NUMERICAL SIMULATION OF FLOW AND SEDIMENT TRANSPORT WITH A COUPLED RIVER-LAKE MODEL

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Abstract

To perform a computation of water environments in a eutrophied lake with accurately evaluating pollutant loads in influent rivers, we attempt to develop a coupled river-lake model in which a river-flow simulation is employed with a new simplified horizontal coordinate system, named a horizontal sigma coordinate system, recently presented by the authors. We apply the coupled river-lake model to the numerical simulation of flow and sediment transport in Lake Teganuma, one of well-known eutrophied lakes in Japan. The computational results for the suspended sediment concentration in the river and lake give acceptable agreements with those of the observed data, demonstrating the fundamental validity of the present model. It is noteworthy that the spatial distribution of erosion rate of sediments has a key role on an accurate computation of sediment transport in an urban river estuary.

Keywords: Coupled river-lake model; Horizontal coordinate system; Pollutant load; Sediment transport; Lake teganuma

1. INTRODUCTION

To manage and control water quality environments in a eutrophied lake, it is quite important to quantitatively evaluate discharge and pollutant loads in influent rivers. In computations of water environments in a lake, the discharge and pollutant loads in influent rivers are usually given as boundary conditions (*e.g.* Matsunashi et al., 2002). However, the observed data at the mouth of influent rivers are poorly complete. Furthermore, in the estuarine section of rivers, the deposition and erosion processes of sediments may vary appreciably owing to hydraulic conditions(Nihei et al., 2004), and hence it is required to evaluate pollutant loads in influent rivers with taking account into the dynamical processes of the deposition and erosion of sediments. For these reasons, it is expected to appropriately perform computations for water environments in a lake by a coupling of river and lake models for flow and material transport.

The horizontal scale in lakes is generally much greater than that in influent rivers. If the horizontal coordinate and grid size in a river model are adopted as same as those in a lake model, the horizontal grid resolution in a river model is not enough fine to accurately evaluate the velocity in river. It is therefore necessary to employ different types of horizontal coordinates in river and lake models.

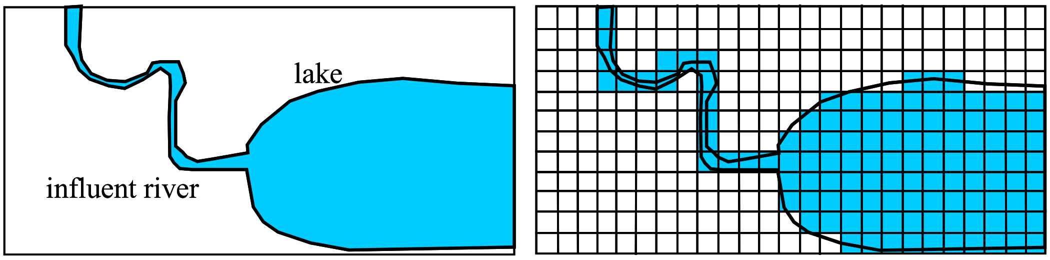
In the present study, we attempt to present a numerical method with the coupling of river and lake models, named a coupled river-lake model. We here introduce the different horizontal coordinates to river and lake models. Especially, in the horizontal coordinate for the river model, we use a new simplified boundary-fitted coordinate system, referred to here as a horizontal sigma coordinate system, recently developed by the authors (Yamasaki & Nihei, 2005). We apply the present coupled river-lake model to the numerical simulation of flow and sediment transport in Lake Teganuma which is one of well-known eutrophied lakes in Japan. To check the fundamental validity of the present model, the computational results are compared with the observed data obtained by the authors (Nihei et al., 2004).

2. OUTLINE OF A COUPLED RIVER-LAKE MODEL

2.1. FUNDAMENTAL CONSTITUTION OF A COUPLED RIVER-LAKE MODEL

To explain a necessary condition for a coupled river-lake model, Fig. 1 represents a schematic view for a lake and an influent river. When the Cartesian coordinate system with a uniform grid resolution is employed for the computational domain shown in Fig. 1 (a), a grid arrangement may be designed as depicted in Fig. 1 (b). It should be noted from Fig. 1 that the boundary shape of the influent river becomes stepwise and furthermore the river width is restricted to the grid size. It means that the numerical accuracy for velocity and sediment transport in the influent river may reduce considerably.

