these in situ investigations in Japan; however, they were unable to detect the maximum because BOU rates are very sensitive to changes in oxygen supply, induced by water exchange. It is also impossible to select a sufficient number of farming areas whose topography and hydrodynamic conditions are similar enough to enable detection of the maximum. Moreover, some researchers intend to detect the maximum by measuring BOU rates at many points in one fishing area. This approach is unsound, however, because the BOU rate depends largely on oxygen flux, which varies significantly within a short distance in a farming area (Abo and Yokoyama, 2003).

These problems suggest that we cannot determine the standard value through in situ investigations. It

is possible, however to utilize a numerical model to determine the standard value. By using a numerical model, we can simulate benthic quality when the organic matter loading rate is changed in a farm. The BOU rate can then be calculated as a function of variations in the organic matter loading rate, and the maximum and standard values for sulfide content estimated.

Numerical model

The numerical model to estimate the maximum BOU rate and determine the standard AVS-S value defined in the criteria used in the Basic Guidelines for the Law deals with three spatial dimensions, and considers advection, dispersion, sedimentation, and degradation of organic matter loading from fish farms (Fig. 2). We first calculate water movements using a multi-level density “primitive” flow model. The flow model divides the area into meshes, and solves the fundamental equations obtained by integrating the equations within the meshes. Secondly, we calculate advection and diffusion of dissolved oxygen, and advection and diffusion of organic matter loadings from fish farms, including their sedimentation (Fig. 2b). We also calculate the aerobic and anaerobic degradation of the organic matter. In this model we express the flow of organic matter very simply (Fig. 2c). Organic matter loading from fish farms sinks at some sedimentation rate, and organic matter in the water column degrades

