Evaluation of flood discharge hydrographs and bed variations in a channel network on the Ota River delta, Japan

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Abstract A channel network consisting of the Ota River floodway and five branched rivers is formed on the Ota River delta. To estimate bed variation and flood discharge distributions in the channel network of the Ota River delta is important for proper river management. The objective of this study is to develop the calculation method of flood flows and bed variations by using time series of water surface profiles measured in the channel network of the Ota River delta. We developed a quasi-3D numerical model for the flood flow and bed variation analyses using time series of observed water surface profiles. The unsteady quasi-3D analysis of flood flows and 2D analysis of bed variations using time series of observed water surface profiles are found to provide good explanations for the flood discharge distributions and bed variations of the channel network on the Ota River delta.

Key words channel network; Ota River delta, Japan; time series of observed water surface profiles; flood discharge distributions; bed variation

INTRODUCTION

A channel network is formed on the Ota River delta, located in Hiroshima prefecture, Japan. The channel network consists of the Ota River Floodway and five branched rivers. Each river flows into Hiroshima Bay and the maximum difference in tidal changes is about 4 m. Therefore, evaluating flood flows, bed variations and flood discharge hydrographs is required for proper river management of the Ota River delta.

Many researchers have studied flood flows and bed variations in a channel network. They mainly developed the flood routing methods of an unsteady 1D flow analysis method in a channels network (e.g. Yen & Osman, 1976; Kanemoto *et al*., 1992; Choi & Molinas, 1993). Ayub *et al*. (2007) studied the sediment dynamics from Ganges River system to Bengal Bay. They developed the 2D flood flow and bed variation analysis method and simulated bed variations and sediment transport with wide seasonal variation and tidal changes. However, in these analyses, hydraulic parameters such as channel resistances have not been properly evaluated, because channel resistances contain various influences such as effects of channel shapes, bed profiles, vegetation, etc.

Effects of river bed profiles, bed variations, vegetation, bifurcation structures, confluences, etc. appear in the time series of observed water surface profiles (Fukuoka, 2005). Fukuoka *et al*. (2004) proposed the unsteady 2D flow analysis method using time series of observed water surface profiles in order to estimate flood discharge hydrographs in any river sections. And, the calculation method using time series of observed water surface profiles has been applied to estimate the flood discharge hydrographs for various river conditions. Fukuoka *et al*. (2006) evaluated the flood discharge hydrographs in the reach with the branched section of the Tone River and the Edo River by a 2D calculation method for flood flow using time series of observed water surface profiles. Abe *et al*. (2009) applied this calculation method to levee breach experiments in the Joganji River and evaluated the inundation discharge hydrographs. Uchida *et al*. (2011) have developed the calculation method of tributary flood discharge hydrographs using the time series of observed water surface profiles along the main channel. This idea can be applied to estimate flood flows and bed variations during a flood in a channel network.

The objective of this study is to develop the quasi-3D calculation method for flood flows and bed variations by using time series of observed water surface profiles in the channel network of the Ota River delta.

