Field measurements and numerical simulation on sediment transport in an urban river estuary

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ABSTRACT: To examine sediment transport in an urban river estuary, we attempt to perform field measurements and numerical simulation in the estuarine section of an urban river. The observed results indicate that the differences of SS fluxes between upstream and downstream regions of the field site vary appreciably in hydrologic events and may be closely related with the maximum discharge in the river. The computational results for suspended solids (SS) concentration are appreciably dependent on the treatment of an erosion rate of sediments in the computation. This fact demonstrates that it is quite important to accurately consider an in situ erosion rate of sediments in computations of sediment transport in the urban river estuary.

1 INTRODUCTION

For appropriate management of water environments in an urban river, lake, and inner bay, it is quite necessary to conduct the monitoring and modeling of pollutant loads from the watershed of urban rivers. To quantitatively evaluate the pollutant loads, we need to accurately obtain a run-off ratio of pollutants in urban rivers. The run-off ratio depends on the complicated flowing-down processes including deposition and erosion processes of pollutants in rivers (Welch and Jacoby, 2004), and then there is little information for the run-off ratio in urban rivers. Especially we have poorly understood an erosional property of sediments in urban rivers under various flow conditions.

In the present study, we attempt to perform field measurements and numerical simulation of sediment transport in an urban river estuary, in which the deposition and erosion processes may vary appreciably due to hydraulic conditions. In the field measurements, we examine the budget of suspended solids (SS) in the estuarine section of the urban river in various hydrologic events and clarify an in situ erosion rate of sediments using a new device recently presented by the authors (Nihei *et al*., 2004a). We also perform the numerical simulation of sediment transport with the measured erosion rates of sediments. In the computation, we adopt a river-flow model based on a new simplified boundary-fitting coordinate system developed by Yamasaki and Nihei (2004).

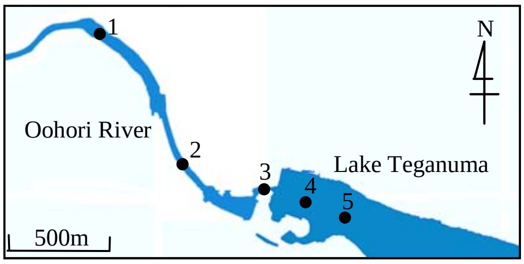


Fig. 1 Location of the study site and the measuring stations.

2 OUTLINE OF FIELD MEASUREMENTS

2.1 *Study site*

The field measurements were done in the estuarine section of the Oohori River flowing into Lake Teganuma, one of well-known eutrophied lakes in Japan, as shown in Fig. 1. The catchment area and length of the Oohori River is about 31 km^2 and 12.9km, respectively. Most of the land use in the catchment is urban district and hence high pollutant loads from point and non-point sources in the catchment flows into Lake Teganuma. Due to the high pollutant loads in the Oohori River, the eutrophication in Lake Teganuma has been appreciable.

2.2 *Method*

To continuously monitor hydrodynamic and SS environments, we conducted continuous measurement for water elevation and turbidity at Stns.1, 3 and 5 as shown in Fig.1; Stns.3 and 1 were at the mouth of the Oohori River and about 1.5km upstream, respectively and Stn.5 was located in the west part of Lake Teganuma. At these stations, we installed memory-type sensors to measure the water elevation, horizontal velocity and turbidity from 18 June to 16 July in 2003. We used the pressure gauges (Diver, Eijikelkamp), the current meter (Compact-EM, Alec Electronics Co., Ltd. in Japan) and the turbidity and Chlorophyll-a sensors with a wiper (Compact-CLW, Alec Electronics Co., Ltd. in Japan).

To measure the discharge, SS and water quality environments in a hydrologic event, we also performed an intensive field survey at Stns.1-3 from 3 July to 4 July in 2003. In this hydrologic event, the maximum rainfall intensity and total amount of rainfall were 17mm/hour and 31mm, respectively. We made water samplings at Stns.1-3 and then analyzed the turbidity, SS and water quality. The velocity in surface layer was observed only at Stn.1 with the current meter. The discharge at Stn.1 was evaluated from the observed surface velocity with a new assimilated method developed by Nihei *et al*. (2004b).

