12th International Conference on Hydroscience & Engineering
Hydro-Science & Engineering for Environmental Resilience
November 6-10, 2016, Tainan, Taiwan.

Analysis of Discharge Capacity and Flood Storage Rate during 2015 Large Flood in the Kinu River

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ABSTRACT

It is necessary to enhance a safety level of flood control in the Kinu River which suffered from huge inundation damage in 2015 flood. However, it is not clear how marked longitudinal change in river cross-sections affected discharge capacity and flood storage volume. We developed a numerical model applying BVC method and 2D bed variation using observed water surface profiles during the 2015 flood in the Kinu River taking account of the inundation due to levee overtopping and breach. The model provided valuable explanations for the discharge capacity and flood flow storage volume.

KEY WORDS: Kinu River; 2015 flood; flood flow and bed variation analysis; water surface profiles; levee over topping and breach; discharge capacity; flood storage rate

INTRODUCTION

The Kinu River is one of major tributaries of the Tone River which is the largest river in Japan. It is necessary to enhance a safety level of flood control in the Kinu River which suffered from huge inundation damage due to levee overtopping and breach in the 2015 large flood. In the Kinu River, especially lower reach from 4 km to 46 km, the longitudinal changes of cross-section are quite large, which affect discharge capacity and storage rate of floods. Therefore, it is important to examine quantitatively the hydraulics of the 2015 flood for the future river improvement works.

Some researches on bed variations or riverbed stabilities at the upper reach in the Kinu River have been carried out, but there are almost no researches of discharge capacity, flood storage volume and bed variations focusing on river characteristics of the lower reach. Fukuoka has proposed the numerical method for flood flows and bed variations using time series of observed flood water surface profiles on the basis of the idea that effects such as plan forms, cross-sections and bed variations appear in time series of observed water surface profiles. This method has been applied for understanding of flood flows and bed variations mechanism in many Japanese rivers (Fukuoka and Watanabe 2002, Tabata and Fukuoka 2014).

The objective of this paper is to develop the numerical model of flood flow and 2D bed variation of the 2015 flood in the Kinu River where extensive inundation due to overtopping and levee breach occurred. Also we calculate the inundation volume, discharge capacity and flood storage rate during the 2015 flood in the Kinu River.

OUTLINES OF THE OBJECTIVE AREA AND THE 2015 FLOOD

Fig.1 and Fig.2 show the plan form and longitudinal distribution of river width and riverine bamboos in the reach from 0.0 km to 46 km of the Kinu River. Solid lines in Fig.2 show the distances from the center of river channel to the levees and banks. In the stretch from 3.0 km to 4.0 km, the river width is narrow, approximately 100 m. From 4.0 km to 37.0 km the river width varies from 200 m to 400 m and the main channel meanders. In the upper reach of 37.5 km, it increases and reaches to 1,300 m wide at 40.25 km. There are densely growing bamboos in the flood plain (pink areas in Fig.2) whose heights are roughly 3-10 m.

Fig.3 shows the water level hydrograph at Mitsukaido (11.0 km). The 2015 flood continued for two days and the water level exceeded over H.W.L. for about 6 hours at Mitsukaido. The Kinu River flood brought inundations due to overtopping at 6 embankment points (white x marks in Fig. 1) and levee breach on the left bank at 21.0 km (red x mark in Fig. 1).

Water levels were measured at drainage pump stations and flood regulating gates in addition to water level gauging stations as shown in Fig.1. By these water level gauges, temporal water surface profiles during the flood were measured in detail.

NUMERICAL METHOD AND CONDITIONS

Numerical Method

We develop a numerical model of flood flow and 2D bed-variation analysis using observed flood water surface profiles in the Kinu River. In this study, the BVC (Bottom Velocity Computation) method developed by Uchida and Fukuoka (2011) is applied to the flood flow analysis. The BVC method is quasi-3D flow analysis model which is capable of evaluating vertical distribution of horizontal velocities and bottom velocities by introducing depth-averaged horizontal vorticity equations and horizontal momentum equations on water surface to shallow water equations.

The bed variation is computed by the continuity equation for sediment and grain sizes (Hirano 1971) using bed load formula (Ashida and Michiue 1972) and suspended load formulas (Itakura and Kishi 1980; Lane and Kalinske 1941). The transport of the suspended sediment is computed by 2D advection and diffusion equations.

