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On the flow resistance and bed variations during Hii River flood

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ABSTRACT: Main channel of the Hii river divides into braided channels, and large sand waves are formed on the bars. It is considered that the flow resistance changes with bed elevation of the main channel during a flood. Therefore, evaluating the temporal variation in the flow resistance is important to understand the flood flows and bed variations in the Hii river. In this study, first, the temporal variation in the resistance during the 2011 May flood of the Hii river is evaluated by the Manning's roughness coefficient in quasi-steady flow analysis. Next, the unsteady flow analysis is conducted using the temporal variation in the roughness coefficient determined by the quasi-steady flow analysis to investigate the mechanism of bed variation in the Hii river. From these investigations, we conclude that the analysis method presented in this study is useful for the flood flow analysis in the Hii river.

1 INTRODUCTION

There are a large amount of sediment yields in the Hii river basin, Shimane Prefecture, Japan, where the Hii river runs through. As shown in Figure 1, the Lake Shinji located at the Hii river mouth has reduced the discharge capacity by raising the water level of the lower Hii river. Ground levels of urban areas along the river are lower than the river bed levels. Therefore, people lived there has suffered from flood damages for a long time. Moreover, the discharge capacity of the current channel is not sufficient for the design flood discharge. For these reasons, the diversion channel is being constructed to decrease the flood discharge to the lower Hii river (see Fig. 1). However, because of a lack of understanding of the flood flows and bed variations in the current channel, effects of the diversion channel on the bed variation in the upstream and downstream of the diversion section have not been understood sufficiently. At first, it is important to understand the mechanism of bed variation in the current channel.

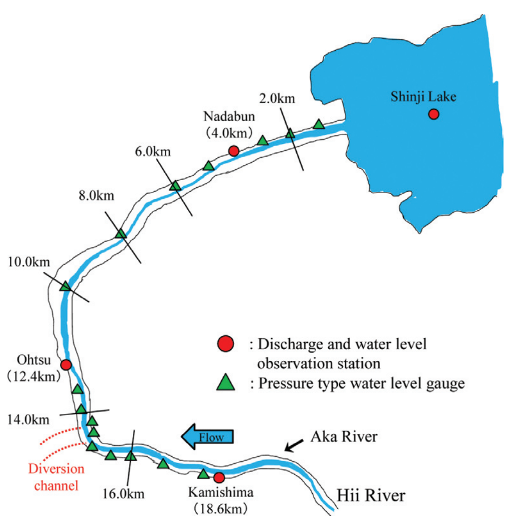

Figure 1. Plan-form and observation points in the objective area of the Hii river.

The main channel in the Hii river divides into braided channels, and large sand waves are formed on the bars as shown in Figure 2. Ueno et al. (1996) observed spatial distribution of bed forms by the echo-sounder during floods. They showed that the height of the sand waves changed corresponding to the increasing and decreasing water levels during the floods. Fukuoka (2011) showed that the mechanism of bed variations during floods could explain with reasonable accuracy by conducting the quasi-three-dimensional flood flow and two-dimensional bed variation analysis so as to coincide with temporal changes in observed water

Figure 2. Bed forms of the Hii River (May 2011).

surface profiles. This analysis method is based on the idea that the various phenomena including flow resistance due to the sand waves and bed variations in rivers are reflected in temporal changes in observed water surface profiles. In the Hii river, the water depth is relatively shallow even during floods. It means that bed variation and sand waves control characteristics of the flood flows and sediment transports in the Hii river.

Detailed water level observations were conducted in 2011 May flood. Both quasi-steady and unsteady flow analyses are conducted in this study. The temporal variation in the flow resistance is evaluated by the Manning's roughness coefficient. First, the temporal variation in the roughness coefficient during the flood is estimated by quasi-three-dimensional flow and two-dimensional bed variation analysis under the assumption of the quasi-steady flow. Next, the unsteady quasi-three-dimensional flow and two-dimensional bed variation analysis considering the temporal variation in the roughness coefficient estimated by the quasi-steady flow analysis was conducted to investigate the mechanism of bed variation in the Hii river.