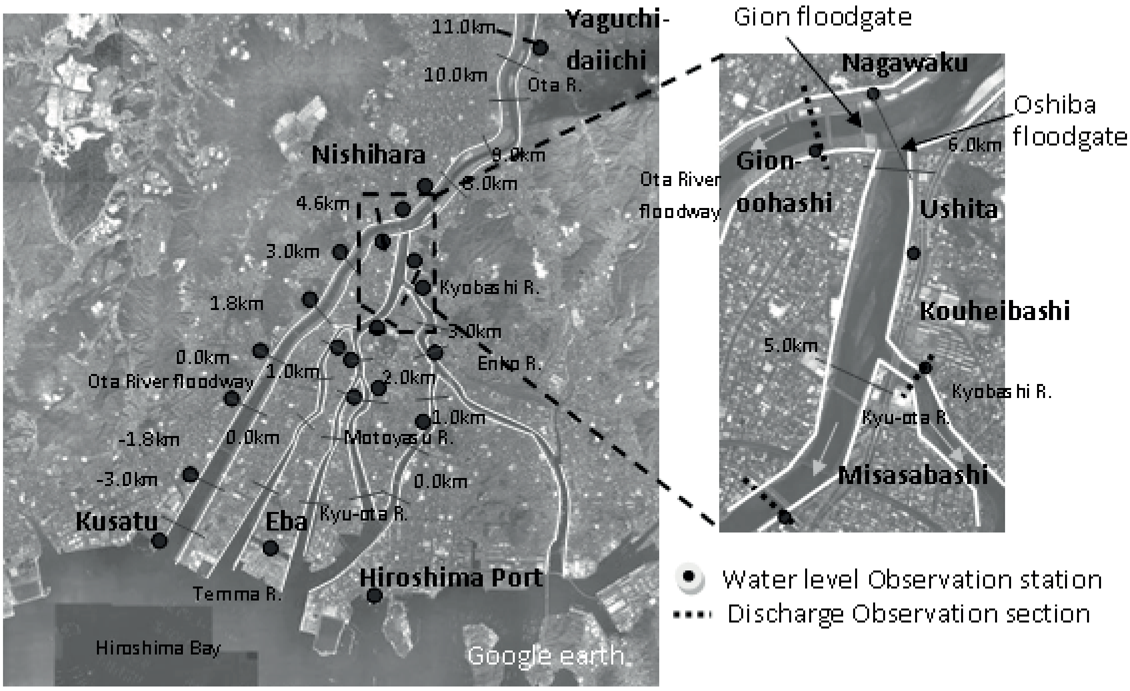


Fig. 1 Ota River delta.

THE OTA RIVER DELTA

A channel network on the Ota River delta consists of the Ota River floodway which was constructed in order to reduce flood inundation in Hiroshima City and five branched rivers (Kyu Ota River, Kyobashi River, Temma River, Motoyasu River and Enko River, see Fig. 1). Each channel flows into Hiroshima Bay where maximum tide difference is about 4 m. At the bifurcation section of the Ota River floodway and the Kyu Ota River, the Gion-Floodgate is located at the side of Ota river floodway and consists of a movable weir with three gates. Oshiba-floodgate is located at the side of the Kyu-Ota River and consists of a fixed weir and movable weir with the three gates.

The characteristics of cross-sectional shape in each channel are as follows. The Ota River floodway is composed of compound cross-sectional channel from 5.8 km to 0.0 km and simple cross-sectional channel from 0.0 km to –3.4 km. The channel widths of the Ota River floodway are about 400 m to 500 m. The branched river is composed of simple cross-sectional channel. The channel widths of the branched rivers (Kyu Ota River, Kyobashi River, Temma River and Motoyasu River) are about 70–150 m from each bifurcation section to 0.0 km. In the downstream of 0.0 km, the channel widths of the branched rivers gradually increase to about 300 m around the river mouth (see Fig. 1).

Figure 1 shows water level observation stations and discharge observation sections of Ota River delta. For understanding the dynamics of flood flow and bed variation in the Ota River delta we installed many water level gauges along the each channel. Flood discharge hydrographs were measured by floats technique at Yaguchi-daiichi (Ota River 11.6 km), Gion-Oohashi (Ota River floodway 5.2 km), Misasabashi (Kyu Ota River 4.2 km) and Kouheibashi (Kyobashi River 5.0 km) observation station. So, we can validate the calculated inflow discharge hydrograph to the Ota River Floodway, Kyu Ota River and Kyobashi River. The cross-sectional bed shape around the bifurcation sections were surveyed at about 50 m intervals of longitudinal distance.

Figure 2 shows the water level hydrographs in the July 2010 flood. In this flood, the high tide occurred about an hour earlier than the flood peak. Figure 3 shows the grain size distributions in the section studied. The bed materials around 13.0 km consist of many cobbles and gravel. On the other hand, the bed materials in the Ota River floodway and the branched rivers (Kyu Ota River, Temma River, Motoyasu River) mainly consist of sands containing little silt and clay.