For understanding the erosional property of sediments in this region, furthermore, we use a new device directly measuring an in situ erosion rate of sediments, recently presented by the authors (Nihei *et al*., 2004a), as indicated in Fig.2. Concerning the procedure of the measurement using the device, we first set the device on river bed, stir a rod in the gap between two cylinders and then measure the turbidity in surface layer. We can calculate the erosion rates from the measured turbidity in surface layer. The measurement of the erosion rate was conducted at Stns. 1 and 3. For the detail of the measurements, one can refer to Nihei *et al*. (2004a).

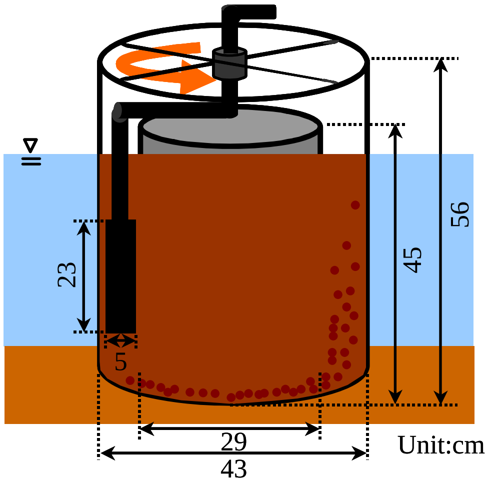


Fig. 2 Schematic view of a new device to measure an in situ erosion rate of sediments.

3 OBSERVED RESULTS AND DISCUSSION

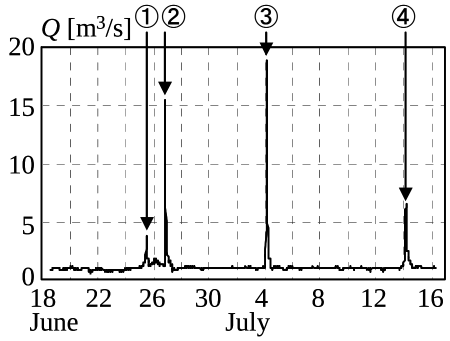
3.1 *Temporal variation of SS environments*

To grasp the fundamental characteristics of sediment transport in the estuarine section of the Oohori River, Fig. 3 shows the temporal variations of the SS concentration observed at Stns.1 and 3 and the discharge at Stn.1. In the period from 18 June to 16 July, there were four hydrologic events, referred to be here as events 1-4, as shown in Fig.3 (a). The event 3 corresponds to the period of the intensive field survey from 3 July to 4 July. In the hydrologic events, the temporal variation of the SS concentration at both the stations appeared considerably with that of the discharge. However, the relationship of the SS concentration between Stns.1 and 3 varied in each hydrologic event: that is, in the events 1 and 4, the maximum values of the SS concentration at Stn.1 were much larger than those at Stn.3 and vice versa in the event 3. In the event 2, the SS concentration at both the stations was comparable. Therefore it should be noted that the differences of the SS environments in each station may vary in the hydrologic events.

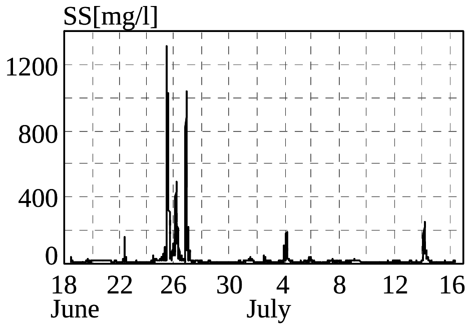
To clarify the SS fluctuations in detail, Fig. 4 shows the time series of the discharge at Stn.1 and SS at Stns.1, 2, 3 and 5 in the event 3 corresponding to the period of the intensive field survey. The SS concentration at Stn.3 was quite larger than those at Stns.1 and 2, as indicated in Fig. 3. Since the lateral inflow from sluices located between Stns.1 and 3 was not confirmed, the increase of the SS at Stn.3 may be caused by the erosion process of river-bed deposits. Furthermore, the fluctuation of the SS concentration in the lake (Stn.5) did not appear in the event 3, indicating that the particulate matters transported from the Oohori River mostly settled down near the river mouth.

