6. Modeling of the role of tideland in eutrophication reduction in Mikawa Bay, Japan

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Nutrient's over-enrichment has resulted in major changes in the coastal system of Mikawa Bay. One important factor which affects eutrophication is decrease of the area of tide land, caused by the change of land use in coastal area. This study examines, by using an eutrophication model with benthic system, to what extent water quality in Mikawa Bay can be improved with the tideland. The benthic system consists of the five state variables of benthic alga, meiobenthos, suspension feeder, deposit feeder and bacteria. Obtained results are summarized as follows: (1) the model simulation acceptably well reproduced seasonal variations of the benthic variables in Mikawa Bay, (2) changes of water qualities by nutrient-reduction scenarios, with and without the benthic system, were analyzed and contribution of the benthic system to decrease of chlorophyll-a concentration was quantitatively evaluated, and (3) the tideland in Mikawa Bay was estimated to be worth, at its largest, 30% reduction of the T-N (total nitrogen) input caused by sediment resuspension.

Key Words : *Benthic system, Eutrophication, Chlorophyll-a, Dissolved Oxygen, Nutrient*

1. INTRODUCTION

In the last four decades, increased water pollution accompanied by red tide and oxygen depleted water has been frequently observed in Mikawa Bay. These phenomena are believed to be due to the increase in the coastal nutrient supply and due to the decrease in the function of the tidal flat ¹⁾.

Tideland in the bay has been recognized as a place of birth and living for diverse range of plants and animal communities, and hence as a place to feed and to rest the migratory birds. From these facts the tideland may be regarded as where mineralization of organic matter by feeding benthos, and utilization of nutrients by photosynthesis of sea-weed and grass take place.

There are many studies concerning the mechanism of the coastal marine ecosystem and attempts to estimate the result of environmental management. For example, Suzuki and Matsukawa ²⁾ estimated the budget of nitrogen and dissolved oxygen of Isshiki, a natural tidal flat area, in Mikawa Bay. Sasaki ³⁾ and Aoyama and Suzuki ⁴⁾ evaluated removable ability of total nitrogen of Isshiki using a material budget model.

In the previous study Anggara and Kitada ^{5,6)} analyzed the mechanism of eutrophication in Mikawa Bay by using a hydrodynamic and water

quality model. In the study, the ecological model included only pelagic system, and the benthic variables were not explicitly considered.

In this study, a tideland ecosystem model was added to the previous eutrophication model ^{5,6)}. The base model is CE-QUAL-W2 ⁷⁾ which consists of laterally integrated 2-dimensional hydrodynamic and water quality equations. The tideland ecosystem model simulates population dynamics reflecting predator-prey interactions, daily change in the water temperature, and nutrient availability.

The objective of this study is to simulate water quality in Mikawa Bay and to quantify the role of tideland benthic system in purification of sea water by using a new model, that is, CE-QUAL-W2 combined with benthic system. The result of the water quality response will be examined by comparing the calculated chlorophyll-a and dissolved oxygen, among various scenarios.

2. METHOD

(1) Study site and data description

a) Study site

Mikawa Bay, located in the middle of Japan (see Fig.1), is enclosed by two peninsulas of Chita and Atsumi. The bay has 365 km² surface water area.

Two big cities in the watershed of the Toyokawa River are Toyohashi and Toyokawa with their populations being 380,000 and 116,000, respectively. Approximately 700,000 people live near the watershed. The watershed is used intensively for agriculture and livestock production. The nutrient is loaded from the land area through two major rivers of Toyokawa and Umedagawa, and the municipal waste water treatment plants of Noda, Nakashima, Toyokawa, and Gamagori (e.g., see Fig.2 for Noda).