2 OBJECTIVE AREA AND FLOOD

Figure 1 shows plan-form and observation points in the objective area. In this area, the time series data of the discharge and water level have been observed at the Kamishima (18.6 km), Ohtsu (12.4 km) and Nadabun (4.0 km) observation stations and simple pressure type water level gauges with data logger were installed at the points designated by triangles. The diversion channel is being constructed at 14.4 km point. The water level gauges were densely installed to investigate water surface profiles in the upstream and downstream of the diversion section.

The Hii river has a separation levee in the upstream area of the confluence point with the Aka river around 20.0 km (see Fig. 1). Because main channel width is narrow due to the separation levee in this area, bed scouring near the river bank has been concerned. On the other hand, main channel width in the downstream of the confluence point becomes wide and the main channel divides into braided channels. In the diversion section, low sand embankment is constructed in a main channel for irrigation purpose as shown in Figure 3. The embankment has been washed away every flood events. Transported sands have been deposited to the downstream and affected the main channel widths around the diversion section year by year. As shown in Figure 2, a large sand bar develops in main channel, and vegetation grows densely on the bar around 13.0 km point.

It was 2011 May flood that the maximum water level was recorded after the pressure type water level gauges were installed. The peak discharge of this flood was 1200 m^3/s at the Kamishima (18.6 km) observation station. From observed data of cross-sectional bed shapes, the height of the sand waves is estimated from 0.5 to 1.0 meters in the objective area. Figure 4 shows the cross-sectional bed

Figure 3. Sand embankment in the main channel.

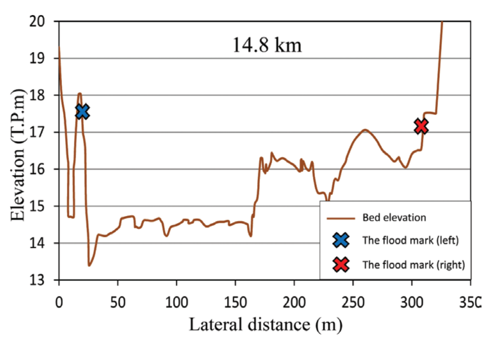

Figure 4. The cross-sectional bed shape and the flood marks at 14.8 km point.

shape and the flood marks at 14.8 km point. The difference between the flood marks and bed elevation is about 3.0 meters on the average. This means that Hii river floods are shallow water flows. It is considered that bed variation and sand wave deformation during the flood have a large influence on temporal changes in water surface profiles.

3 ANALYSIS METHOD

In this study, we estimate the temporal variation in the flow resistance and investigate the mechanism of bed variations from 14.0 km to 15.6 km during the flood.

3.1 *Governing equations*

Since the diversion section is located in a curved reach, the three-dimensionality of the flow plays important roles on the flood flows and sediment transports. For the above reason, quasi-three-dimensional flow analysis (Uchida & Fukuoka, 2011) is adopted in this study. The bed variation analysis takes both bed load and suspended load into account. A rate of the bed load transport is calculated by Ashida and Michiue formula (Ashida & Michiue, 1972). The concentration of the suspended load is calculated by a three-dimensional advection-diffusion equation (Okamura & Fukuoka, 2012) to evaluate the high sediment concentration transport near the bed and effects of the vertical distribution of the velocity properly. The equation is written as:

