Spatial Distribution of Sediment Quality in Tokyo Bay through Benthic-Pelagic Coupled Modeling Approach

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A critical aspect of water quality modeling, particularly for long term predictions and considering measures against hypoxia and anoxia, is the long-term estimation of sediment quality. The objective of this study is to reproduce spatial distribution of sediment quality in Tokyo Bay, particularly particulate organic carbon content (POCC) of sediment, by adopting integrated, benthic-pelagic coupled, layer-resolved, and process based ecosystem model. This model could reproduce spatial distributions of sediment quality, including water content (WC), POCC, total nitrogen content (TNC) and total phosphorous content (TPC), showing the largest contents at the central part of the inner bay. Robustness of the model for long term formation of sediment quality has been proved through this study.

Key Words : layer-resolved sediment quality model, spatial distribution, particulate organic carbon content

1. INTRODUCTION

Tokyo Bay is one of the most polluted bays in the world facing difficulties in controlling hypoxia and anoxia during summer even after considerable efforts during the past decades for reducing external loads into the bay. To consider measures for improving hypoxia and anoxia, it is essential to develop a predictive model capable of reproducing long-term water and sediment quality considering their interactions. Many of the models have considered only seasonal and annual reproduction¹,² while some of the others have done decadal reproduction coupling with sediment models but mostly limited to two-layer or multi-layer models excluding the formation process of sedimentary bed itself³,⁴.

We have been developing a long-term predictive model aiming to reproduce long-term dynamics of water and sediment quality, including realistic process of sediment formation⁵,⁶. Their reproducibility was, however, validated comparing with only a data set of water quality, and thus further validation for sediment quality should be made along with the model improvement. The objectives of the present study are therefore to consider reproducibility of sediment properties, including their spatial variation and the performance of realistic sediment formation capacity. In order to improve the reproducibility of spatial distribution of sediment quality, calculation of the porosity considering the accumulation and erosion of inorganic sediment and organic materials is essential, which will be examined in this paper. Robustness of the model for long term simulation will also be considered by applying to 20-year period computations.

2. METHODOLOGY

(1) Description of benthic and pelagic sub-models
An integrated benthic-pelagic coupled, layer resolved and process based ecosystem model was developed to reproduce the water quality and sediment quality in Tokyo Bay. Integrated model constituents were a multi layered ecosystem model, a quasi-three dimensional hydrodynamic model which has been developed based on Navier-Stokes equations with the hydrostatic and Boussinesq approximations, a wave hindcasting model and a sediment deposition and erosion model considering inorganic sediment transport. Model state variables and included processes were shown in Fig.1. Adopted expressions for biochemical kinetic processes were basically based on formulae adopted in conventional models.

The pelagic model was based on the three-dimensional advection-diffusion equation in sigma coordinates while the benthic model was based on the one-dimensional vertical advection-diffusion equation in Cartesian coordinates. Governing differential equations were solved using finite difference method with the fourth order Runge-Kutta method. Model parameters were basically set following the reference values and sensitivity analyses during the tuning process.

The thickness of each layer in bed was renewed after each time step based on updated POCC, and then the concentrations of state variables were renewed accordingly. In particular, change in WC due to change in POCC at each time step was considered in the model. According to Fig.2 change in water volume changes the layer thickness. It was assumed that the volume of dry sediment during the half time step was constant and this gave us the relationship shown in equation (1) where \( V_T \) is the total volume of the control volume, \( \phi \) is the porosity and \( n \) is the time step.

\[
V_T^{n+1} = V_T^n (1 - \phi^n)/(1 - \phi^{n+1})
\]  

The magnification factor expressed by \( M_F = (1 - \phi^n)/(1 - \phi^{n+1}) \) was computed and after each time step the layer thicknesses and the concentrations of the state variables were renewed.

(2) Coupling of benthic model and pelagic model

Benthic and pelagic models were coupled through interaction layer flux exchanges. Particulate matter settling flux or erosional flux depending on the bed shear stress and critical shear stress on settling or erosion, inter boundary flux between sediment-water interface due to advection and diffusion were considered in the model.