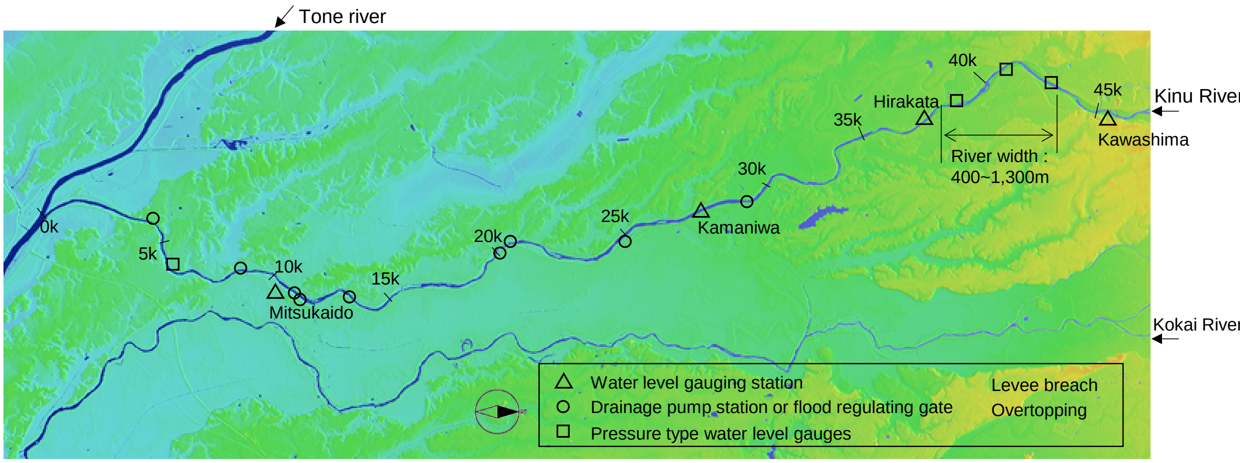

Fig. 1 Plan form of the Kinu River.

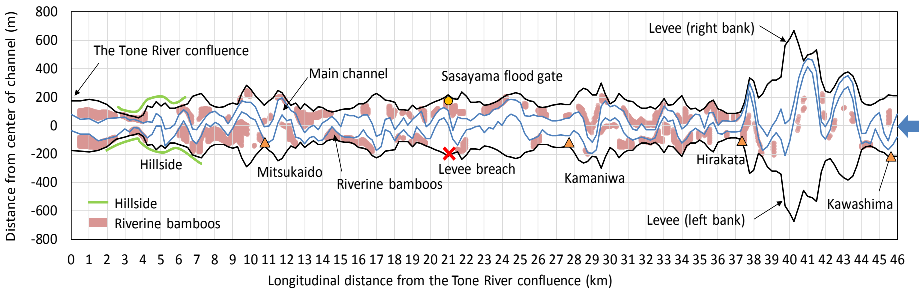

Fig. 2 Longitudinal distribution of the river width and riverine bamboos.

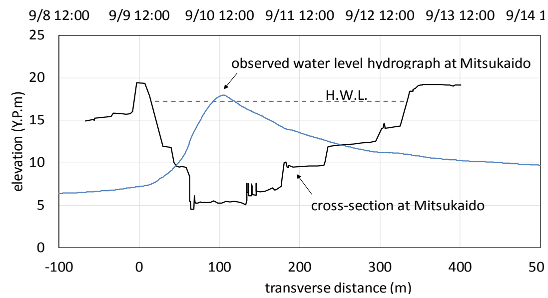

Fig. 3 Observed water level hydrograph and cross-section at Mitsukaido.

Conditions for Numerical Computations

The numerical model was applied for the reach from 4.25 km to 46.0 km. The upstream and downstream boundary conditions were given by observed water level hydrographs at the Kawashima gauging station and Shintei drainage pump station. Since over topping flows over levee crests occurred in the 2015 flood, the numerical grid was made taking account of topography of levees and inland areas at several places where heights of levee crest were low. Discharge hydrographs outflowing from the levee breached point was estimated so that the calculated water surface profiles agreed with the observed ones around the levee breached point (Fukuoka et al. 2008), especially Sasayama flood regulating gate which is located at the opposite bank of levee breach point considering observed breach time and temporary change of breach width. Fig.4 shows grain size distributions used for the analysis. The bed materials are mainly composed of gravels at upstream from 37.2 km where the river width is narrower compared to its upstream reach, and are mainly composed of sand at downstream of 37.2 km. Manning roughness coefficients of the main channel and flood plain were set based on the longitudinal distributions of the averaged particle diameters and the ground cover conditions, respectively. The vegetation permeability coefficients of the densely bamboos were adjusted finely so that the calculated water surface profiles agreed with the observed ones during the 2015 flood on the whole. Manning roughness coefficients and vegetation permeability coefficients used in the analysis are shown in Table 1.