$$\frac{\partial c_k}{\partial t}+\frac{1}{J}\left(\frac{\partial \Delta\eta \cdot u^{\xi} c_k}{\partial \xi}+\frac{\partial \Delta\xi \cdot u^{\eta} c_k}{\partial \eta}\right)+\frac{\partial c_k\left(u^{\sigma}-\sigma^{t}-w_{0k}\right)}{\partial \sigma}$$
$$=\frac{\partial}{\partial \tilde{\xi}}\left(\varepsilon_s \frac{\partial c_k}{\partial \tilde{\xi}}\right)+\frac{\partial}{\partial \tilde{\eta}}\left(\varepsilon_s \frac{\partial c_k}{\partial \tilde{\eta}}\right)+\cos\theta^{\eta\xi}\left\{\frac{\partial}{\partial \tilde{\xi}}\left(\varepsilon_s \frac{\partial c_k}{\partial \tilde{\eta}}\right)+\frac{\partial}{\partial \tilde{\eta}}\left(\varepsilon_s \frac{\partial c_k}{\partial \tilde{\xi}}\right)\right\}$$
$$+\frac{\varepsilon_s}{J}\left(\frac{\partial c_k}{\partial \tilde{\xi}}\frac{\partial \theta^{\xi}}{\partial \tilde{\eta}}+\frac{\partial c_k}{\partial \tilde{\eta}}\frac{\partial \theta^{\eta}}{\partial \tilde{\xi}}\right)+\frac{\partial}{\partial z}\left(\varepsilon_s \frac{\partial c_k}{\partial z}\right)+q_{suk(z=z_b)} \quad (1)$$

where, c_k = concentration of suspended load of the each particle size d_k, σ^t = grid movement velocity of σ direction, w_{0k} = falling velocity of d_k, ε_s = diffusion coefficient, q_{suk} = Pick up rate of suspended load of d_k from bed surface. Here, σ direction is divided by six grids between water and bed surfaces. The vertical velocities u^{σ} were given by continuity equation. The pick up rate of suspended load from bed surface is calculated by Kishi-Itakura formula (Itakura & Kishi, 1980). The critical tractive forces for d_k and mean particle size d_m are calculated by the modified Egiazaroff formula (Asida & Michiue, 1972) and Iwagaki formula (Iwagaki, 1956), respectively.

3.2 *Quasi-steady flow analysis*

The flow resistance is evaluated by the roughness coefficient of the Manning's equation. Since various resistances during a flood occur in a river, determination of the roughness coefficient by the unsteady flow analysis is not easy. We estimate the roughness coefficient by quasi-steady quasi-three-dimensional flow and two-dimensional bed variation analysis for this reason. The upstream and downstream boundary conditions are given by observed water level hydrographs at the Kamishima (18.6 km) and Shinji Lake (–1.0 km) observation stations shown in Figure 1.

The upstream and downstream boundary conditions are given by the water level hydrographs shown by solid lines in Figure 5. The water level hydrographs are divided by 8 time zones (A–H). The divided time zones correspond to the time when the discharge was measured. The observed water surface profiles reflect the temporal variation in the resistance due to the bed elevation variation. The roughness coefficients are determined so that the calculation results agree with the observed water surface profiles and discharges at the Kamishima (18.6 km) observation station in each time zone (A–H). Here, because the discharge measurement was not conducted in the period of low water level, the discharge at the Kamishima observation station is estimated by using the rating curve in A, G and H time zones.

3.3 *Unsteady flow analysis*

We investigate the mechanism of bed variation in 14.0 km–15.6 km by using the quasi-three-dimensional unsteady flow and two-dimensional bed variation analysis and the roughness coefficient estimated by the quasi-steady flow analysis. The upstream and downstream boundary conditions are given by the water level hydrographs shown by plots in Figure 5.

3.4 *Analysis conditions*

In this analysis, the initial bed forms are created based on the data of cross-sectional bed shapes measured on December 2010. The measurements were conducted at intervals of 200 meters from