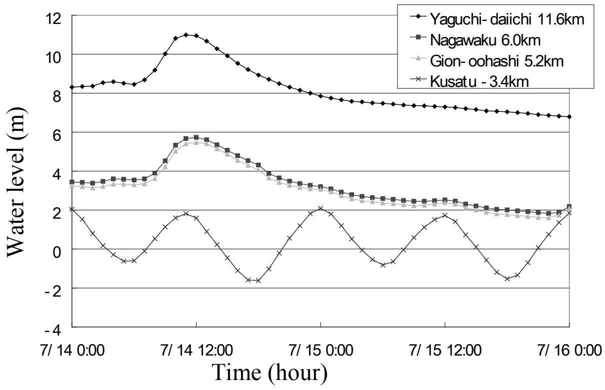


Fig. 2 Water level hydrographs in the flood of 2010.

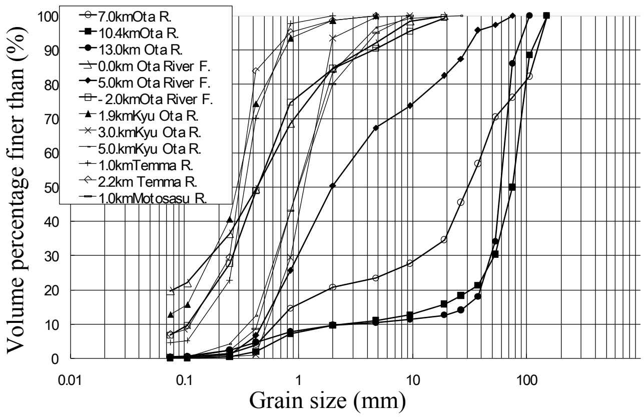


Fig. 3 Grain size distributions in the channels of the Ota River delta.

FLOOD DISCHARGE HYDROGRAPHS AND BED VARIATIONS OF A CHANNELS NETWORK ON THE OTA RIVER DELTA

Flood calculation method using time series of observed water surface profiles of a channel network

In the channel network it is difficult to determine channel resistances and discharge distribution ratio at bifurcation sections, since flood flows in each channel have an influence on each other. The effects of channel resistance, discharge distributions, etc. appear in the time series of observed water surface profiles. So, we determine channel resistances to agree with time series of observe water surface profiles. Therefore, this analysis method using the observed water surface profiles is able to evaluate flood flows, bed variations and discharge distributions in actual river conditions of the Ota River delta.

Figure 4 shows the flow chart of determination of channel resistances and flood discharge distributions in the channel network. In this study, the channel resistance and flood discharge distribution ratio at bifurcation sections were determined from upstream sections toward downstream sections by a calculation method using time series of observed water surface profiles, since the inflow discharge upstream of the channel network is the discharge hydrograph measured at Yaguchi-daiichi observation station. The detailed determination procedure is as follows.

First, we conduct the unsteady quasi-3D flood flow and 2D bed variation analysis in which channel flow resistances are given by conditions of channel shape, bed profile and vegetation. When the calculation results do not reproduce the temporal observed water surface profiles, mean bed profiles after the flood in section (0) and discharge hydrograph at Yaguchi-daiichi observation station, the channel flow resistances in section (0) and downstream of section (0) are adjusted so as to agree with temporal observed water surface profiles in section (0) and discharge hydrograph at Yaguchi-daiichi observation station. The channel flow resistances downstream of section (0) are also adjusted by the observed water level hydrograph at the Nishihara observation station. The channel flow resistances in section (0) are adjusted so as to agree with temporal observed water surface profiles in section (0) (see Fig.4).