Modeling of depositional flux or erosional flux of particulate matter is one of the most important processes in order to reproduce consistent spatial distribution of sediment quality. Depositional flux were calculated from equations (2a) and (2b) while erosional flux were calculated from equations (3a) and (3b):

\[
F_D = \sigma_{ij} C_{ij}^{n+1} \left( 1 - \frac{\tau_b}{\tau_D} \right) \quad \text{if} \quad \tau_b < \tau_D \quad (2a)
\]

\[
F_D = 0 \quad \text{if} \quad \tau_b > \tau_D \quad (2b)
\]

\[
F_E = E_o \left( \frac{\tau_b}{\tau_E} - 1 \right) \quad \text{if} \quad \tau_b > \tau_E \quad (3a)
\]

\[
F_E = 0 \quad \text{if} \quad \tau_b < \tau_E \quad (3b)
\]

where \( F_D \) is the depositional flux calculated at the bottom of the water column, \( F_E \) is the erosional flux, \( \tau_b \) is the bed shear stress (BSS) modeled as the vector summation of current induced bed shear stress (CBSS) and wave induced bed shear stress (WBSS), \( \tau_D \) is the critical BSS for deposition, \( \tau_E \) is the critical BSS for erosion, \((i,j,k)\) refer to a grid point,
$C_{ijk}^{n+1}$ is the concentration of any particulate matter in water column, $\sigma_{ijk}^\sigma$ is the settling velocity of corresponding particulate matter and $E_o$ is the empirical erosion rate parameter.

(3) Application of model to Tokyo Bay

a) Model grid system

Model grid system for both benthic and pelagic sub models were generated to coincide to each other with (2 km × 2 km) horizontal resolution while vertical grids were generated independently. The pelagic model has 10-sigma layers in vertical while the benthic model has 25 layers with changing thicknesses.

b) Initial and boundary conditions

Uniform initial conditions were given for all the state variables in the pelagic model referring to the data while initial POCC was given with zero values for all other state variables of benthic model. Boundary conditions were given at the bay entrance and rivers.

c) Model forcing and validation

The model was forced by hourly meteorological data, daily river discharge data and instantaneous tidal motion. Simulation was started form April 1999 and continued for twenty-year period with the same annual boundary conditions. The model was validated through detailed comparison of seasonal variations of variables in the water column with those of observations for the period of April 1999 to March 2000(6,10).

3. RESULTS AND DISCUSSION

The model was first tuned and examined through the sensitivity analysis of critical parameters and then validated comparing with observed spatial variation in sediment quality(9) along with the analysis of model robustness.

(1) Sensitivity analysis on sediment layers

Sediment model comprised with multi layers where layer thicknesses were changing based on POCC. Confirming the thickness of total effective sediment layer, the number of layers and the initial layer thicknesses were important in estimating sediment flux which was affecting both water and sediment quality. Hence, a sensitivity analysis was made for one year period of computation assuming initial particulate organic carbon is totally refractory to examine the effects of total sediment layer thickness, number of layers within the sediment, individual layer thicknesses and surface layer thickness in sediment on overall results especially, on sediment flux. It has been found that the thickness of the surface layer of sediment has a considerable effect on the sediment flux release while the others have no significant effect. Fig.3 shows the variation of ammonia flux for different surface layer thicknesses in sediment column at one data collected station called Chiba Light House (CLH). It was clear that when the surface layer thickness of the sediment gets smaller flux can easily release to the water column resulting increase in bottom concentration of nutrients in water while reducing surface concentration of nutrients in sediment. At the same time, since the oxygen flux to sediment which has been considered as sediment oxygen demand (SOD) has increased (Fig.4) with the reducing surface layer thickness in sediment, duration of hypoxic or anoxic water has increased.

Fig.3 (a) Simulated bottom ammonia variation in water column, (b) surface ammonia variation in sediment column, (c) bottom oxygen variation in water column with (I) 1mm, (II) 3mm and (III) 5mm surface layer thickness in sediment.
ensuing increased duration of flux release (Fig.5). On the other hand when the thickness of the surface layer of sediment was increased, increased concentrations of nutrients have released flux with a larger peak value during a short period. Those sensitivity analysis results have confirmed the consistency of the model. According to the Fig.6 simulated bottom dissolved oxygen concentration in water column when the surface sediment layer thickness got 1mm, was more realistic with data\textsuperscript{10}. Hence, this analysis has been concluded that the multi-layered sediment model with maximum 1mm surface layer thickness gives the most realistic reproducibility of flux release in Tokyo Bay.

(2) Spatial distribution of sediment quality

Spatial distribution of sediment quality parameters such as WC, POCC, TNC and TPC, were validated with the data collected for the year 2001\textsuperscript{9}. Simulated results of spatial distributions of sediment quality parameters in the twentieth year of simulation have been used for the validation (Fig.7). The computed spatial distribution of POCC was consistent with the measurements showing high concentration at the central part of the bay. Over estimation of POCC may be a result of under estimation of accumulated inorganic sediment in the model. Mainly, inorganic sediment enters to the water column at river boundaries which have been considered as uniform during each month of the year and settles down in the water and accumulates on the surface of the sediment. There is a possibility to change those monthly inorganic sediment concentrations during extreme weather conditions. Other than that, modeling of settling velocity of particulate matter may have an important effect on settled quantities where the model has considered constant settling velocity depending on the type of material.