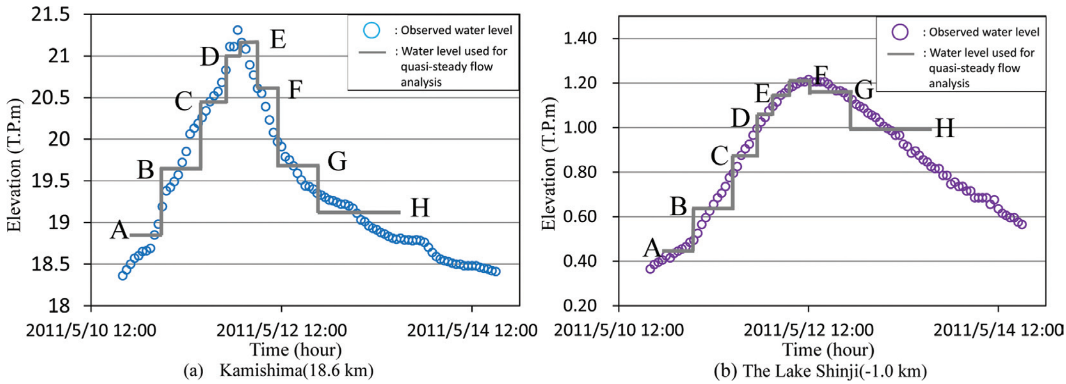

Figure 5. Boundary conditions of quasi-steady and unsteady flow analysis.

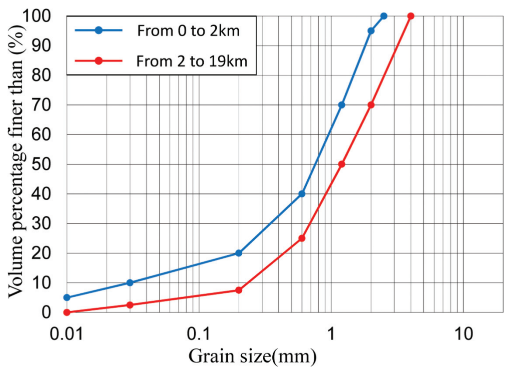

Figure 6. Particle size distributions used to the analysis.

Table 1. Manning's roughness coefficient of the main channel in each time zone.

	0 km~10 km ($m^{-1/3} \cdot s$)	10 km~15 km ($m^{-1/3} \cdot s$)	15 km~19 km ($m^{-1/3} \cdot s$)
A	0.030	0.035	0.026
B	0.030	0.035	0.026
C	0.038	0.039	0.030
D	0.032	0.031	0.026
E	0.045	0.043	0.032
F	0.048	0.039	0.030
G	0.043	0.035	0.027
H	0.031	0.023	0.022

14.0 km to 15.6 km and at intervals of 500 meters in the other areas. Figure 6 shows particle size distributions used for the analysis. They are determined from the data of bed materials survey in the objective area in 2002.

4 ANALYSIS RESULTS AND CONSIDERATIONS

4.1 *Temporal variation in the flow resistance during 2011 May flood*

Table 1 shows the Manning's roughness coefficients of the main channel estimated by the quasi-steady flow analysis in the time zones (A–H). The flow resistance varies with the variation in water level in each area, and the Manning's roughness coefficients almost correspond to changes in water levels. The height of the sand waves seems to be a maximum at the peak water level.

Attention has been paid on the rise of the water level in the river mouth. Funabashi et al. (2006) showed that the main causes of the water rise were the growth of the sand waves and the sediment deposition as seen in Figure 7. Table 1 shows that the roughness coefficient in the 0.0 km–10.0 km varies over a wide range and has a maximum value 0.048. This proves that the sand waves develop actively compared with the other areas and has a significant influence on the water level rising in the lower Hii river.

4.2 *Flood flow and bed variation analysis considering the flow resistance variation during a flood*

Figure 8 shows comparison between observed and calculated water surface profiles and average bed elevations by the unsteady flow analysis. The calculated water surface profiles were determined so as to coincide with observed ones. The variation of the average bed elevations seem to be small from the comparison between brown plots and black