Fig. 1. The watershed of Mikawa Bay

For the simulations, the initial fields of all water qualities were estimated by inter-/extra-polations of the observed data (Aichi Prefectural Office⁸⁾); the observation points are shown as A13, A10, A5, A7 and A14 in Fig. 2. The same method was used for the initialization of benthic organisms, using the measurements obtained by Aichi Prefectural Office⁹⁾; the observation points are shown as St.1, St.2, St.3, St.5 and St.7 in Fig.2.

b) Boundary values

State variables at upstream (terrestrial) and downstream (ocean) boundaries were specified as follows.

At the ocean boundary, surface water elevation was given hourly by an average of the water surface elevations observed at Maisaka, Toba and Nagoya¹⁰⁾, near Mikawa Bay.

Water quality variables were estimated by using data in Ise bay and Mikawa Bay near the boundary. At the terrestrial boundary, fresh water loading and mass inflow of water quality variables from the Toyokawa River, the Umeda River and the other rivers, and sewage treatment plants such as Nakashima, Noda, Toyokawa, and Gamagori were given daily¹³⁾

Fig. 2. The segmentation model of Mikawa Bay, the thick solid line indicates longitudinal axis in two-dimensional model; A5-A14 show monitoring points. Two waste water treatment plants are shown as "Noda" and Nakashima" WTPs. Two AMeDAS (Automatic Meteorological Data Acquisition System) stations are also indicated as "Toyohashi St." and "Irago St."

c) Meteorology

The meteorological data, such as wind velocity, temperature, humidity and precipitation were given at every segments by the average of data at Toyohashi St. and Irago St. in Fig.2¹¹⁾.

d) Initial biomass of benthos

Observations by Aichi Prefectural Office⁹⁾ were used to determine the initial fields of macro benthos and also to compare with the model calculation.

In this study, the 1998 data was used for hydrodynamic and water quality calculation, while the data in 1996 was used for benthos model calculation because of lack of the benthos data in 1998. Furthermore, the 1996 benthos data were available only four times in a year, i.e., May, August, October and December. Bacteria concentration was not available at all.

(2) Model development

a) Grid segmentation

An ecological model was coupled with the hydrodynamic and water quality model, "CE-QUAL-W2". CE-QUAL-W2 is a laterally integrated 2-dimensional model where all lateral variations in the model variables are assumed to be less important than those in the longitudinal and vertical directions. The available monitoring data⁸⁾ supported this assumption. Thus, the water body of Mikawa Bay, as shown in Fig.2, was simplified in a 2-dimensional space where the longitudinal directions is the line connecting monitoring points of A13, A10, A5, A7 and A14. The water body along the longitudinal line was discretized into 30 equally spaced segments and 24 vertical layers as depicted in Fig. 3. Length of the segment was 855 m and

thickness of the layer was 1.1 m. As shown in Fig.3 each middle segment had multiple active layers and two boundary layers; these boundary layers at the sea surface and at the bottom of sea were treated as the layer without thickness. The depth of segment varied from 6.6 m (6 active layers) to 24.2 m (22 active layers).

Fig. 3. Discretization of water body of Mikawa Bay.

As described, there are two major rivers and four major waste water treatment plants (WTP) which flow into the bay. For example, the input loading from the Toyokawa River, and the Noda and Toyokawa WTPs was introduced into the bay at segment 1, while that from the Umeda River and the Nakashima and Gamagori WTPs was at segment 6.

b) Pelagic equation

The water quality model can treat 23 constituents; 13 of which were used in this application; they were chlorophyll-a, ammonium (NH_4^+), nitrate (NO_3^-), orthophosphate (PO_4^{3-}), dissolved silica, particulate silica, labile dissolved organic matter (LDOM), labile particulate organic matter (LPOM), refractory particulate organic matter (RPOM), refractory dissolved organic matter (RDOM), chemical oxygen demand (COD), dissolved oxygen (DO) and salinity. These water quality constituents are linked to one another (see Fig. 4) to simulate: 1) phytoplankton's uptake and release of nutrients and CO_2 through photosynthesis and respiration; 2) remineralization of carbon and nutrients through phytoplankton mortality, excretion and water column respiration; 3) consumption, production, and transport of dissolved oxygen through respiration, re-aeration, and photosynthesis; and 4) recycling of nutrients and consumption of DO through sediment diagenesis.

