FLOOD ANALYSIS IN THE NUTA RIVER BASIN DURING THE HEAVY RAIN IN JULY 2018

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In July 2018, heavy rainfall in western Japan caused severe flood damage. Overflows and several levee breaches in tributaries occurred in the Nuta River basin, which flows in the eastern part of Hiroshima Prefecture, and the area suffered flood inundation. This study conducted on-site observations in the Funaki district, where flood damage was significant, and investigated the behavior of flood water during flooding. Subsequently, we discussed flood flow characteristics and the effect of upstream Fukutomi and Mukunashi Dams from the obtained water-level data and runoff analysis results. Horizontal two-dimensional simulations were used to show the influence of tree growth on the flood flow.

Key Words : *rainfall-runoff analysis, RRI model, two-dimensional (2-D) flood flow simulation, tree growth*

1. INTRODUCTION

From July 5th to 7th, 2018, there were record levels of heavy rainfall over a wide area from the southern to eastern areas of Hiroshima Prefecture. Many of the rivers in the prefecture, particularly the small- and medium-sized ones, were exposed to rainfall levels that reached or exceeded their river management plans, causing large-scale flooding. The lower Nuta River, which flows through the eastern area of Hiroshima Prefecture, also experienced wide-ranging and major flooding damage. **Figure 1** shows the Nuta River basin. On the tributaries flowing into the lower reach of the Numata River, the following locations were breached and caused extended flood damage: four locations in the Suga River (including the breaches due to the overbank flow returning into the river from the right bank inundated area), one location in the Butsutsuji River, three locations in the Nashiwa River (including the Miyoshi River and the Ohara River), and one location in the Tenjo River. As indicated, one of the factors that increased the flood damage in the lower Nuta River was the overflow from tributaries or levee breaches and inundations. To reduce flood damage, it is necessary to understand

the runoff characteristics of flood flow.

In this study, we first present an outline based on survey results of flood damage in the Nuta River in the Funaki district, which also experienced major erosion damage on the levee. Next, we present an overview of the overall characteristics from the obtained water-level data. Subsequently, we conduct rainfall-runoff analyses and analyze the flood water composition in a discharge hydrograph, focusing on the Funaki district. Finally, we conduct two-dimensional flood flow analysis and evaluate flood flow characteristics, as well as the causes of increased water-level.

2. OUTLINE OF FLOOD DAMAGE IN FUNAKI DISTRICT

During the flood event, the Funaki district avoided levee breaches at the main stream of the Nuta River, though, the levees experienced major erosion because of overflows, and major flood damage occurred from the both banks near the Funaki Long Bridge. **Figure 2** shows the damage in Funaki district and the flood depth within the levee area, and **Fig.3** shows

Fig.1 Nuta River basin.

Fig.2 Overview of flooding upstream and downstream of the Funaki Long Bridge on the Nuta River.

Fig.3 Flood mark near the Funaki Long Bridge.

the flood marks and levee elevation profiles. Wide-ranging levee erosion, flood inundation, and sediment deposition damage were induced by overflows from the right bank levee just upstream from Funaki Long Bridge. Severe levee erosion damage and large-scale road embankment failure occurred due to the overflow from the right bank downstream from the Funaki Long Bridge (**Photo 1**). These eroded sediments were widely deposited in the inundated area. Although the levee breaches were avoided, severe erosion damage was observed longitudinally over a wide range of the right bank levee just upstream from

Photo 1 Road embankment collapse on the right bank downstream of the Funaki Long Bridge.

Photo 2 Erosion damage on the right bank upstream of the Funaki Long Bridge.

Fig.4 Outline of the Suge River flooding²⁾.

Fig.5 Flood mark of the Suge River.

Funaki Long Bridge. Levee bodies are primarily composed of sand; the embankments for residential land inside the levee area were also eroded (**Photo 2**). Low-lying areas on the left bank, and flooded areas over 2 m in depth were observed (**Fig.2**). Further, levee breaches were observed on the left bank side of the Suge River, which is a tributary that flows downstream of the Funaki Long Bridge, at two locations on both the right bank and left bank (**Fig.4**). The flood marks are shown in **Fig.5**. The Suge River levee was extremely low near the confluence of the Nuta River, and was affected by the high water-level near the confluence in the main stream of the Nuta River. Near the Nuta River junction point, there was no levee on the left bank side of the Suge River. However, a small area surrounded by mountains was inundated from the left bank (**Fig.4**). From the above, it is presumed that a large amount of flood water overflowed and inundated from the right bank near the confluence into the residential area. According to interview surveys, the right bank levee near the Nuta River confluence was first breached [1], after which the inundation area on the right bank of the Suge River was flooded. Subsequently, the left bank levee [2] was breached after the end of the night of July 7th. The flood waters in the inundation area on the right bank of the Suge River flowed back to the river during this time as the river channel water-level decreased due to the levee breaches. The backflow to the river channel caused the walls of private houses to collapse and parapet levees to fall towards the river channel direction. At this time, despite the considerable erosion damage to the levee, there was virtually no erosion or sediment accumulation within the residential side of the breached levee [3]. we confirmed that the levee was breached due to the return flow to the river channel. Scour hole pools formed and deposited sediments were also found on the left bank levee breached points.