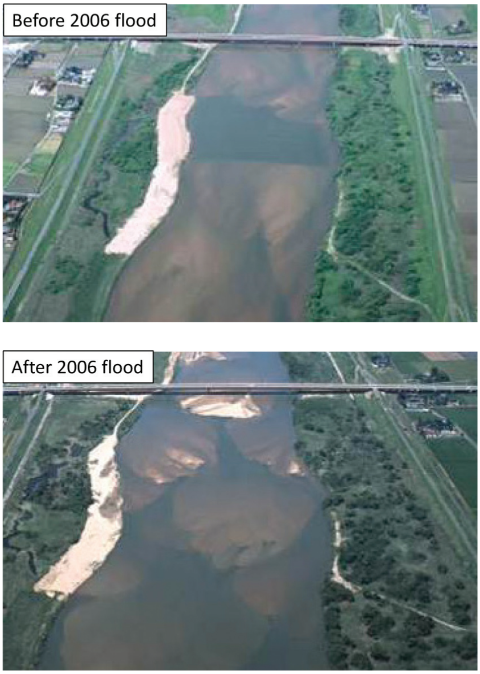

Figure 7. The growth of the sand waves before and after 2006 flood at 2.0 km point.

broken line in Figure 8. Figure 9 shows that the calculated discharge hydrographs can also explain the observed discharge hydrographs at three observation stations. From these considerations, we can estimate the temporal variation in the flow resistance by using the quasi-steady flow analysis. It is concluded that the analysis presented in this study gives a useful method for the flood flow and bed variation analysis in the Hii river.

Figure 10 shows contours maps of the bed variation from 14.0 km to 15.6 km during the 2011 May flood. Figure 10a and Figure 10b show that calculation results of the bed variations are about 0.1 meters on the average in the peak water level and about 0.3 meters on the average in the falling period. The comparison between Figures 10b, c, shows that the bed variations extend downstream in the falling period. Figure 11 shows a relationship between the calculated sediment discharge hydrographs and flood discharge hydrograph at 14.8 km point. We can see that amount of the suspended load is much larger than that of the bed load. The bed load is increasing in the falling period, although the variation pattern of the suspended load almost corresponds to that of the flood discharge. This reason may be explained as follows. In the falling period, irregularity of the bed height increases as in Figure 10, and flood flows

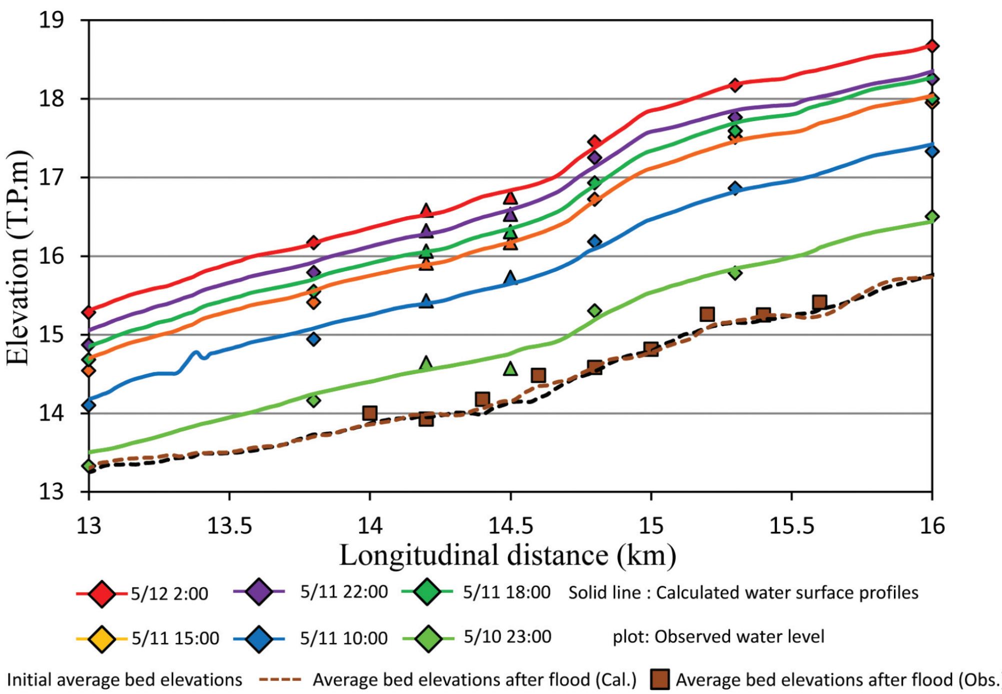

Figure 8. Comparison between observed and calculated water surface profiles and average bed elevations.