The hydrodynamic model includes turbulent transport process using Prandtl's mixing length concept. Eddy viscosity is formulated to vary according to the mixing energy available from wind

and shear of sea water flow as well as positive/negative buoyancy due to vertical density stratification. Eddy diffusivities are estimated multiplying the eddy viscosity by some constants. Detailed description of the fundamental equations can be found in Cole and Wells⁷⁾.

c) Benthic equation

Figure 4 also illustrates the food web system of ecological model. These food web relations and the benthic equations were adapted from the tidal flat model of Tokyo Bay used by Nakata and Hata¹⁴⁾. Each box in Fig.4 represents one state variable. In the food web, double arrow line and dotted line stand for predation and decomposition processes, respectively. The fundamental equations in the benthos model are as follows:

Mass concentration of Benthic Alga (BA), Φ_{BA} is computed by Eq. (1):

$$\frac{\partial \Phi_{BA}}{\partial t} = PP - RES_{BA} - MORT_{BA} - EXCR_{BA} - PRED_{BA} \quad (1)$$

where PP is the production rate of benthic alga, and is expressed using a light intensity function $f(I)$ and a nutrient function $f(N)$:

$$PP = PPR \times f(I) \times f(N) \quad (2)$$

where PPR is a constant of maximum quantity of photosynthesis which is a function of temperature $f(T)$. PPR is computed by Eq.(3):

$$PPR = FBDIA \times RPP \times f(T) \quad (3)$$

where FBDIA is the mass concentration of existing benthic alga at a layer which receives maximum light intensity and RPP is a constant of specific photosynthesis rate of benthic alga (day^{-1}).

RES_{BA} in Eq. (1) is the rate for respiration, and given by:

$$RES_{BA} = ARS_{BA} + RRS_{BA} \quad (4)$$

where ARS_{BA} is the respiration during production and RRS_{BA} is the basic respiration. The term of ARS_{BA} is a function of production of alga PP multiplied by a constant:

$$ARS_{BA} = ARS_{BAF} \times PP \quad (5)$$

where ARS_{BAF} is a fraction of activity respiration photosynthesis by benthic alga. The basic respiration RRS_{BA} in Eq. (4) can be written as:

$$RRS_{BA} = \Phi_{BA} \times RRS_{BAF} \times f(T) \quad (6)$$

where RRS_{BAF} is the specific rest respiration of benthic alga (day^{-1}). The mortality ($MORT_{BA}$) of benthic alga in Eq. (1) is written as:

$$MORT_{BA} = \Phi_{BA} \times MORT_{BAF} \times f(T) \quad (7)$$

where $MORT_{BAF}$ is the mortality rate of benthic alga (day^{-1}) and a constant. The excretion ($EXCR_{BA}$) in Eq.(1) is a function of alga production PP and given as:

$$EXCR_{BA} = EXCR_{BAF} \times PP \quad (8)$$

where $EXCR_{BAF}$ is a fraction of extra release on photosynthesis by benthic alga. In this model, benthic alga is a prey for meiobenthos (MB) and deposit feeder (DF). The prey (PRED) term in Eq. (1) is expressed as:

$$PRED_{BA} = f(MB) + f(DF) \quad (9)$$

Area mass density of meiobenthos (MB), Φ_{MB} (gN m^{-2}), can be written as:

$$\frac{\partial \Phi_{MB}}{\partial t} = GRA_{MB} - RES_{MB} - MORT_{MB} - EXCR_{MB} - PRED_{MB} \quad (10)$$

In Eq. (10), the grazing (GRA_{MB}) is expressed as:

$$GRA_{MB} = \Phi_{MB} \times up_{MB} \times f(T) \times f(DO) \times f(food_{MB}) \quad (11)$$

where grazing of meiobenthos depends on meiobenthos itself, the specific up-take rate of meiobenthos up_{MB} (day^{-1}), and functions of temperature $f(T)$, dissolved oxygen $f(DO)$ and the food available $f(food_{MB})$.