Next, channel flow resistances downstream of section (1) are adjusted with the observed water levels at Ushita observation station which is the downstream end of section (1). We adjust Manning's roughness coefficients in section (1) with temporal observed water surface profiles in section (1). If the calculation results reproduce the temporal observed water surface profiles and mean bed elevations in section (1) and section (0), the discharge hydrograph of each river in section (1) are evaluated by this method. A similar process is conducted from section (1) to section (5).

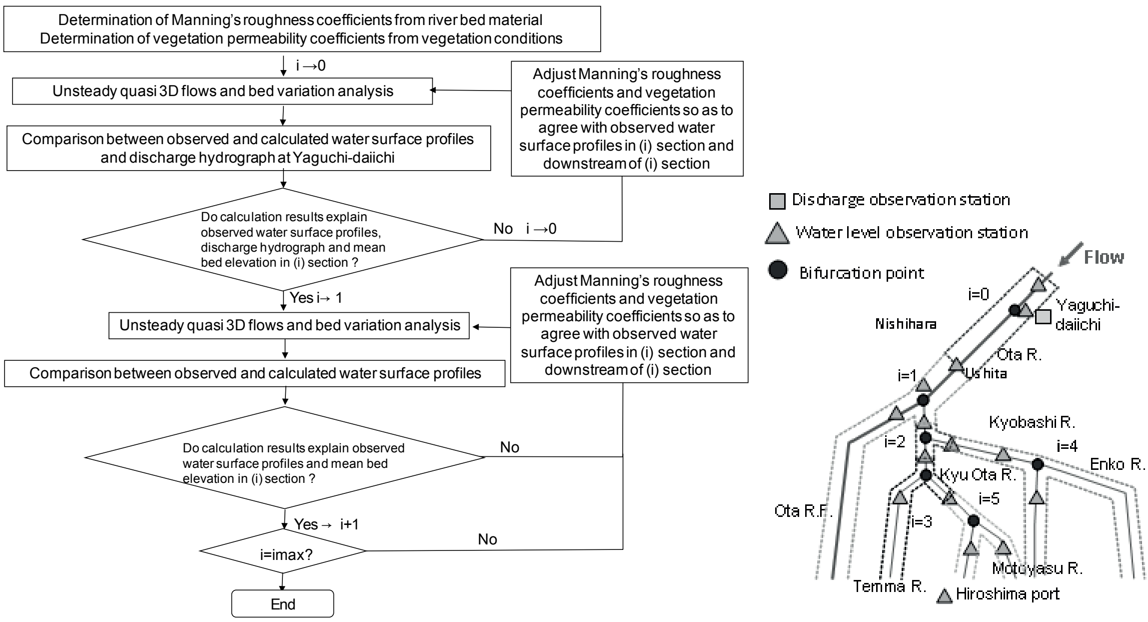


Fig. 4 Flow chart of determination of flood discharge distribution ratio in the Ota River delta.

In the calculation method, the calculated discharge hydrographs in section (1) and (2) are validated by using observed discharge hydrographs in section (1) and (2). We check the channels resistances by comparing with bed materials and bed profiles when those are determined so as to agree with time series of observed water surface profiles.

Therefore, the present calculation method gives the discharge hydrographs in each river reach by determining the channels resistances' so as to agree with temporal observed water surface profiles.

The unsteady quasi 3D flow and 2D bed variation analyses using time series of observed water surface profiles

It is necessary to consider 3D effects of flood flows which control bed variation at the bifurcation sections. We applied the unsteady quasi 3D flow analysis (Uchida *et al.*, 2009) and 2D bed variation analysis using the time series of the observed water surface profiles. The vertical velocity distributions assumed by a cubic curve are determined by using depth averaged velocity and the difference between water surface and bottom velocities. The shear stresses on the river bed and vegetations resistance are calculated by equation (1):

$$(\tau_{sw\xi}, \tau_{sw\eta}) = (gn^2 / h^{1/3} + gh / K^2)\sqrt{u^2 + v^2}(\widetilde{U}, \widetilde{V}) \quad (1)$$

where $\tau_{sw\xi}$ and $\tau_{sw\eta}$ = channel flow resistances by river bed roughness and vegetation in direction of ξ and η ; n = Manning's roughness coefficients; K = vegetation permeability coefficients ; $\widetilde{U}$ and $\widetilde{V}$ = velocities in direction of ξ and η ; u and v = velocities in directions x and y, respectively.