3.2 *Deposition and erosion processes*

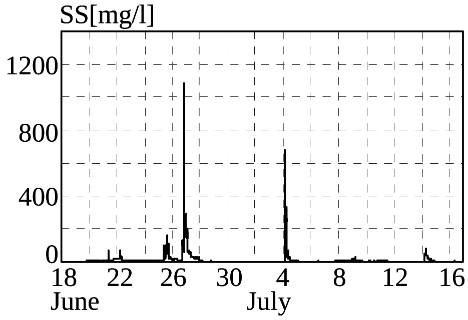
To discuss the relationship between the deposition and erosion processes in each flood event, we calculate the total SS fluxes at Stns.1 and 3 ($\sum L_1$, and $\sum L_3$, respectively) in each flood event. Figure 5 represents the differences of the total SS fluxes at two stations ($=\sum L_1 - \sum L_3$) and



(a) Dischsarge at Stn.1.



(b) SS at Stn.1.



(c) SS at Stn.3.

Fig.3 Temporal variations of discharge and SS.

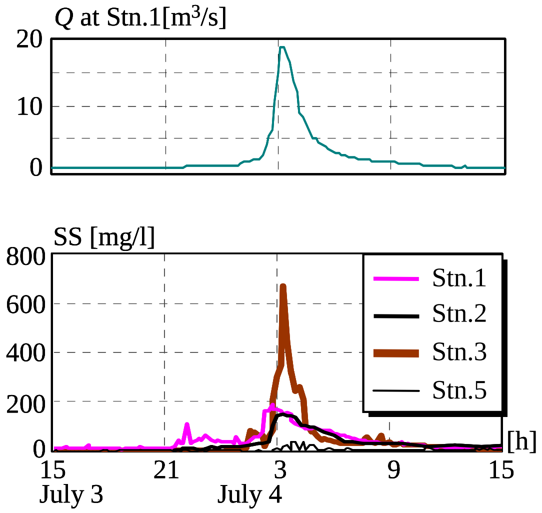


Fig.4 Comparison of SS concentration at Stns.1, 2, 3 and 5 in the event 3.

the maximum discharge $Q_{\max}$ at Stn.1 in four flood events. Noteworthy in the figure is that $\sum L_1 - \sum L_3$ decreases as the maximum discharge $Q_{\max}$ increases. This result means that when the river discharge increases, the fluid shear stress acting on the river bed exceeds the threshold value of the sediment movement and then the pick-up rate of river-bed deposits increases appreciably. These facts demonstrate that the maximum discharge may significantly influence on the sediment transport in the urban river estuary.

To clarify the erosional property of sediments in the estuarine section, Fig. 6 illustrates the erosion rate of sediments P_k versus flow velocity U at Stns.1 and 3. The measured results were obtained using the device as shown in Fig. 2. U means the velocity in the gap between two cylinders. The fitting curves for the measured data are also depicted in the figure. The erosion rate of sediments at Stn.3 was quite larger than that at Stn.1 in the same flow conditions, and hence larger amount of sediments around Stn.3 may be picked up as a river-flow increases.

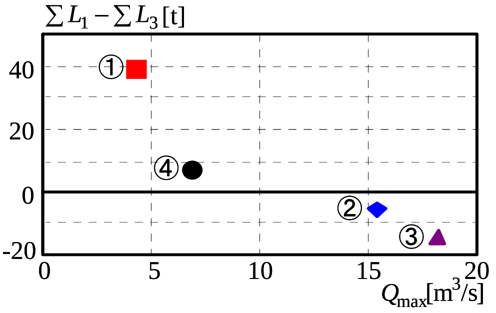


Fig.5 Maximum discharges and the differences of the total SS fluxes, $\sum L_1 - \sum L_3$, in each flood event.