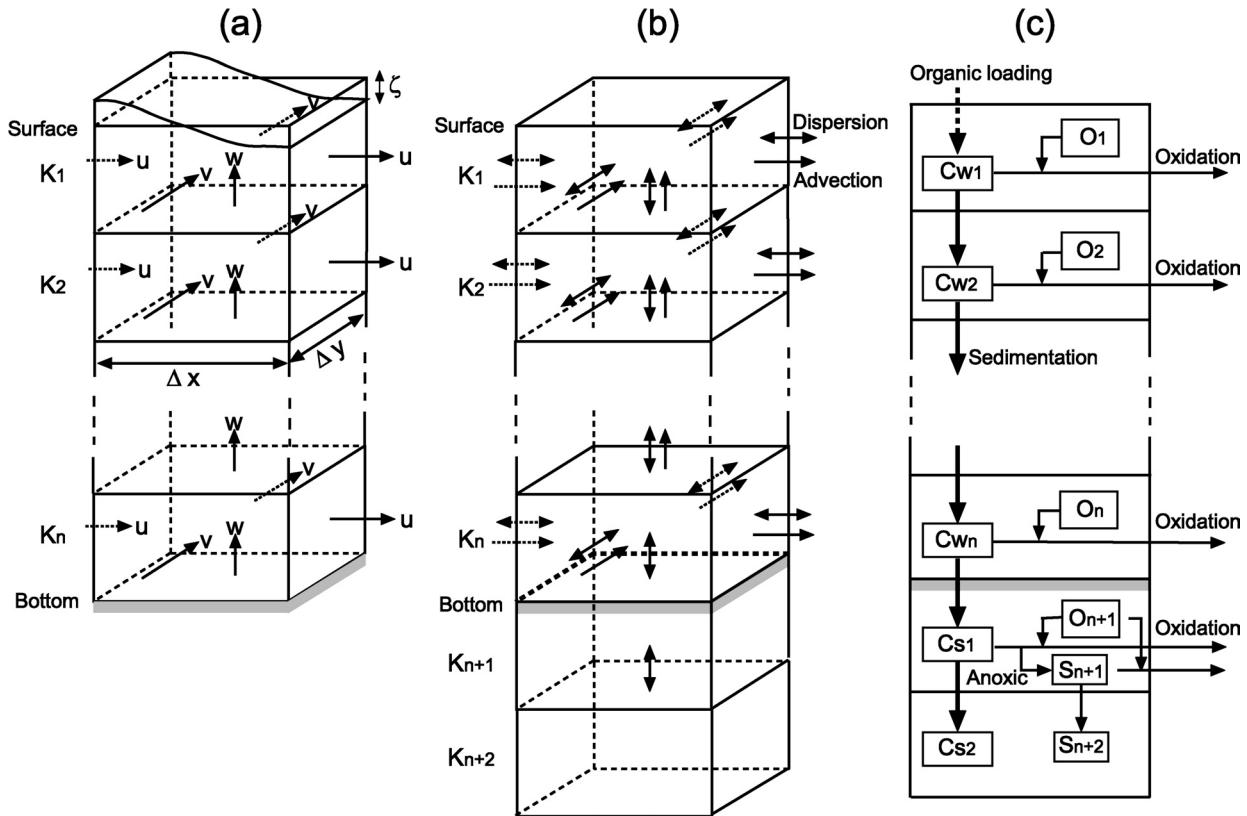


Fig. 2. Schematic views of the three-dimensional numerical model. (a) Multi-level stratified flow model. (b) Advection and diffusion of organic matter and dissolved oxygen. (c) Flow chart of the sedimentation, oxidation and anoxic decomposition of organic matter.

aerobically. Once organic matter accumulates on the bottom, it degrades both aerobically and anaerobically. Reduced substances derived from anaerobic degradation of organic matter consume oxygen through chemical oxidation.

The relational equations and parameters used were according to Omori et al. (1994). Using this model, we calculated approximate stationary solutions under the given conditions.

Assessment of the assimilative capacity of aquaculture environment in Gokasho Bay

We examined application of the numerical model to assess the existing aquaculture environment in Gokasho Bay. Gokasho Bay is located on the southern coast of central Japan facing the Pacific Ocean (Fig. 3). This bay is a typical semi-enclosed estuary consisting of three branches: the main inlet, the Hasama-ura inlet, and a third branch. Fish farms are concentrated in Hasama-ura inlet. In this bay aquaculture is prosperous and about 1000 metric

tons of fish are produced annually. We divided the Gokasho Bay area into meshes of 100 m² and 5 m depth, and identified some meshes as fish farming sites (Fig. 4). Organic matter is assumed to be loaded into the surface layers from fish farming site meshes. With this geometry, we simulated changes in the BOU rate relative to the organic matter loading rate from the fish farming sites.

First, we calculated movement of organic matter loaded from fish farming sites when the organic matter loading rate was equal to the real value for the existing farms in Gokasho Bay. The organic matter content of the sediment and the BOU rate were compared for Gokasho Bay (Fig. 5), with a unit of organic matter content given as an oxygen equivalent ($\mu\text{molO}_2/\text{cm}^3$). Organic matter from fish farms accumulated mainly on the sea bottom near the fish farming sites. The BOU rate was high near the shore of Hasama-ura inlet because of the large oxygen supply at the sea surface; the dissolved

oxygen concentration in the bottom water of the shallow area was consequently high. Other than in the shallow area, the BOU rate was high at the outer side of the fish farming area (at the mouth of Hasama-ura inlet), where there was high organic matter loading and a large supply of oxygen. The BOU rate was low at the inner side of the fish farming area, where the oxygen supply was very small due to oxygen depletion.

Next, we simulated the BOU rate when the organic matter loading was changed, in order to estimate the maximum BOU rate at each fish farming site (Fig. 6). The organic matter loading rate was represented as a unit of oxygen equivalent of feed fed per day ($\mu\text{molO}_2/\text{cm}^2/\text{day}$), and the organic matter loading rate to the sea surface was assumed to be the same at each farming site. At farming site 1, the BOU rate varied relative to the organic

matter loading rate, with the maximum BOU rate occurring when the organic matter loading rate was $3 \mu\text{molO}_2/\text{cm}^2/\text{day}$. This value was an allowable organic matter loading rate maximum for farming site 1, with the aquaculture environment of farming site 1 regarded as healthy when the organic matter loading rate was within $3 \mu\text{molO}_2/\text{cm}^2/\text{day}$. In farming sites 5, 7, and 11, the BOU rate reached its maximum when the organic loading rate was 10, 25, and $95 \mu\text{molO}_2/\text{cm}^2/\text{day}$, respectively; these values were taken as the allowable organic matter loading rate maximums for each farming site. These values are plotted and contour lines drawn showing the organic matter loading rate limits in Gokasho Bay (Fig. 7). The values are high at the mouth of the Hasama-ura inlet and very low at the innermost part of the inlet. The limit values increase sharply towards the mouth of the inlet. As the actual organic