RESULTS AND CONSIDERATIONS

Flood Flows and Bed Variations

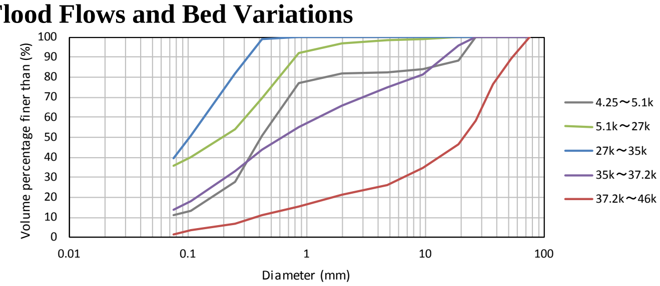

Fig. 4 Grain size distributions used for the analysis.

Table 1 Manning roughness coefficient and vegetation permeability coefficient.

Section	Manning roughness coefficient ($m^{-1/3}\cdot s$) main channel	flood plain	vegetation permeability coefficient (m/s)
4.25～5.1km	0.028	0.025～0.040	10～70
5.1～27km	0.025	0.025～0.075	10～70
27～35km	0.025	0.025～0.055	10～70
35～37.2km	0.030	0.030～0.055	10～40
37.2～46km	0.035	0.025～0.055	10～70

Fig. 5 shows the comparison between the computed and observed water surface profiles and longitudinal distributions of the averaged bed elevations in the Kinu River. In this figure, we can see that the computed water surface profiles could coincide with the observed ones on the whole. Also the water surface profiles at the peak time almost matched observed flood marks. Computed averaged bed elevations after the flood almost agreed with observed ones.

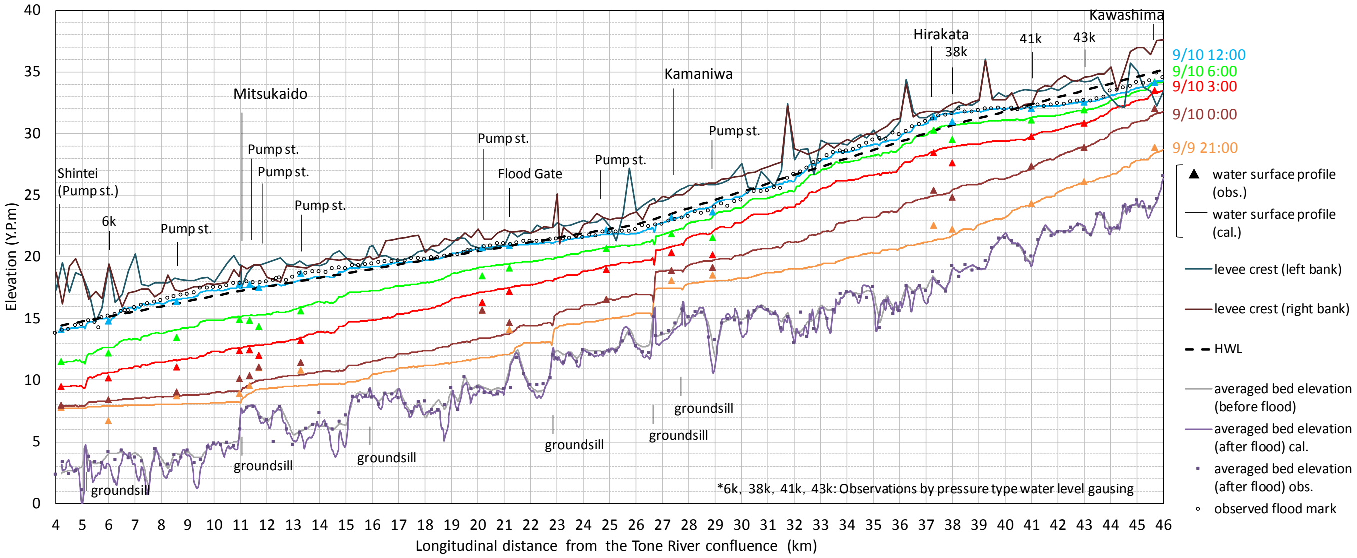

Fig. 5 Comparison between the computed and observed water surface profiles and longitudinal distributions of the averaged bed elevations in the Kinu River.