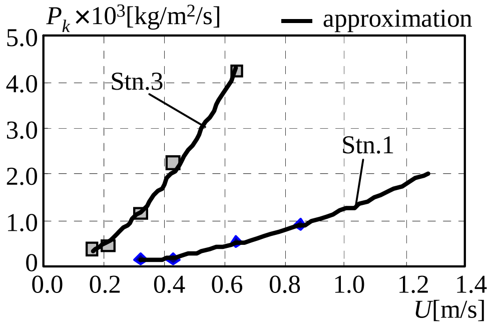


Fig.6 Erosion rate of sediments P_k versus flow velocity U.

4 NUMERICAL SIMULATION

4.1 *Outline of a river-flow model*

To examine SS budget in the urban river estuary, we perform the numerical simulation of sediment transport in the Oohori River. In the computation for the sediment transport in rivers, it is necessary to take account into horizontal morphology of river channel to accurately evaluate flow fields. A generalized coordinate system is widely applied to computations for river flow. However, the generalized coordinate system is more complicated and has higher computational load than Cartesian coordinate system. In the present study, we adopt a river flow model based on a new simplified boundary-fitting coordinate system, named “horizontal sigma coordinate system”, recently provided by the authors (Yamasaki and Nihei, 2004).

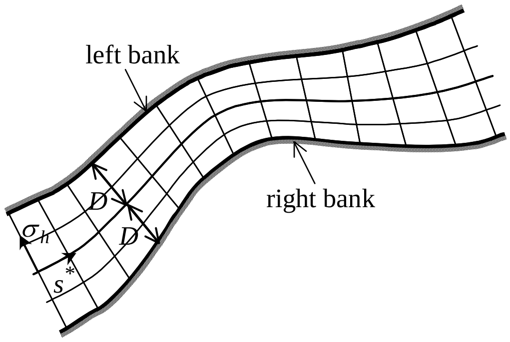


Fig.7 Definition of a new horizontal coordinate system (Yamasaki and Nihei, 2004)

The horizontal sigma coordinate system is based on fundamental concept of sigma coordinate systems, one of simplified boundary-fitting coordinate systems in vertical direction, originally developed by Philips (1957). The sigma coordinate systems are defined along water surface and bottom boundary with less computational load. We shall attempt to apply the sigma coordinate systems into a horizontal coordinate system. Figure 7 illustrates the definition of the horizontal sigma coordinate system $\left(s^*, \sigma_h\right)$, given as

$$s^* = s \,, \tag{1}$$

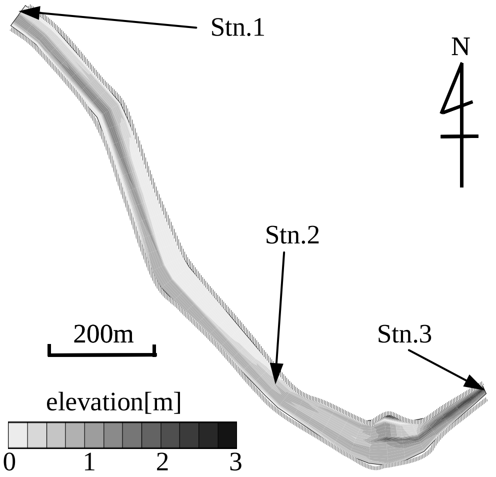


Fig.8 Computational domain.

$$\sigma_h = \frac{-D+n}{2D}, \tag{2}$$

where s and n represent the streamwise and spanwise directions of an orthogonal curvilinear coordinate, respectively, and D means a half of river width as shown in Fig.7. In the present study, the governing equations for a two-dimensional river-flow model based on the orthogonal curvilinear coordinate are transmitted into those based on the horizontal sigma coordinate system. For the detail of the horizontal sigma coordinate system, one can refer to Yamasaki and Nihei (2004).