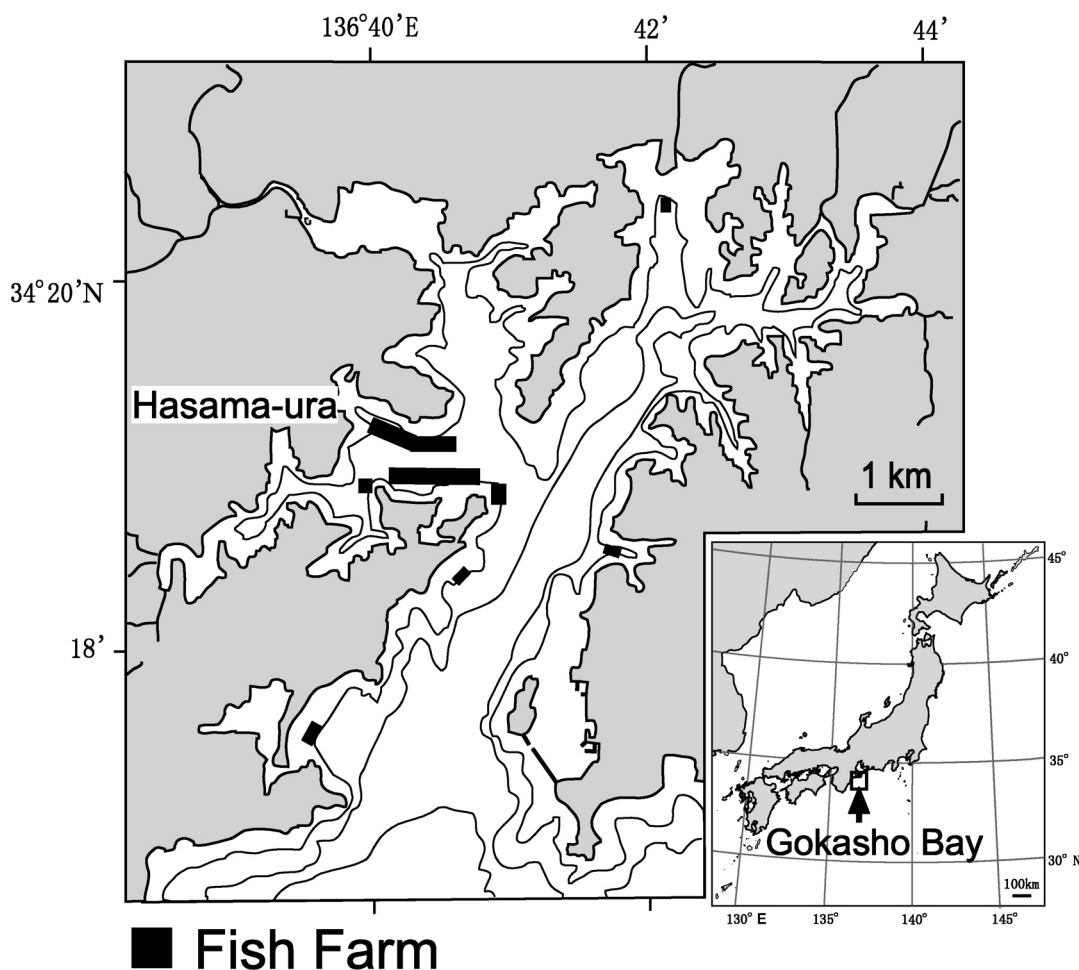


Fig. 3. Map of Gokasho Bay. Solid areas denote fish farming sites.