In the branched rivers (Kyu Ota River, Kyobashi River, Temma River, Motoyasu River), there are a number of bridges with piers. The effects of drag forces on bridge piers are estimated by equation (2):

$$(F_\xi, F_\eta) = 0.5 \times C_D A / J \sqrt{u^2 + v^2}(\widetilde{U}, \widetilde{V}) \quad (2)$$

where F_ξ and F_η = drag forces by pier in direction, respectively; Cd = 1.0; Cd = drag force coefficients ; A = project area of pier; J = Jacobian.

The conventional bed variation analysis is conducted by using bed load formula (Ashida & Michiue, 1972) and continuity equations for sediment and grain sizes (Hirano, 1971). The critical tractive force for sediment mixtures is calculated by the modified Egiazaroff formula (Egiazaroff, 1965; Ashida & Michiue, 1972). The suspended sediment transport is calculated by depth averaged continuity of concentrating of suspended load.

The boundary conditions are time series of observed water level hydrographs at Yaguchi-daiichi (11.6 km) and Hiroshima Port observation stations.

Calculation results

Table 1 shows Manning's roughness coefficients and vegetation permeability coefficients which are determined so as to satisfy temporal observed water surface profiles. It is found that Manning's roughness coefficient values contain effects of topography such as sand waves because the coefficients are large compared with those caused by bed materials. (e.g. Manning's roughness coefficient in the Temma River is about 0.012 ($m^{-1/3} \cdot s$) by using Strickler's empirical formula.)

Table 1 Manning's Roughness coefficients and vegetation permeability coefficients.

Manning's roughness coefficients ($m^{-1/3}$ s)						
Ota River, Ota River floodway			Kyu Ota River		Temma River	
12.4–5.8 km	Main channel	0.03	6.2–2.2 km	0.025	3.6–(–2.4 km)	0.03
	Flood channel	0.035	2.2–(–1.6 km)	0.022	Motoyasu River	
5.8–2.0 km	Main channel	0.028	Kyobashi River		2.6–(–2.4 km)	0.022
	Flood channel	0.035	5.2–2.4 km	0.033	Enko River	
2.0–(–3.4 km)	Main channel	0.022	2.4–(–0.8 km)	0.02	2.6km–(–3.1 km)	0.035
	Flood channel	0.035				
Vegetation permeability coefficients (m/s)						
Ota River			Kyu Ota River			
8.0–9.6 km	Right bank	40	6.2–5.0 km	40		
10.4–10.8 km	Right bank	50				
10.8–11.4 km	Right bank	40				
8.0–8.8 km	Left bank	50				
9.6–10.6 km	Left bank	50				

Figure 5 shows the comparison between observed and calculated water surface profiles and mean bed elevations. The calculated water surface profiles show good agreement with observed water surface profiles while they are a little higher than observed water surface profiles in the flood rising period. After 14:00 h, the water surface profile slope became steeper downstream of about 1.0 km due to the ebb tide. Water surface profiles in the Temma River, Kyu Ota River and