Fig. 6 shows the comparison between the computed and observed discharge hydrographs at the observation stations in the Kinu River. The solid lines and plots indicate the computed and observed values which are considered the inundation volume due to overtopping and levee breach. The discharge observations carried out at the three observation stations Hirakata (37.0 km), Kamaniwa (27.4 km) and Mitsuaido (11.0 km) during the 2015 flood. Although there are no confluences along the reach from Hirakata to Kamaniwa, the observed discharges between the time of flood starting (10 Sep. at 8:00) and flood peak (10 Sep. at 11:00) at Hirakata are smaller than ones at Kamaniwa which is located at downstream of Hirakata. The computed discharges at Kamaniwa and Mitsukaido could elucidate the observed ones, while the peak discharges estimated slightly larger than observed ones. The difference between computed and observed discharge at Hirakata is a subject for the future investigation.

Fig. 7 shows the computed hydrographs of the total inundation discharge in the left bank side due to overtopping and levee breach. The inundation discharges due to overtopping increased until 12:50 10 Sep. when the levee breach occurred, and then decreased. The inundation due to levee breach continued for about 10 hours. The computation model revealed that the inundation volume due to overtopping was 26,420,000 m^3 and one due to levee breach was 12,770,000 m^3. The measured total inundation volume was about 40,000,000 m^3, which agreed well with the computed result.

Discharge Capacity and Flood Storage Rate

The water level almost reached or was over the levee crest except for the stretch around Kamaniwa. This fact indicates that the Kinu River was lacking in discharge capacity on the whole. Especially the discharge capacity was not enough in the reach around Hirakata. In general, temporal water surface profiles in large rivers are almost parallel to the longitudinal riverbed surface during the flood. However, as shown in Fig.5, the water surface profiles in the reach from 37.0 km to 43.0 km around Hirakata became almost horizontal as the water level

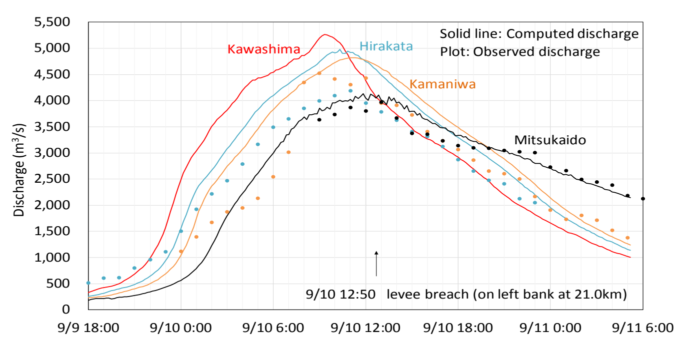

Fig. 6 Comparison between the computed and observed discharge hydrographs.

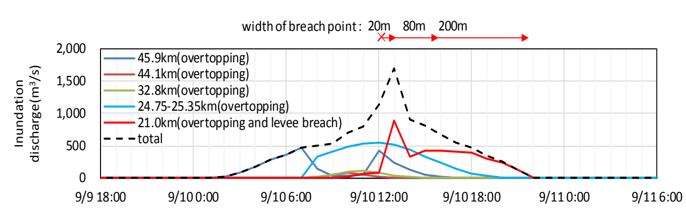

Fig. 7 Computed inundation discharge hydrographs due to overtopping and levee breach.

increased, while they were parallel to the longitudinal riverbed surface until 10 Sep. at 0:00. This is considered as follows. Fig.8 and Fig.9 show the temporal changes in depth averaged velocity contours and stream lines at the reach from 37.0 km to 42.0 km and velocity contours in the cross-section at 40.25 km where river width is very wide in 1,300 m. The velocities were quite large in the main channel at 2:00. Since the water level rose over the elevation of flood plain as the flood discharge increased at 5:00, flows in the main channel with large velocities and flows on the flood plain with small velocities were exchanged by complex meandering patterns. Then velocities became

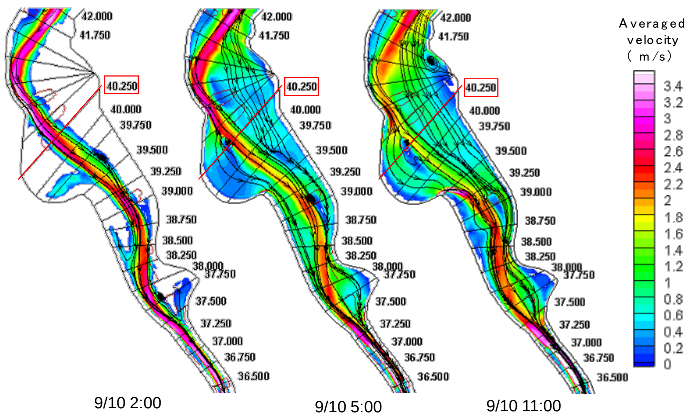

Fig. 8 Temporary changed in depth averaged velocity contours and stream lines in the reach from 36.0 km to 42.0 km.