3. FLOOD FLOW CHARACTERISTICS BASED ON WATER-LEVEL OBSERVATION DATA

The water-level hydrographs measured using a water-level gauge in the main stream of the Nuta River during heavy rain are shown in **Fig.6**. The water-level observation points and catchment areas of the main stream and tributaries are shown in **Table 1**. The locations of the water-level gauges are shown in **Fig.1**. Nakagochi, which is located upstream of the Nuta River, experienced its first and second peaks on the night of July 6th and morning of July 7th, respectively, whereas the peaks at Funaki and Shippo in the downstream areas were not prominent. As will be

Fig.6 Water-level fluctuation in the Nuta River.

Table 1 Elevation and catchment areas of water level observation points.

River name	Observation point	Catchment area (km ²)	Presence of dam in catchment area
Nuta River	Kodo	103.4	Fukutomi Dam
	Nakagochi	141.4	Fukutomi Dam
	Funaki	367.5	Fukutomi Dam Mukunashi Dam
	Shippo	479.6	Fukutomi Dam Mukunashi Dam
Nyuno River	Nakashima	10.32	None
	Shippei	38.39	None
Mukunashi River	Mukunashi	56.42	None
	Waki	104.3	None
	Okujo	165.3	Mukunashi Dam
Suge river	Sugekawa-bashi	20.66	None
Nashiwa River	Minamikata	31.46	None
Buttsuji River	Hongo	24.08	None
Tenjo River	Nutahigashi	18.01	None

discussed later, this was because the first and second inflow peaks from the Mukunashi River, which has a large catchment area, were cut off by the Mukunashi Dam and discharged overall as a single hydrograph. Consequently, the flood hydrographs that were naturally discharged from the rain had two peaks, but the Fukutomi and Mukunashi Dams reduced the first and second peaks, causing a hydrograph with a single

Fig.7 Water-level fluctuation in the upstream of the Nuta River and Nyuno River.

Fig.8 Water-level fluctuation in the upstream of the Nuta River and Mukunashi River.

gradual waveform to flow into the downstream region.

Comparisons between the hydrographs of the mainstream water-level upstream of the Nuta River and those of the Nyuno and Mukunashi Rivers are shown in **Fig.7** and **Fig.8**. The wave-form of the water-level hydrograph immediately after the Nyuno River confluence (Nakagochi) is more similar to that before the Nyuno River confluence than that of Kodo located in the upper main stream. Furthermore, the flood hydrograph of Nakagochi is shaped by the Nyuno River confluence rather than the main stream. This could be because the peak waveform of the main stream flood hydrograph was cut by the Fukutomi Dam. Similar to the Nyuno River, there were two clear peaks for the Mukunashi River at the water-level observation points of Mukunashi and Waki, which were located upstream from the Mukunashi Dam. However, the peak flow at Okujo downstream from the dam decreased because of the flood control

Fig.9 Water-level hydrographs in the downstream of the Nuta River and in- flowing tributaries.

Fig.10 Water-level fluctuation of the observation points excluding the dams as catchment areas.

Fig.11 Water-level fluctuation of observation points downstream of the Fukutomi and Mukunashi Dams.

of the dam, causing the mild single waveform hydrograph.

The water-level hydrographs of the lower mainstream Nuta River, and those of the water-level observation points at the downstream tributaries (Suge River, Nashiwa River, Buttsuji River, and Tenjo River) are shown in **Fig.9**. We can observe that there is no downstream tidal effect during the peak flooding period even at Shippo, located near the mouth of the main river. Additionally, the two water-level peaks, which cannot be seen in the water-level hydrographs downstream of the main river, can be clearly confirmed in each of the water-level hydrographs in the tributaries. It can be observed that the basin rainfall runoff effects are more dominant than those of the mainstream backwaters at the observation points on the tributaries.