The respiration of meiobenthos respiration (RES_{MB}) is given by:

$$RES_{MB} = ARS_{MB} + RRS_{MB} \quad (12)$$

where ARS_{MB} and RRS_{MB} are given by:

$$ARS_{MB} = ARS_{MBF} \times GRA_{MB}, \quad (13)$$

and

$$RRS_{MB} = \Phi_{MB} \times RRS_{MB} \times f(T) \quad (14)$$

where ARS_{MBF} and RRS_{MBF} (day^{-1}) are a fraction of activity respiration uptake and relative rest excretion of meiobenthos, respectively.

The excretion ($EXCR_{MB}$) in Eq. (10) is written as:

$$EXCR_{MB} = GRA_{MB} \times (1 - ASS_{MBE}) \quad (15)$$

where ASS_{MBE} is assimilation efficiency of meiobenthos. The mortality ($MORT_{MB}$) in Eq. (10) is written as:

$$MORT_{MB} = \Phi_{MB} \times MORT_{MBE} \times f(T) \times f(DO) \quad (16)$$

where $MORT_{MBE}$ is the natural mortality rate of meiobenthos (day^{-1})

Area mass density of Suspension Feeder (SF), Φ_{SF} (gN m^{-2}), can be written as follows:

$$\frac{\partial \Phi_{SF}}{\partial t} = FIL - RES_{SF} - MORT_{SF} - EXCR_{SF} - PRED_{SF} \quad (17)$$

Filter (FIL) is:

$$FIL = \Phi_{SF} \times up_{SF} \times f(T) \times f(DO) \times f(par) \quad (18)$$

where up_{SF} is the maximum uptake rate of suspension feeder (day^{-1}), and $f(par)$ depends on the suspended solid and chlorophyll-a concentrations. The equations for respiration, mortality and excretion are similar to those of meiobenthos.

Kinetic equation for Deposit Feeder (DF), Φ_{DF} (gN m^{-2}), is expressed as:

$$\frac{\partial \Phi_{DF}}{\partial t} = GRA_{DF} - RES_{DF} - MORT_{DF} - EXCR_{DF} \quad (19)$$

where the grazing (GRA_{DF}) can be written as:

$$GRA_{DF} = \Phi_{DF} \times up_{DF} \times f(T) \times f(DO) \times f(food_{DF}) \quad (20)$$

Benthic alga, bacteria and meiobenthos are energy sources for deposit feeder.

Mass concentration of Bacteria (Bac), Φ_{Bac} ($gN m^{-3}$), is written by:

$$\frac{\partial \Phi_{BAC}}{\partial t} = UPT - RES_{BAC} - MORT_{BAC} - EXCR_{BAC} - PRED_{BAC} \quad (21)$$

where UPT is the uptake term,

$$UPT = \Phi_{BAC} \times up_{BAC} \times f(T) \times f(DO) \times f(BAC) \quad (22)$$

where $f(BAC)$ is a function of bacteria density.

Bacteria is a prey for meiobenthos and deposit feeder, RES_{BAC} , $MORT_{BAC}$, $EXCR_{BAC}$ and $PRED_{BAC}$ are similar to those of meiobenthos.

3. RESULTS AND DISCUSSIONS

(1) Comparison between calculation and observation

a) Chlorophyll-a and Dissolved Oxygen

Figure 5 compares the calculated results with observation for (a) chlorophyll-a and (b) DO near water surface (layer 2), and (c) DO near the bottom (layer 8) at segment 2. In Fig. 5, two calculation results are presented by “solid line” for case “without tideland” and by “dash-dotted line” for that “with tideland”, while the observation is expressed with open circle (o).