To avoid these problems, we need to choose different types of the horizontal coordinates and grid resolutions to river and lake models. For this purpose, we adopt a river model based on a new simplified boundary-fitted coordinate system which has high numerical accuracy and less computational load, named a horizontal sigma coordinate system (Yamasaki and Nihei, 2005). On the other hand, in the lake model, we use the Cartesian coordinate system, mostly taken for lake-flow computations. To consider the interaction of the river and lake models, the computational results of the river and lake models are exchanged at the mouth of influent rivers.



(a) Schematic view (b) Grid arrangement

Fig. 1 An example of grid arrangement based on the Cartesian coordinate system for river and lake models

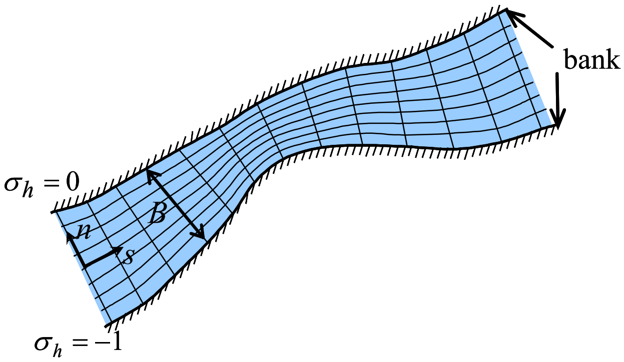


Fig. 2 Definition of the horizontal sigma coordinate system

2.2. OUTLINE OF A RIVER MODEL

On the horizontal coordinate system in the river model, as mentioned above, we introduce the horizontal sigma coordinate system based on the fundamental concept of a sigma coordinate system in vertical direction originally developed by Phillips (1957). The original sigma coordinate system makes use of a boundary-fitted coordinate along water surface and bottom with less computational load. Yamasaki and Nihei (2005) applied the original sigma coordinates used in the vertical direction to the horizontal coordinate system. The horizontal sigma coordinate system can precisely express bank boundaries with less computational load. Fig. 2 shows the definition of the horizontal sigma coordinate system $\left(s^*, \sigma_h\right)$, given as

$$s^* = s \qquad \sigma_h = \frac{n - B/2}{B}, \tag{1}$$

where s and n represent the streamwise and spanwise directions of an orthogonal curvilinear coordinate, respectively, and B means the river width. The continuity and horizontal momentum equations for a two-dimensional river model based on the orthogonal curvilinear coordinate are translated into those with the horizontal sigma coordinate system as

$$\frac{\partial \eta}{\partial t} + \frac{1}{(1+N)B}\frac{\partial}{\partial s^*}\left(HU_s^* B\right) + \frac{1}{B}\frac{\partial}{\partial \sigma_h}\left(HU_n^*\right) + \frac{HU_n}{(1+N)R} = 0, \tag{2}$$

$$\frac{\partial U_s^*}{\partial t}+\frac{U_s^*}{1+N}\frac{\partial U_s^*}{\partial s^*}+\frac{U_n^*}{B}\frac{\partial U_s^*}{\partial \sigma_h}+\frac{U_s^* U_n}{(1+N)R}=-\frac{g}{1+N}\left[\frac{\partial (H+z)}{\partial s^*}+\frac{\partial (H+z)}{\partial \sigma_h}\frac{\partial \sigma_h}{\partial s}\right]$$
$$+\frac{1}{1+N}\frac{\partial}{\partial s^*}\left(\frac{A_H}{1+N}\frac{\partial U_s^*}{\partial s^*}\right)+\frac{1}{B^2}\frac{\partial}{\partial \sigma_h}\left(A_H\frac{\partial U_s^*}{\partial \sigma_h}\right)-\left(\frac{C_f}{H}+\frac{aC_b}{2}\right)U_s^*\sqrt{U_s^{*2}+U_n^2}, \tag{3a}$$

$$\frac{\partial U_n}{\partial t}+\frac{U_s^*}{1+N}\frac{\partial U_n}{\partial s^*}+\frac{U_n^*}{B}\frac{\partial U_n}{\partial \sigma_h}-\frac{U_s^{*2}}{(1+N)R}=-\frac{g}{B}\frac{\partial (H+z)}{\partial \sigma_h}$$
$$+\frac{1}{1+N}\frac{\partial}{\partial s^*}\left(\frac{A_H}{1+N}\frac{\partial U_n^*}{\partial s^*}\right)+\frac{1}{B^2}\frac{\partial}{\partial \sigma_h}\left(A_H\frac{\partial U_n^*}{\partial \sigma_h}\right)-\left(\frac{C_f}{H}+\frac{aC_b}{2}\right)U_n\sqrt{U_s^{*2}+U_n^2}, \tag{3b}$$