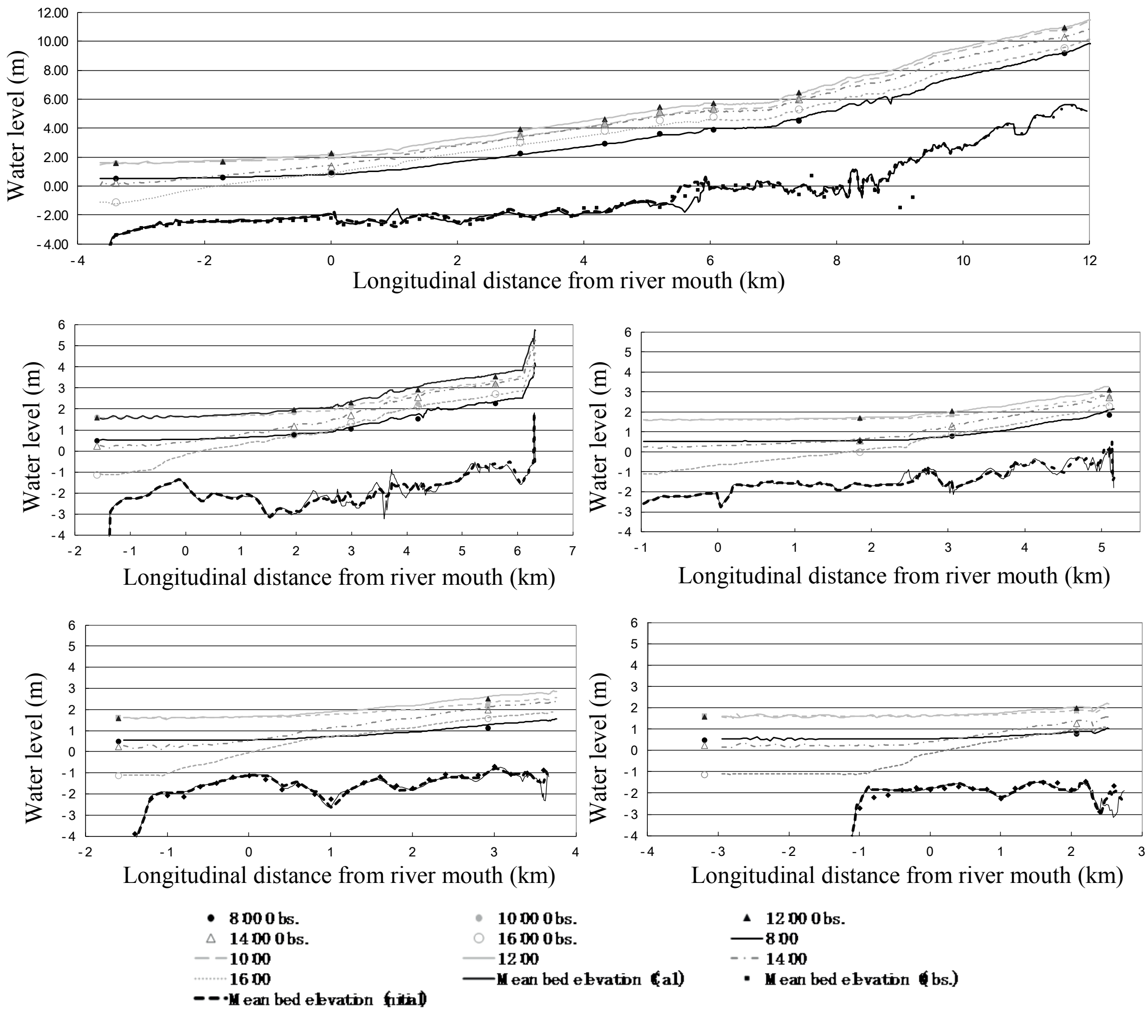


Fig. 5 Comparison between observed and calculated water surface profiles.

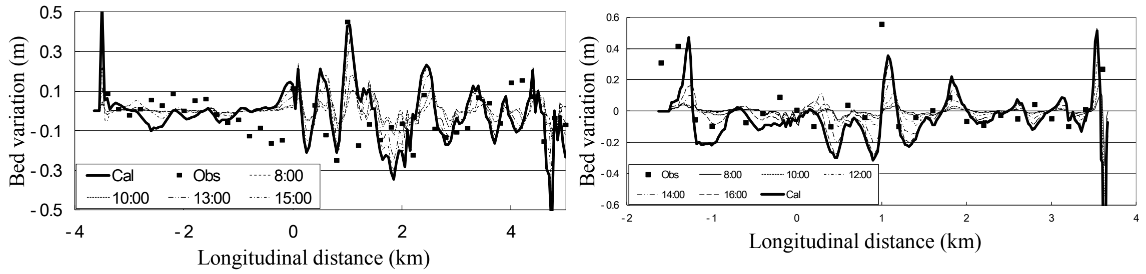


Fig. 6 Change in the mean bed elevations.