In general, the model reproduced seasonal variation found in the observation although it failed on several occasions; for example, the model over-predicted chlorophyll-a around September and October (Fig. 5a), and either under- or over-predicted DO near the bottom layer for December-March or July-August as indicated in Fig. 5c.

Figure 5a suggests that the benthic system can reduce chlorophyll-a concentration in shallow area (segment 2), for example, by $17.7 mg/m^3$ in September which is about 14% of the chlorophyll-a concentration, $127.5 mg/m^3$, without the benthic system and similarly by $22.0 mg/m^3$ in October corresponding to 29 % of the chlorophyll-a, $75.0 mg/m^3$, without the “tideland”. The tideland’s effect on chlorophyll-a was prominent in September and August (Fig. 5a).

Fig. 4. Block diagram showing relationship among state variables in pelagic and benthic system.

(a) Chlorophyll-a in the surface layer at Segment 2.

(b) DO in the surface layer at Segment 2.

(c) DO in the bottom layer at Segment 2.

Fig. 5. Temporal variations of (a) chlorophyll-a, (b) DO in the surface water, and (c) DO in the bottom water at segment 2; open circle($\circ$) for observation at A13 (Fig. 2), solid line for the case without “tideland”, and dash-dotted line for that with “tideland”.

Calculated DO in Figs. 5b,c indicates only small effect of the “tideland”. Model calculation also qualitatively reproduced nature of DO found in observation; that is, higher DO concentration in the surface layer (Fig. 5b) than in the bottom layer (Fig. 5c) around June to October; this means simulation soundly reproduced stably-stratified thermal structure in the area in summer time.

b) Benthic state variables

Figures 6a-d show one year variations of the calculated and observed mass densities of benthos. Initial density of each organism in the benthic system is listed in Table 1, and the parameters used for the calculation are shown in Table 2.

It may be noted that comparison between observation and calculation in Fig. 6 remains only at qualitative level since the benthos’ observation was made in 1996 while the water qualities were observed in 1998, and so the target year of the simulation was 1998. In Fig. 6e, bacteria concentration is also shown, though there is no observation available for comparison.

In Fig. 6, observed mass densities of benthic algae, meiobenthos and deposit feeder show their peaks in August, and these patterns are quite closely correlated with variation of TN concentration in Anggara and Kitada (2004).

The calculation reproduced relatively well seasonal variation of “meiobenthos” (Fig. 6b) and gave qualitative fits to the annual average

(a) Benthic algae

(b) Meiobenthos

(c) Deposit Feeder

(d) Suspension Feeder

(c) Bacteria

Fig. 6. Comparison of the model calculation and the observation on the seasonal variation of benthic organism. Solid circle (●) is the observation data, and the solid line is the calculation result.

Table 1. Typical initial values of microorganism applied in the study

Organism	Existing amount
Benthic alga	2.2 (g N/m ³)
Meiobenthos	0.045 (g N/m ²)
Deposit feeder	0.35 (g N/m ²)
Suspension feeder	2.4 (g N/m ²)
Bacteria	0.035 (g N/m ³)

concentrations of “benthic algae” (Fig.6a), “Meiobenthos” (Fig.6b), and “deposit feeder” (Fig.6c); that is, the observed annual averages are 3.5 gN/m³ for “benthic algae”, 0.12 gN/m² for “Meiobenthos”, and 0.44 gN/m² for “deposit feeder”, while those of the calculated were 2.7gN/m³, 0.16 gN/m², and 0.63 gN/m², respectively.

The “suspension feeder” includes shell fish such as philippinarum (“asari” in Japanese), and may have its peak value in spring and early summer. The calculation in Fig. 6d qualitatively captured this feature; the annual average of the calculated suspension feeder of 1.2 gN/m³ was again close to the observed value, 1.4 gN/m³.

Seasonal patterns of mass densities of the calculated “bacteria”, “meiobenthos”, and “deposit feeder” showed small variations and were similar each other as in Figs.6b,c,d, reflecting they get food mainly from detritus. These features of the small seasonal variations in “bacteria” and “deposit feeder” were observed also in the “Banzu” tideland in Tokyo Bay (Nakata and Hata⁽¹⁴⁾).