Groups of observation points that either include or exclude the dam in the catchment area are shown in **Table 1**. **Figure 10** shows comparisons of water-level changes observed at the observation points excluding the dam in the catchment area and the average of those water-level changes. Except for the Nyuno River, which has a sharp peak waveform, the individual waveforms are all within ± 0.5 m of the average waveform. We observe that the water-level in all the upstream river regions change in a similar manner during the flood. **Figure 11** shows comparisons of the average changes in water-level at the observation points excluding the dam in the catchment area (same as **Fig.10**), and the individual water-level changes within the same time period at the observation points downstream of the Fukutomi and Mukunashi Dams. As is self-evident from the function of the dam, it can be observed in **Fig.11** that the water-level increases in the river channels at the observation points, which include the dams in the catchment area that are controlled to a significant extent to reduce the flow during the elevated water-level period. The peak water-level downstream of the Fukutomi Dam in particular is 1.5 m lower than in areas without dams, and the amount of change is approximately - 0.5 m or less compared to the average values during the flood. The water-level changes downstream of the Mukunashi Dam are relatively higher than the average value for the small water-level variation of 3 m or less in the horizontal axis (averaged water-level change without the dam). However, these are not significant, relative to the other points in **Fig.10**. In addition, for large water-level change of 3 m or higher, the water-level change downstream from the dam is clearly smaller than that of the average value. Furthermore, during the flood discharge falling stage (i.e., horizontal value decreases), the fact that the shape of the graph does not rise on the left and is maintained at a roughly flat level signifies that the water-level is not increased

by the dam discharge. Therefore, detailed quantitative assessment of the effects of the two dams using runoff and flood analysis is necessary; however, the results indicate that the significant flood control effects of the dams from the observed water-level change the hydrographs.

4. RAINFALL RUNOFF ANALYSIS

(1) Analysis method / conditions

The Rainfall Runoff Inundation (RRI) model^{(3),(4)}, which can be applied to rivers with minimal hydrological and river data, was used for the runoff analysis. The RRI model is a distributed run-off model that divides entire watersheds into grid cells, and calculates temporal variations in water volume on each grid cell using the continuity equation. The surface and river flows were determined by water surface gradients using the Manning Equation, assuming a diffusion wave approximation. Infiltration flows into the ground were calculated by dividing the basin slope into mountainous and plain areas. Lateral (horizontal) infiltration flows in the mountainous areas were calculated using Darcy's law, and vertical infiltration flows in the plains were calculated using Green-Ampt equation for infiltration capacity.

The calculation period included the run-up period, and was set at 144 hours from 0:00 on July 3rd, to 0:00 on July 9th. The 50 m mesh elevation data published by the Geospatial Information Authority of Japan was used for the ground data. Each grid cell used in the analysis had a grid spacing of 150 m. A high-resolution land cover map was used for the land cover data. The land cover distribution is shown in **Fig.1**. The XRAIN-GIS rainfall amount was used for rainfall data. The river channel cross-section was set as rectangular, and parameters for the river channel shape were determined by comparisons with the river cross-sections of the river management plans and ensuring that the river channel width was equal. However, details on the river channel cross-section were unclear, and it was difficult to accurately analyze the outflow from the river channel and assess the inundation flow volume from levee breaching. Therefore, we did not consider inundation water from the rivers and calculations were made by deepening the river channel by 10 m overall to avoid generating overbank flow inundation, including at the Funaki district where the large amount of flood water inundated as indicated in the foregoing section. Therefore, the flow calculated in this study was estimated as larger than the flood flow that actually passed through the river channel. The boundary conditions at the downstream end of the river was set as the water-level data observed at Shippo, located at the lower Nuta River.

Fig.12 Comparisons of the discharge hydrographs.

Table 2 Slope flow parameters.

Parameters	Units	Plains		Slope areas	Parameter range
		Urban	Grass land		
Manning's roughness on slope cells	$\text{m}^{1/3}/\text{s}$	0.3	0.6	1.0	0.15~1.0
Soil depths	m	1.0	2.0	2.0	0.5~2.0
Effective porosity	(10^{-1}) -	4.71	3.98	3.98	-
Vertical saturated hydraulic conductivity	(10^{-7}) m/s	5.56	8.83	-	-
Suction at the wetting front defined	(10^{-1}) m	2.73	2.185	-	-
Lateral saturated hydraulic conductivity	m/s	-	-	0.2	0.01~0.3

For the inflow boundary condition at upstream ends, the discharge hydrographs from the Fukutomi and Mukunashi Dams were given just downstream of the dams. The inflow discharge hydrographs into the dams were used for the parameter calibration as shown below. Comparisons of the flow hydrographs

Fig.13 The discharge hydrograph and composition at the Funaki station.

are shown in Fig.12. The peak inflow at the Fukutomi Dam decreased, but the waveforms of the hydrographs at the Fukutomi and Mukunashi Dams were roughly matched. The parameters used in this analysis are shown in Table 2. These were set based on the parameter settings⁴⁾. It seemed that increasing the soil thickness reduced the flow rate, whereas increasing the lateral saturated hydraulic conductivity increased the flow rate. The setting values for sandy clay soil⁴⁾ were used for the mountainous areas and grasslands in the plain areas for the porosity, vertical saturated hydraulic conductivity, and wet front suction pressure parameters. The setting values for silty clay soil⁴⁾ were used for the urban regions of the plain areas. The parameters with a significant influence on the flow rate under these analysis conditions were the soil thickness and lateral saturated hydraulic conductivity; these values were adjusted to recreate the dam inflow hydrographs.