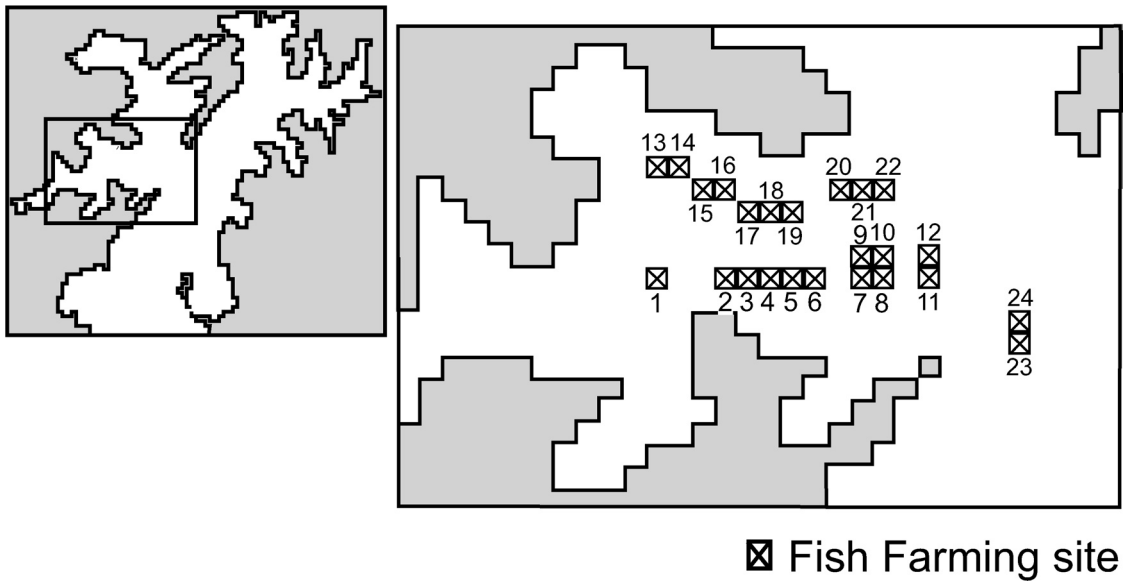


Fig. 4. The model geometry of Gokasho Bay. Squares with crosses indicate fish farming sites 1-24.

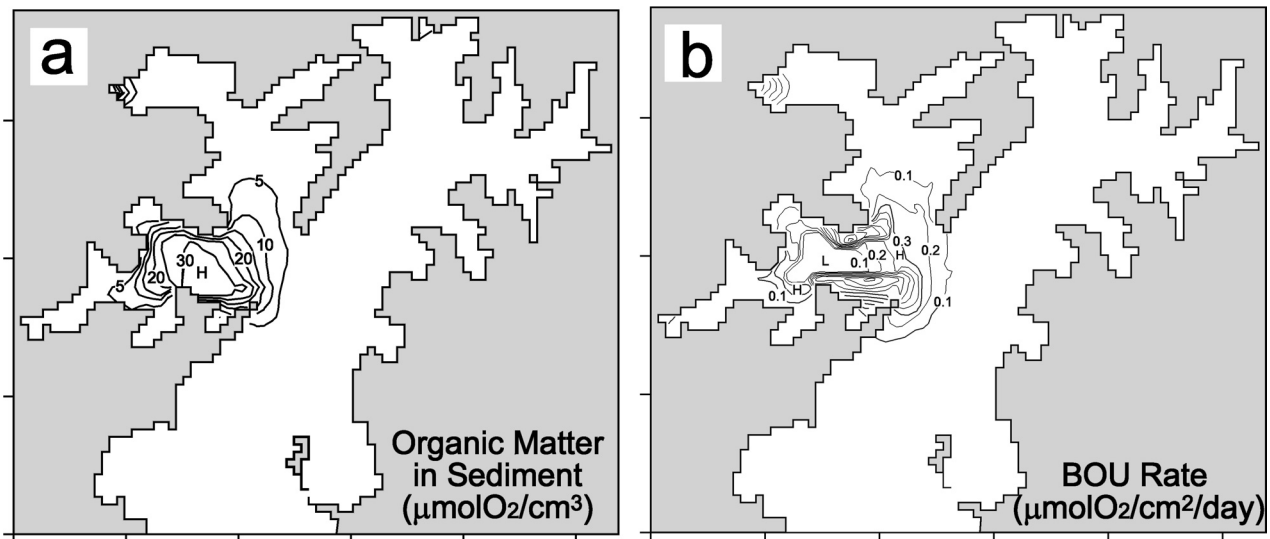


Fig. 5. Distribution of organic matter content in (a) sediment and (b) benthic oxygen uptake rate, calculated by the numerical model.