Motoyasu River downstream of 1.0 km are much steeper than those of the Ota River floodway owing to channel width reduction.

Figure 6 shows time change in calculated and observed mean bed elevations in the Temma River and the Ota River floodway, respectively. It is found that the mean bed elevations change about 20 cm during the 2010 flood in the Ota River delta. The calculated bed variations are able to explain the observed bed variations upstream and downstream of 0.0 km.

The maximum change in the bed elevations downstream of 0.0 km occurred between 15:00 h and 16:00 h when the water surface profiles are steepest in the flood (see Fig. 7). In contrast, the maximum bed variations upstream of 0.0 km occurred in the flood peak. This shows that the calculation method using time series of observed water surface profiles is especially important to understand the flood flow and bed variation in the estuary.

The sediment transport in the Ota River Floodway and Temma River are shown in Fig. 8. Since suspended load is more than bed load downstream of 0.0 km, it is found that effects of suspended load on bed variations downstream of 0.0 km are large compared with upstream of 0.0 km.

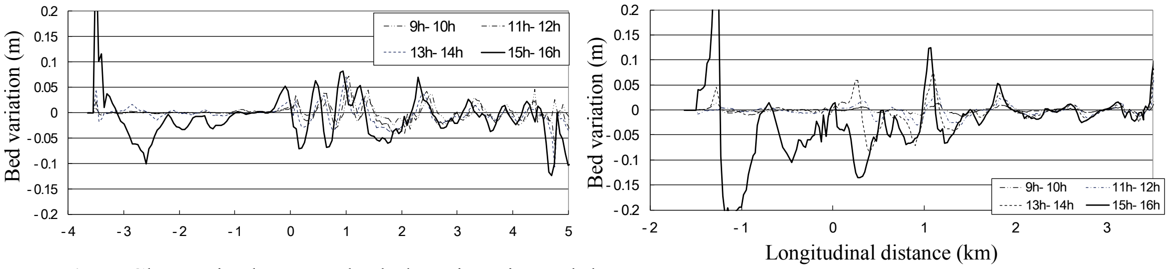


Fig. 7 Change in the mean bed elevations in each hour.

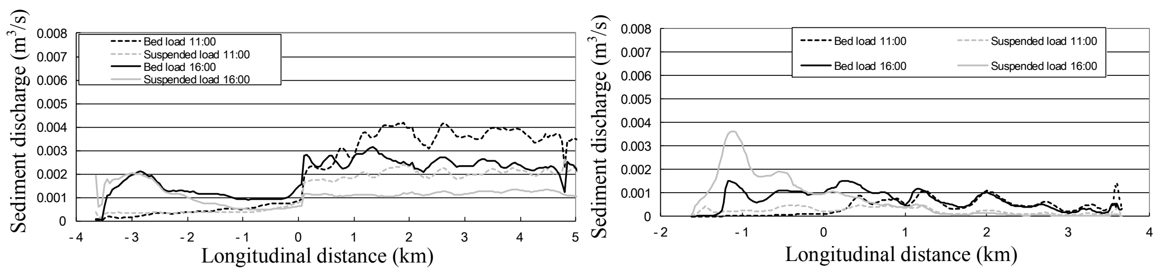
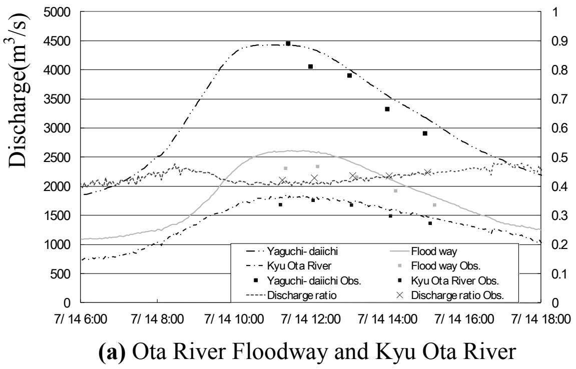
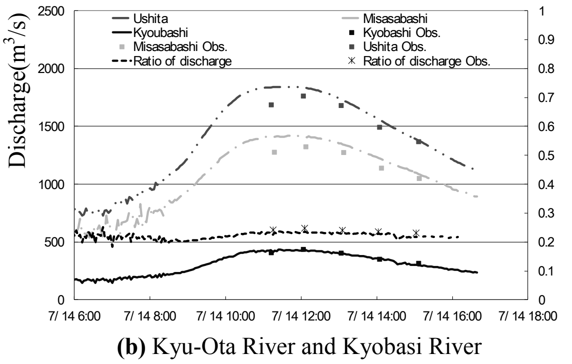