By considering uncertainties included in the observation it may be concluded that the model reasonably well represents ecological interactions and that the model can reproduce complex seasonal biomass behavior consistent with the observed characteristic, for example, high activity in warm season.

Table 2. List of parameters used in the benthic equations

Symbol	Description	Value *
RPP	Specific photosynthetic rate of benthic alga	1.0
ars _{BA}	Fraction of activity respiration photosynthesized by benthic alga	0.05
rrs _{BA}	Specific rest respiration of benthic alga	0.03
extra _{BA}	Fraction of extra release on photosynthesized by benthic alga	0.07
mor _{BA}	Mortality rate of benthic alga	0.04
up _{MB}	Specific uptake rate of meiobenthos	0.4
ars _{MB}	Fraction of activity respiration uptake by meiobenthos	0.4
rrs _{MB}	Relative rest excretion of meiobenthos	0.01
ass _{MB}	Assimilation efficiency of meiobenthos	0.5
mor _{MB}	Natural mortality rate of meiobenthos	0.01
up _{SF}	Maximum uptake rate of suspension feeder	4.0
ars _{SF}	Fraction of activity respiration uptake by suspension feeder	0.3
rrs _{SF}	Relative rest excretion of suspension feeder	0.01
ass _{SF}	Assimilation efficiency of suspension feeder	0.7
mor _{SF}	Natural mortality rate of suspension feeder	0.03
up _{DF}	Specific uptake rate of deposit feeder	0.4
ars _{DF}	Fraction of activity respiration uptake by deposit feeder	0.4
rrs _{DF}	Relative rest excretion of deposit feeder	0.03
ass _{DF}	Assimilation efficiency of deposit feeder	0.6
mor _{DF}	Natural mortality rate of deposit feeder	0.01
up _{Bac}	Specific uptake rate of bacteria	2.5
ars _{Bac}	Fraction of activity respiration uptake by bacteria	0.3
rrs _{Bac}	Relative rest excretion of bacteria	0.02
ass _{Bac}	Assimilation efficiency of bacteria	0.4
mor _{Bac}	Natural mortality rate of bacteria	0.1

* the values determined based on Suzuki et al.⁽¹⁾. Unit is day⁻¹

(2) Prediction of water quality improvement by “tideland”

Effects of the “tideland” on water qualities were quantitatively examined using calculation results by the two models; one without “tideland (without benthic system)” and another one with “tideland”. For the investigation, following scenarios were considered: (1) no reduction in nutrient’s inputs (2) 30% reduction in nutrient loading from the freshwater entering the bay from rivers and waste water treatment plants (WTPs), and (3) 30% reduction in the nutrient input from sediment. Simulation cases associated with the scenarios are listed in Table 3.

Effects of the nutrient reduction measures were evaluated by focusing on the two most important indices of eutrophication, DO and chlorophyll-a concentrations.

Figures 7 and 8 show cumulative frequency of the calculated chlorophyll-a concentrations, based on one-day averaged values for one year of 1998, in 6 cases shown in Table 3; Figure 7 is for “surface” water, while Figure 8 is for “bottom” water.

From Figs 7 and 8, the following things can be known: (i) Comparison of solid line (no “tideland”) with dash-dotted line (with “tideland”) suggests the “tideland” can reduce chlorophyll-a concentration by about 14 mg/m^3 at its largest near the coast line (Fig. 7a), which corresponds to 11% of the largest chlorophyll-a concentration, and this effect gradually decreases toward the mouth of the bay (see Figs. 7b and 7c). (ii) Meanwhile, reduction in the bottom layer (Fig. 8) is visible only in the shallow area near the coast (see the difference between solid and dash-dotted lines in Fig. 8a), and the effect of the “tideland” is almost invisible at the middle (Fig. 8b) and the mouth of the bay (Fig. 8c). (iii) 30% reduction of the nutrient inputs through rivers and WTPs leads to slight decrease of the chlorophyll-a concentration (compare solid line and open square in Fig. 7). (iv) Figures 7a and b also indicate that “tideland” (dash-dotted line) has almost same effect as 30% reduction of nutrient release from sediment (the symbol “+”) on the chlorophyll-a reduction. (v)