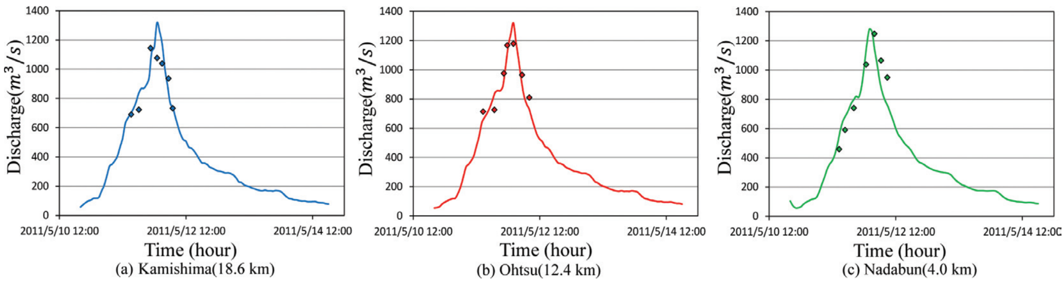

Figure 9. Discharge hydrographs at the observation stations.

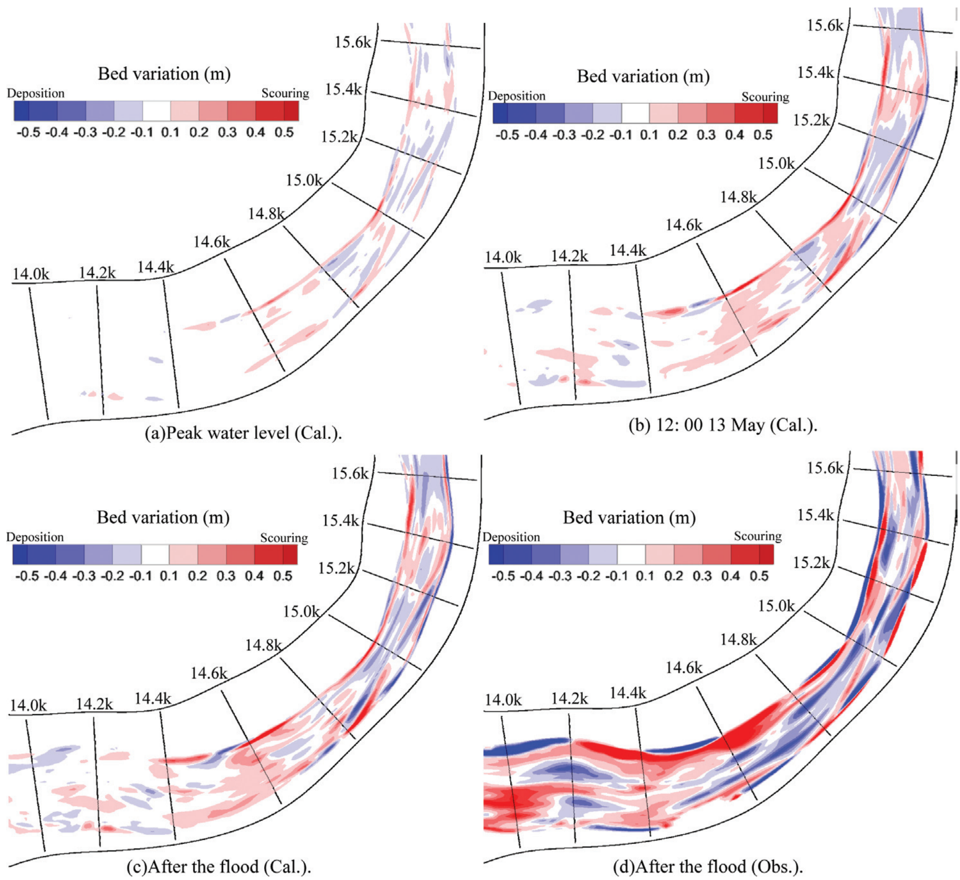

Figure 10. Contours maps of bed variation from 14.0 km to 15.6 km during 2011 May flood.