$$U_n^*=U_n+B\frac{U_s^*}{1+N}\frac{\partial \sigma_h}{\partial s}, \tag{4}$$

where U_s and U_n mean the depth-averaged velocities in s and n directions, respectively, U_s^* and U_n^* represent the depth-averaged velocities in s^* and σ_h directions, respectively, H is a total depth ($=\eta+h$), η shows water elevation, h is a water depth g is the gravitational acceleration, A_H describes a horizontal kinematic eddy viscosity, z is the bed height, R denotes the curvature radius in s^* direction, $N=n/R$, C_f means the coefficient of bottom friction $\left(=gn_m^2/h^{1/3}\right)$, n_m is the Manning coefficient and a and C_b represent the vegetation density and the coefficient of vegetation drag, respectively.

The equation for the sediment transport based on horizontal sigma coordinate system is expressed as

$$\frac{\partial (HC)}{\partial t}+\frac{1}{(1+N)B}\frac{\partial \left(HU_s^*CB\right)}{\partial s^*}+\frac{1}{B}\frac{\partial \left(HU_n^*C\right)}{\partial \sigma_h}$$
$$=A_H H\left[\frac{1}{(1+N)^2}\frac{\partial^2 C}{\partial s^{*2}}+\frac{1}{B^2}\frac{\partial^2 C}{\partial \sigma_h^2}\right]+P_k-D_p, \tag{5}$$

where C denotes the suspended sediment concentration (SSC) and P_k and D_p represent the erosion and deposition rates of sediments, respectively. The deposition rate of sediments D_p is formulated by

$$D_p=w_0\alpha_s C, \tag{6}$$

where w_0 is a settling velocity of sediments and α_s means the correction factor if the vertical distribution of SSC is not uniform. When the vertical distribution of SSC is assumed to be a well-known exponential function, α_s is given as

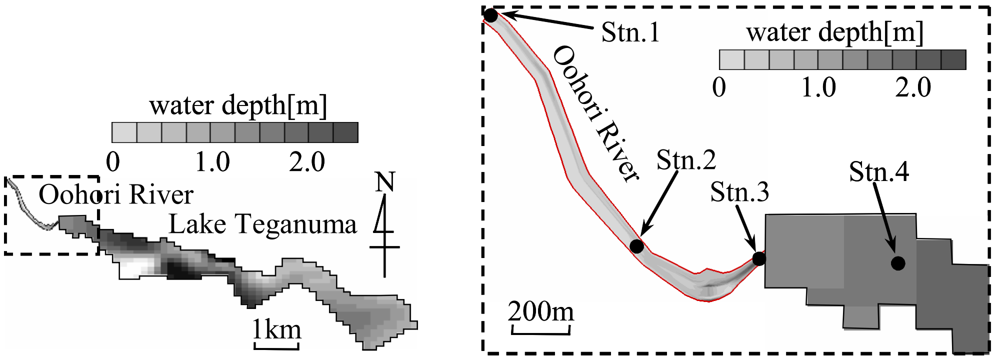
$$\alpha_s=\frac{6w_0}{\kappa U_*}\Bigg/\left[1-exp\left(-\frac{6w_0}{\kappa U_*}\right)\right], \tag{7}$$

where κ shows the Karman constant (=0.40) and U_* represents the friction velocity.

Although the erosion rate of sediments P_k is generally described with a power function as the depth-averaged velocity U or bottom shear stress τ_b, it is doubtful whether this formula for P_k may apply to various flow conditions. We therefore adopt the erosion rate of sediments measured with a new device which can directly obtain an in situ erosion rate of sediments, recently presented by the authors (Nihei et al., 2004).

2.3. OUTLINE OF A LAKE MODEL

We use a two-dimensional lake model for flow and sediment transport. The governing equations in the model are the continuity, horizontal momentum and sediment-transport equations based on the Cartesian coordinate system. The erosion and deposition rates in the equation for the sediment transport are represented with the same treatment for the river model described in the above.