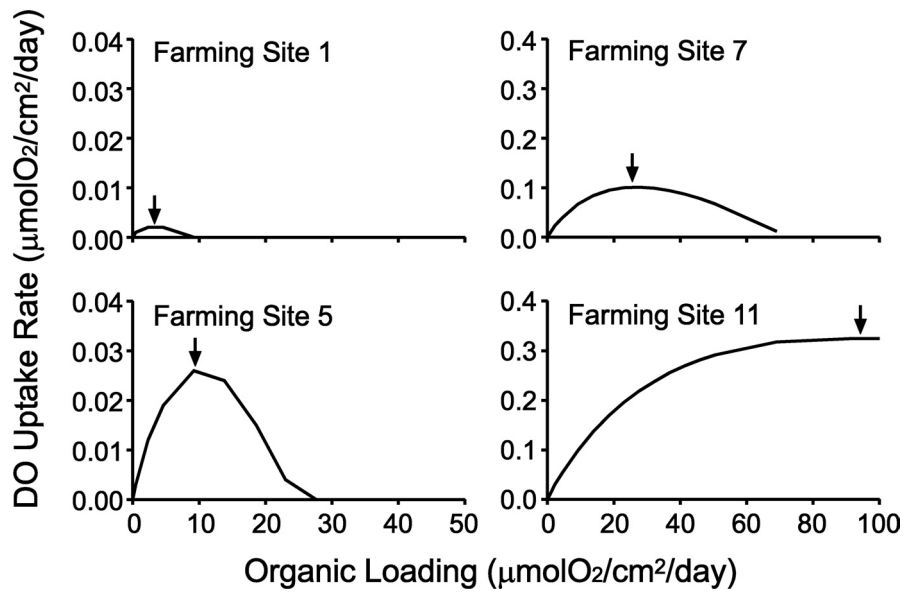


Fig. 6. The relationships between the benthic oxygen uptake rate and organic matter loading rate at fish farming sites 1, 5, 7, and 11 (see Fig. 4), as calculated by the numerical model.

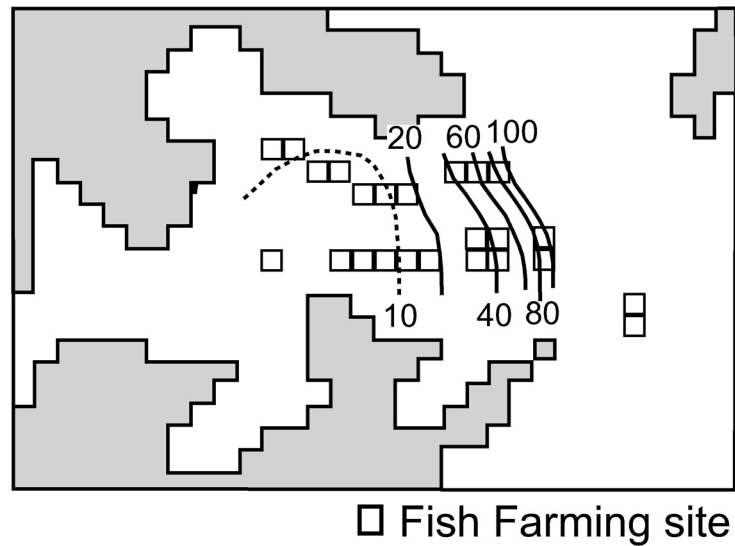


Fig. 7. Isopleths of the limit values of the organic matter loading rate ($\mu\text{molO}_2/\text{cm}^2/\text{day}$) in Gokasho Bay, estimated by the numerical model.

matter loading rate in each mesh of the farming sites is estimated at about $20 \mu\text{molO}_2/\text{cm}^2/\text{day}$, there is sufficient capacity for aquaculture at the mouth of the inlet. However, the capacity is very small at the inner part of the inlet, where it is one-tenth of the capacity at the inlet mouth.

Conclusion

The numerical model is an effective tool for assessing the limit of organic matter loading from fish farms for ensuring healthy aquaculture environments, on the basis of the environmental criterion adopted in the Basic Guidelines for the Law to Ensure Sustainable Aquaculture Production. Before the model can be practically applied to determine the standard sulfide value of the criterion, the model needs to be reexamined and the parameters defining the aquaculture ecosystem refined. We will also attempt to carry out an in situ investigation of the benthic quality of a fish farming area to refine the model for practical application.

To improve aquaculture environments with the goal of sustainable aquaculture production, we should ensure that production levels are within an area's capacity; infection caused by overstocking can be addressed through reduction in production or rearrangement of aquaculture pens within an aquaculture area. The model can serve as an effective tool for suggesting appropriate spatiotemporal use of aquaculture grounds.

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