tend to concentrate in the deeper parts of braided channels. It would be increasing the transport rate of the bed road.

From the comparison between Figure 10c, d, the analysis reproduces bed scoring around 15.0 km where the main channel width is relatively narrow but doesn't reproduce the longitudinal bed variation including the deposition around 14.4 km where the main channel width is gradually expanding. In addition, although the bed variation occurred about 0.5 meters on the average, the calculated bed variation remains about 0.3 meters on the average. This difference may be explained as follows. Applicability of the present bed variation

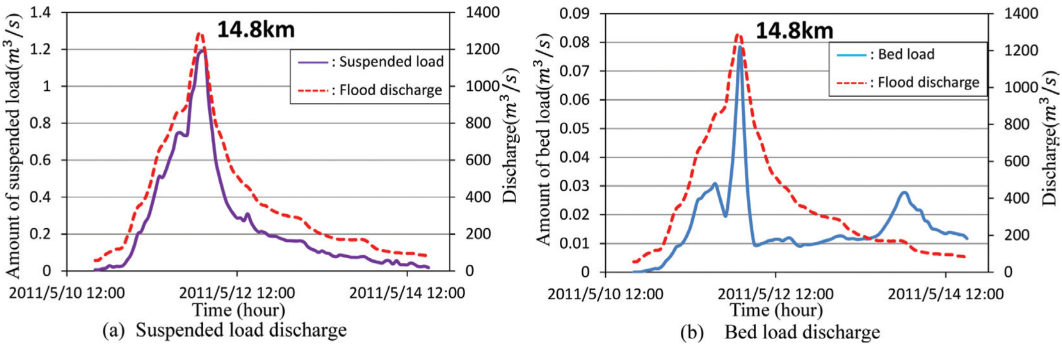

Figure 11. Relationship between calculated sediment discharge hydrographs and flood discharge hydrograph at 14.8 km point.

model for the braided channel is questioned. The bed variation in braided channel is closely related to plan form, cross-sectional form and sediment particles. The Hii river has almost uniform sand particles which move even in the normal flow condition. Their effects on the formation of braided channel are examined in detail. Flood flows concentrate in the deeper parts of the braided channels, and cause the non-equilibrium sediment transport due to the spatial difference of the flow velocity in the low water level. As a result, the bed variation would be large. Since the initial bed forms in this study are created from the data of cross-sectional bed shapes measured at intervals of 200 meters, the initial bed forms couldn't reproduce properly the deeper parts of the channel. In addition, the sediment is transported rather actively even in the ordinary flow conditions, and bed forms changes in shape continuously. Since initial cross-sectional bed shapes used were measured on December 2010, the initial bed forms may be different from those of the 2011 May flood. It is required to measure initial cross-sectional bed shapes properly for further improvement of the flood flow and bed variation analysis in the Hii river.

5 CONCLUSIONS

1. The temporal change in the flow resistance due to bed variation during May 2011 flood in the Hii river was evaluated by the Manning's roughness coefficient using in the quasi-steady flow analysis.
2. The unsteady flow analysis could reproduce the temporal changes in observed water surface profiles and discharge hydrographs at the observation stations by using the temporal variation in the roughness coefficient estimated by the quasi-steady flow analysis. We concluded that two-step analysis method presented in this study was useful for the flood flow and bed variation analysis in the Hii river.
3. We pointed out the importance of the initial bed forms in braided channel for the further improvement of the flood flow and bed variation analysis in the Hii river.

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