The computed spatial distribution of WC was consistent with the measurements showing high concentration at the central part of the bay. Simulated WC was somewhat over estimated due to the over estimation of POCC. According to the data analysis, it has been revealed that the WC and POCC have a positive correlation, which was well reproduced in the model.

Moreover, the computed spatial distribution of TNC and TPC were consistent with data showing high concentrations at the central part of the bay. Even though the particulate organic carbon (POC) was modeled with three components, particulate organic phosphorus (POP) and particulate organic nitrogen (PON) have not been modeled. Only inorganic components of phosphorous and nitrogen were modeled with dissolved and attached fractions. Hence, in order to validate the model for spatial distribution of nutrients, POC was converted into PON and POP through the Redfield ratio of C: N: P=106:16:1. After adding inorganic and organic components of N and P, TNC and TPC were obtained. Similar to the relationship of WC and POCC, TNC and TPC show positive correlations with the WC and those correlations were well reproduced in the model. Even though the TPC followed the data quantitatively, TNC showed large discrepancy with the data. One of the reasons for this discrepancy may be the difference in C: N ratio at the site from the Redfield ratio. Overestimation of POCC may also cause some overestimation of TNC and TPC.

\textsuperscript{10}Observed and simulated (with 1mm surface layer thickness) dissolved oxygen concentration in water column at CLH
Fig. 8 and Fig. 9 show the long-term computational results. Fig. 8 shows the spatial distribution of POCC with 5-year interval of simulation giving the same pattern of variation increasing the POCC at the central part of the bay. The highest concentration at the central part of the bay was varying yearly until the steady state was reached. Moreover, Fig. 9 shows the results for the formation of sediment bed during 20-year period, with high POCC at the surface and bottom mud layers. Those long term simulated results have confirmed the robustness of the model for long term computations. The spatial distribution of settled particulate matter can be explained in detail with the consideration of BSS since settling or erosion is controlled by BSS. Deposition and erosion of particulate matter were modeled based on the BSS and, critical BSS on deposition and critical BSS on erosion. Since the total BSS has been modeled as a vector summation of CBSS and WBSS, effect of each component can be analysed independently.

The CBSS was highest near the bay mouth while the WBSS stress showed its highest near to the coast. Hence, the total BSS showed the lowest at the central part of the bay (Fig. 10). These results have shown the bottom dynamics were current dominated in the inner part of the bay while it was wave dominated closer to the coast. BSS has a direct correlation with the sediment grain size distribution at the surface of the bed which has been assumed uniform in the model. In general, towards the bay mouth the sandy bottom with intense CBSS creates erosive effect on sediment. Furthermore, the up-welling areas may also have a high potential to build erosional effect due to high CBSS on sediment. The outer coast with higher bottom sand fraction than the central part of...
the bay and shallower characteristics can be affected by south-westward wind causing erosive effect on sediment. In contrast, the central part of the bay, with high cohesive sediment, can be considered as the low energy area where exists reduced wave effect with depth and reduced current effect with insufficient CBSS to reach the critical BSS on erosion ensuing the highest deposition within the bay. Even though the spatial distribution of total BSS has showed generally expected variation, results may be further improved if the sediment grain size distribution is considered in the model.

4. CONCLUSIONS

We have developed a long-term predictive model aiming for reproducing long-term dynamics of water quality and sediment quality in estuaries, including realistic process of sedimentary bed formation. The bed model is based on a multi-layer concept capable of considering the vertical profile of sediment quality, including the porosity, WC, and POCC. Through the sensitivity analysis, we found that adopting the thickness of 1 mm for the surface bed layer gave the most realistic results in terms of nutrient flux release in Tokyo Bay. The robustness of the model was also confirmed applying to a long-term computation.

Using this model, we performed 20-year computation for reproducing sediment quality in Tokyo Bay and found that the computed spatial variation in sediment quality, including POCC, are basically consistent with those in measurements, showing that their highest contents are observed around the central part of the inner bay associated with BSS distribution.

Further improvements should be made especially in the modelling of settling of particulate materials considering the effect of turbulence. More considerations on boundary conditions must also be significant to improve the computational results, including the effect of the oceanic waters intruding into the bay and inorganic sediment flux discharged into the bay through rivers. This modeling approach will be useful for considering long-term strategy to improve anoxia and hypoxia in polluted bays.

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