(a) Whole domain (b) Estuarine section of Oohori River

Fig. 3 Computational domain

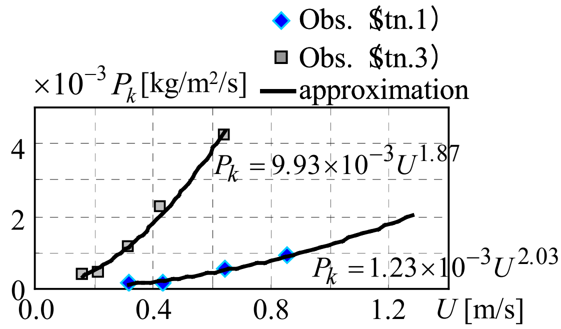
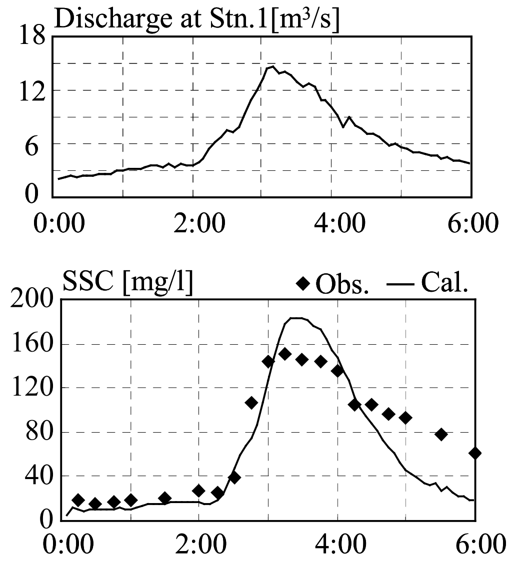


Fig. 4 Erosion rates of sediments in Oohori River (U: velocity)

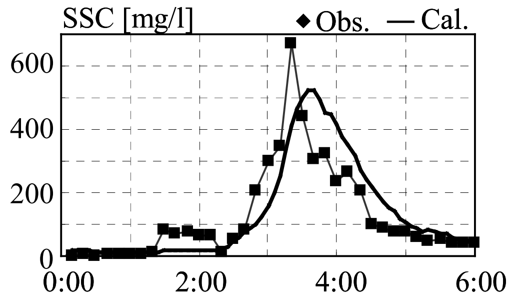
3. NUMERICAL SIMULATION OF FLOW AND SEDIMENT TRANSPORT IN LAKE TEGANUMA

3.1. COMPUTATIONAL CONDITION

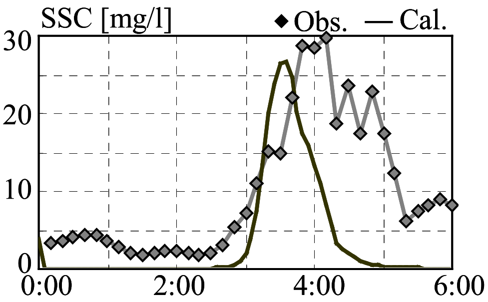
With the coupled river-lake model, we perform the computation of flow and sediment transport in Lake Teganuma and Oohori River, one of influent rivers into Lake Teganuma. The computational domain and horizontal map of water depth are shown in Fig. 3. To compare the computed results with the observed data, the numerical simulation has been done for the period from 0:00 to 6:00 on July 4 in 2003 in which the hydrologic event occurred and we conducted the field measurement for monitoring the discharge at Stn.1 and the SSC at all



(a)Stn.2



(b)Stn.3



(c)Stn.4

Fig. 5 Time series of the observed and computed SSC in the case2

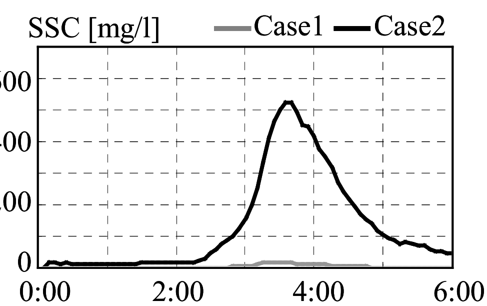


Fig. 6 Time variations of the computed SSC in the case1 and case2

stations (Nihei et al., 2004). The horizontal grid resolution in the lake model is 126m*77m. On the other hand, in the river model, the grid sizes in the streamwise and spanwise directions are 20m and from 1.2m to 6.0m, respectively. As the boundary conditions in the river model, we imply the observed data for water elevation and SSC at the upstream boundary (Stn.1), and employ no-slip condition on right and left bank boundaries. In the lake model, the discharge and SSC computed with the river model is given at the mouth of Oohori River.