Table 3. Scenario of calculation case[#]

Base case	Without “tideland”
Case 1	Same as “base case” but for with “tideland”
Case 2	30% reduction in nutrient inputs through rivers and WTPs without “tideland”
Case 3	30% reduction in nutrient resuspension from sediment without “tideland”
Case 4	Same as Case 2 but with “tideland”
Case 5	Same as Case 3 but with “tideland”

[#]Calculations with “tideland” includes the benthic system

Examination of predicted chlorophyll-a concentrations in Fig. 7 shows that various methods of nutrient emission control are more effective in the shallow area near the Toyokawa River than the downstream area near the open sea.

Figure 9 shows calculated DO in the surface layer at segment 2 under the various conditions (see Table 3). From Fig. 9, it can be inferred that the benthos system at the tideland shows no-visible effect on the

(a) Chlorophyll-a: surface layer at segment 2.

(b) Chlorophyll-a: surface layer at segment 11.

(c) Chlorophyll-a: surface layer at segment 29.

Fig. 7. Comparison of cumulative frequency distributions of chlorophyll-a (mg m^{-3}) concentration for all cases (Table 3) at segment 2, 11 and 29 near the surface in 1998.

DO in the surface water near the river mouth; this situation was the same also in the middle and the mouth areas of the bay, though figures for them are not shown in this paper. The assumed control measures of nutrients also do not show visible change in DO (see the cases 2 to 5 in Fig. 8). These results in Fig. 8 partly suggest DO concentration is mainly determined by fluid dynamical nature of the bay water; that is, O_2 gas transfer at the air-sea water interface and its transport by vertical mixing in the water affected by density stratification, etc. DO behavior in the bottom layer was similar to that in the surface layer.

(a) Chlorophyll-a: bottom layer at segment 2.

(b) Chlorophyll-a: bottom layer at segment 11.

(c) Chlorophyll-a: bottom layer at segment 29.

Fig. 8. Same as Fig. 7 but for the bottom layer.

Fig. 9. Comparison of cumulative frequency distributions of model calculated dissolved oxygen ($mg\ L^{-1}$) in all cases (Table 3) in the surface layer at segment 2.

4. CONCLUSION

A model which combined benthos system with CE-QUAL-W2⁷⁾ was developed and used to examine effects of the benthic system in tideland on chlorophyll-a and dissolved oxygen concentrations under the scenarios of reduction in nutrient emissions (Table 3). The major findings are as follows:

- (1) The model reproduced the seasonal variations of chlorophyll-a and DO shown in the observation. The model also reasonably well represented seasonal patterns of benthic species such as meiobenthos and suspension feeder.
- (2) The results of various scenarios for nutrient loading reduction with and without “tideland” (benthic system) suggested that the benthic system can decrease chlorophyll-a in shallow area but gives almost no effect on dissolved oxygen concentration. Effect of the “tideland” (benthic system) in Atsumi Bay on the chlorophyll-a reduction was equivalent to the scenario of 30% reduction in nutrient resuspension from sediment.
- (3) The decrease in chlorophyll-a due to the benthic system in the tideland were propagated to the middle of Atsumi Bay, but not to the mouth of the bay.
- (4) Finally, as shown in the temporal variations of chlorophyll-a concentrations affected and not-affected by the “tideland” system (Fig. 5a), effects of the tideland are not always same, suggesting importance to consider simultaneously physical, chemical, and biological factors of the problem. We recognize further investigation is necessary to this problem; especially on the benthic model.

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