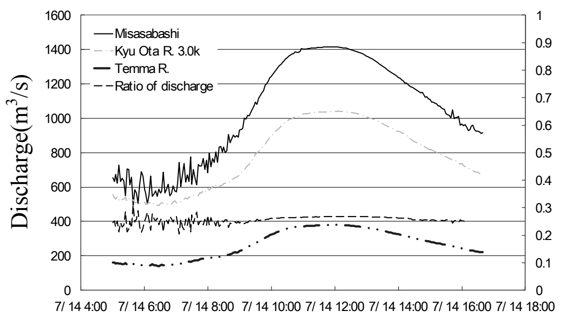
Fig. 8 Sediment transport of suspended load and bed load.



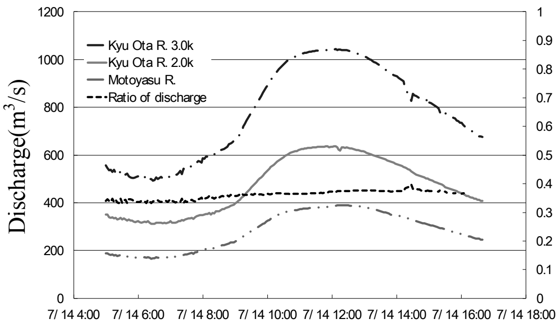
(a) Ota River Floodway and Kyu Ota River



(b) Kyu-Ota River and Kyobasi River



(c) Kyu Ota River and Temma River



(d) Kyu Ota River and Motoyasu River

Fig. 9 Observed and calculated hydrographs and discharge distribution ratio at river bifurcation sections.

Figure 9 shows the calculated and observed discharge hydrographs and the discharge ratio at each bifurcation section. The discharge distribution ratio is defined as the ratio of discharge of branched river to total discharge. It is demonstrated that the calculation method using time series of observed water surface profiles can estimate well the discharge distributions in the channel network. The discharge distribution ratio at each river bifurcation is found nearly constant with time, regardless of tidal changes.

CONCLUSIONS

The following conclusions were derived from in this study:

(1) Unsteady quasi-3D flood flow analysis and 2D bed variation analysis using time series of observed water surface profiles in a channel network is developed to estimate dynamics of flood flow and bed variation. It is found that the calculation method provides fairly good results for flood flow and bed variation in the channel network of the Ota River delta.

(2) The bed variation in the channel network of the Ota River delta is closely related to time series of water surface profiles affected by tidal changes. Therefore, the calculation method using time series of observed water surface profiles of flood flow is important for evaluating flood flows and bed variations in the estuary.

(3) The calculation method including sediment transport of suspended sediments is important for estimating bed variations around the river mouth of the Ota River delta because the river bed materials consist of fine sands and channel widths gradually increase to about 300 m from 70 m around the river mouth.

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