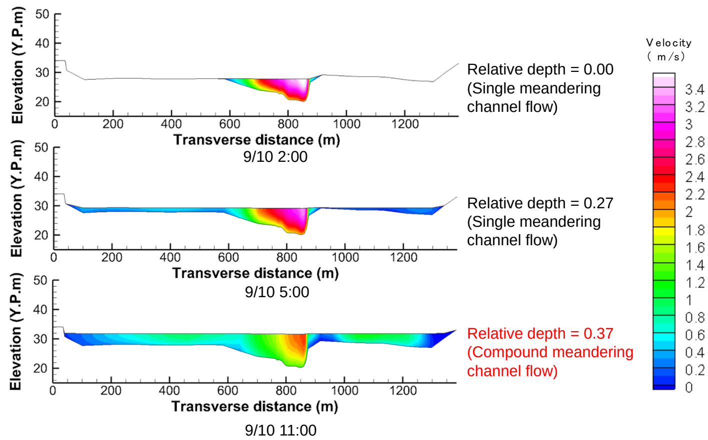

Fig. 9 Temporary change in velocity contours in the cross-section at 40.25 km.

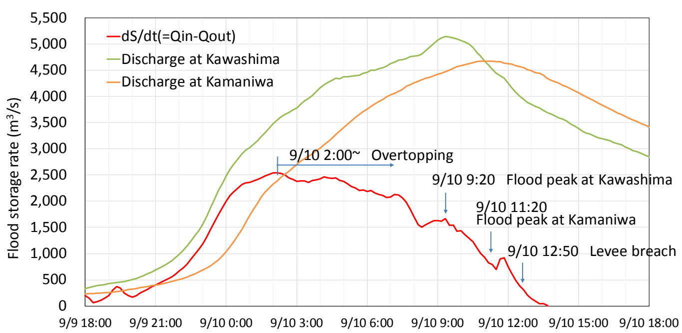

Fig. 10 Flood storage rate in the reach from 4.25 km to 46.0 km in the Kinu River.

small at the flood peak as shown in velocity contour at 11:00 in Fig.8 and Fig.9. It was investigated that flow characteristics in compound meandering channels depend on the relative depth which is defined by the ratio of the depth on the flood plain to the depth in the main channel (Okada and Fukuoka 2002). When the relative depth is from around 0.3 to 0.5, flows in the main channel and on the flood plain mix intensively, then shear stresses increase and average velocities in cross-section decrease. At the flood peak level the relative depth was 0.37. Then, the average velocities decreased due to mixing, and the water level rose.
Next we estimated the flood storage rate by the following equation.

$$dS/dt = Q_{in} - Q_{out} \qquad (1)$$

Where, S: flood storage volume, t: time, Q_{in}: computed discharge hydrograph at 46.0 km, Q_{out}: computed discharge hydrograph at 4.25 km.

Fig.10 shows the flood storage rate in the reach from 4.25 km to 46.0 km in the Kinu River. The computed flood storage rate were 1,670 m^3/s and 790 m^3/s at the flood peak at Kawashima and Kamaniwa. These values were almost 32 % and 17 % of the peak discharges at Kawashima and Kamaniwa, respectively. Also the flood storage volume in the reach from 4.25 km to 46.0 km which were estimated by time integrating storage rate from 9 Sep. at 18:00 to 10 Sep. at 13:00 was 78,000,000 m^3. It was the value which eliminated the inundation volume and almost comparable to water volume during the flood in four dams located in the upstream area of the Kinu River. This means that the flood storage volume in the Kinu River was quite large, because of the plan shape of the river.

CONCLUSIONS

We applied the numerical model for analysis of flood flow and 2D bed variation to the 2015 large flood in the Kinu River, using observed water surface profiles taking account of inundations due to both of overtopping and levee breach. The following conclusions were derived in this study.

(1) It was estimated that the total inundation volume due to overtopping was 26,420,000 m^3 and the inundation volume due to levee breach on the left bank at 21.0 km was 12,770,000 m^3.
(2) The developed model clarified that the discharge capacity was not enough in the meandering reach around Hirakata. Because the relative depth in meandering river flow was 0.37, velocities decreased and the water level rose highly.
(3) The flood storage rate was 1,670 m^3/s at the time of peak discharge at Kawashima and almost equivalent to 32 % of the peak discharge. Furthermore, the flood storage volume in the reach from 4.25 km to 46.0 km was 78,000,000 m^3 and it was indicated that the flood storage volume in the Kinu River was quite large.

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