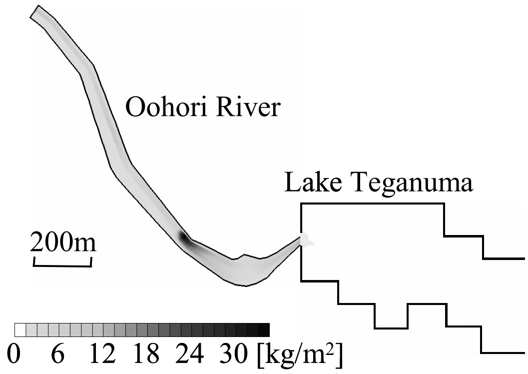
The erosion rate of sediments P_k in the sediment-transport equation is modeled with the observed data obtained by using the new device. Figure 4 represents the observed data for the dependence of the erosion rate of sediments P_k on flow velocity U at Stns.1 and 3. The measured result illustrates that P_k at Stn.3 is quite larger than that at Stn.1 in the same flow conditions, showing the appreciable spatial variation of P_k in the urban river estuary. To investigate the influence of the spatial variation of P_k on the sediment transport in the river and lake, we set two cases of the erosion rate of sediments P_k: in case1, P_k measured at Stn.1 is given to be uniform spatially, while in case2, the measured values at Stns.1 and 3 are adopted in the upstream and downstream regions of the river, respectively.

3.2. COMPUTATIONAL RESULTS

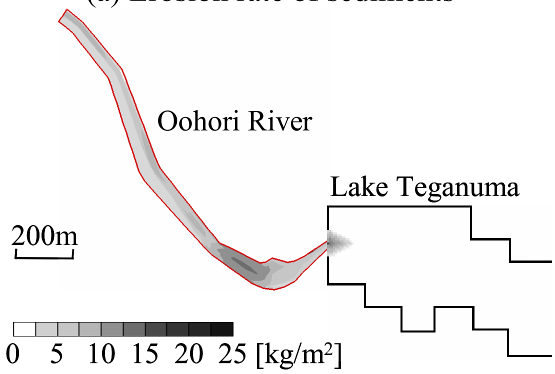
Fig. 5 exhibits the comparison of the computed SSC in the case2 with the observed SSC at Stns.2, 3 and 4 corresponding to the positions in the river, river mouth and lake, respectively. In the figure the time series of the computed discharge at Stn.1 is also depicted. The computational results for SSC give acceptable agreements with the measured data, indicating the fundamental validity of the present coupled rive-lake model in which the horizontal sigma coordinate system is introduced.

To examine the spatial distribution of the erosion rate of sediments on the sediment transport in the river and lake, Fig. 6 displays the computed results of SSC at Stn.3 in the case1 and case2. The computed SSC in the case1 is much less than that in the case2. The result demonstrates that the evaluation of the spatial distribution of the erosion rate of sediments has a key role on the computation of the sediment transport in the estuarine section of the urban river.

Fig. 7 represents the summations of the erosion and deposition rates of sediments during the computational period in the case2. The summation of the erosion rate of sediments in the lake is quite less than that in the influent river. It is noteworthy that there are appreciable spatial variations of P_k in the river estuary and the erosion rate of sediments near Stn.2 becomes remarkably large. The spatial variation of P_k is mainly caused due to that of the streamwise velocity in the river. On the other hand, the peak value of the deposition rate of sediments D_p appears in the downstream region of Stn.2 in which the peak of P_k is found. The larger deposition rate of sediments is also observed around the river mouth due to the rapid decrease of the velocity. The computational result also reveals that most of the sediments flowing from the influent river deposits near the river mouth.



(a) Erosion rate of sediments



(b) Deposition rate of sediments

Fig. 7 Spatial distributions of the summations of the erosion and deposition rates of sediments during the computational period in the case2

4. CONCLUSIONS

We develop a coupled river-lake model to investigate water environments in a lake with accurately evaluating discharge and pollutant loads in influent rivers. We apply the present model to Lake Teganuma. The main conclusions in the present study are as follows:

(1) We present a coupled river-lake model, in which the river model is based on a new horizontal boundary-fitted coordinate, named a horizontal sigma coordinate system.

(2) The computed results of SSC give acceptable agreements with the observed SSC in the influent river and lake, demonstrating the fundamental performance of the present coupled river-lake model.

(3) The computational results indicate that the evaluation of the erosion rate of sediments has a key role on an accurate computation of sediment transport in an urban river estuary.

ACKNOWLEDGEMENTS

This study was partially supported by Japan Society for the Promotion of Science, Grant-in-Aid for Scientific Reserch (C) (2) (no.16560453). The authors would like to express their deep thanks to students in hydraulics laboratory, Department of Civil Eng., Tokyo University of Science, for their help in conducting field observations in the present study.

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