4.2 *Computational condition*

To compare the computed results with the observed data, a two-dimensional computation for river flow with the present river-flow model described above has been done for the period from 0:00 to 6:00 July 4 in 2003. The computational domain of 1400m*110m covers the estuarine section of the Oohori River as shown in Fig.8. The mesh sizes in the streamwise and spanwise directions are 30m and from 1.2 to 6.0m, respectively. At the upstream boundary of the computational domain, we set the observed data for the water elevation and SS, while an open boundary condition is employed for the other variables. At the downstream boundary, we also give the observed data for water elevation and an open boundary condition for the other variables, respectively. The no-slip condition is used on right and left bank boundaries.

To investigate the influence of the erosion rates of sediments on the sediment transport in the estuary of the urban river, we set two cases of the erosion rates of sediments P_k in the computation: in case 1, the erosion rate P_k measured at Stn.1 is given to be uniform spatially, while in case 2, the measured values at Stns. 1 and 3 are adopted in the upstream and downstream regions, respectively.

4.3 *Results*

Figure 9 displays the computed and observed results of the discharge at Stn.1 and SS concentration at Stns. 1 and 2. The computational results give good agreements with measured results, indicating the fundamental performance of the present numerical model based on the horizontal sigma coordinate system. The computed results for the SS concentration at Stn. 3 in the cases 1 and 2 are indicated in Fig. 10. In the case 1, which the erosion rate is given to be uniform spatially, the computed SS is much less than the observed SS. On the other hand, in the case 2 considering the effect of the spatial variation of the erosion rate, the computational results give acceptable agreements with the observed data. These results demonstrate 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.

5. CONCLUSIONS

We have done the field measurements and numerical simulation in the estuary of the Oohori River and the west part of Lake Teganuma, to investigate the sediment transport in an urban river. The main conclusions in the present study are as follows:

(1) The observed results indicate that the differences of the SS fluxes between Stns.1 and 3, located at upstream and downstream stations in the estuarine section, vary appreciably in each hydrologic event and may be closely related with the maximum discharge.

(2) The computation for sediment transport in the estuary of the Oohori River has been done with a river-flow model based on the horizontal sigma coordinate system. The computational results represent that the numerical accuracy for the computation of the sediment transport may be considerably dependent on the treatment of the erosion rate of sediments.

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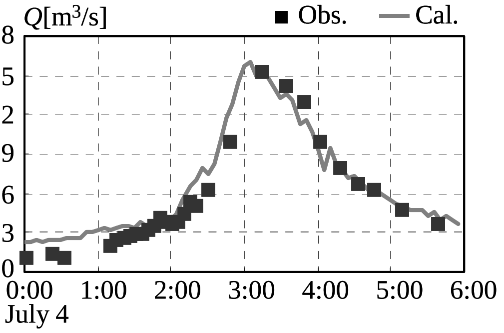
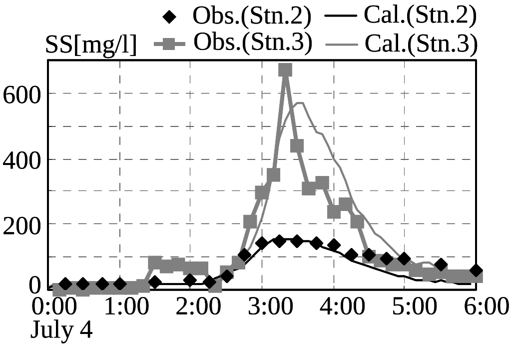


(a) Discharge at Stn.1



(b) SS at Stns.2 and 3

Fig.9 Comparison of the discharge and SS between observed and computed results.

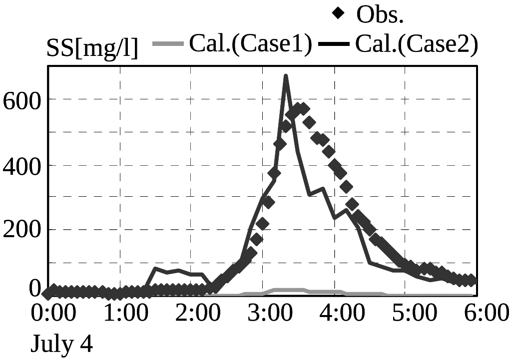


Fig.10 Computed SS at Stn.3 in the cases 1 and 2.

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