(2) Analysis results

The analyzed discharge hydrograph and flow rate composition fractions in the Funaki station are shown in Fig.13. Among them, the actual discharge hydrograph are used for the Fukutomi and Mukunashi Dams. In this analysis, the first and second peak flow rates were $1,006 \text{ m}^3/\text{s}$ and $1,115 \text{ m}^3/\text{s}$, respectively. Consequently, the dam discharge was 54.8% of the flow rate through the Funaki station. The river management plan discharge at the Funaki point was $1,140 \text{ m}^3/\text{s}$ ⁵⁾, and could be inferred as the flood was within the scope of the management plan. A loop of the observed water level and analyzed discharge at the Funaki station are shown in Fig.14. The curve depicts a counterclockwise motion, and high water-level conditions continue even for the discharge falling stage after the second peak. This was probably caused by the increasing in resistance to flow in the river channel, decreased water-level gradients during the falling stage owing to unsteady characteristics, and the influence of flood water flowing back to the river channel from the inundated area. The details will be

topics for future research.

The emergent operation of the dam for the excess flood was avoided in this flood, and flood control was conducted according to operational regulations¹⁾. Although a special disaster prevention operation that effectively utilizes the dam's water storage capacity considering the downstream damage conditions was impossible with current operational regulations, it is useful for evaluating the river capacity and the dam effectiveness to discuss the effect of the special operation for this event. Flooding damage occurred downstream of this flood; therefore, we conducted verifications by combining the dam's effect with the effect of ideal operations for maintaining the inflow and discharge at the same level by storing the reservoir water-level in the Mukunashi Dam up to the surcharge water-level after the second inflow peak. Comparisons of the dam's reservoir water-level and observed discharge values are shown in **Fig.15**. **Figure 16** compares various flow hydrographs at the Funaki point for floods with the actual dam operation and the ideal special operation as explained above, and assumed flood without the dam. The discharges at the Funaki station for the flood without the Mukunashi Dam were estimated as 1,156 m³/s and 1,193 m³/s for the first and second peaks, respectively, which were considered to have exceeded the management plan discharge. Therefore, we can infer that the Mukunashi Dam considerably lowered the discharge to this flood event. Meanwhile, the discharge is assumed to decrease only by a marginal amount after the second peak even with the ideal special operation of maximizing the dam reservoir water-level to minimize the downstream damage conditions. A special warning for heavy rain was issued at the time of the second peak, and it was assumed that its effects were extremely limited relative to the risk of maximizing storage. Therefore, it can be concluded that the principal cause of damage from the Nuta River flooding was flood flow that exceeded the flow capacities of current flood control facilities and river channels. Further research on the mitigation of damage from these types of external flood forces is necessary.

5. FLOOD FLOW ANALYSIS

(1) Analysis methods / conditions

A horizontal two-dimensional analysis was conducted to investigate the flood flow conditions of Funaki district. Shallow water flow equations converted to a general coordinate system expressed by physical components^{6,7)} were used for the governing equations to be applied to the Nuta River. The approximately 3-km section upstream from the confluence of

Fig.14 Calculated discharge and observed water-level in the Funaki station.

Fig.15 Inflow / outflow discharge and reservoir water-level of the Mukunashi Dam.

Fig.16 Effect of the Mukunashi Dam on the discharge hydrograph at the Funaki station.

the Suge River, including the curved section of the Funaki district, was set as the calculation domain. The water-level hydrographs were used as the boundary conditions for the downstream end. The analyzed discharge at the Funaki station determined by the rainfall runoff analysis with RRI model was used for the discharge at the upstream end. Calculations in the

rainfall runoff analysis were conducted under non-overflow conditions with side walls, meaning that the discharge in the analysis was larger than the actual flood discharge passing through the river channel. Furthermore, this study focused on the influence of tree growth on the flow within the river channel at the flood peak. Therefore, decreased discharge influences caused by overflowing from the bank were not considered for simplicity. The water-level at the Funaki point, observed relatively upstream of the downstream end was reproduced by the analyzed water-level at the downstream end⁷⁾. The bottom roughness was set at an equivalent roughness of $k_s = 3$ cm based on on-site river bed materials. The fundamental equations included a tree resistance component with an equation that used the vegetation permeability coefficient $k^8)$ to assess the influence of tree growth (1):

$$(\tau_x, \tau_y) = (u_x, u_y) \rho g h \frac{\sqrt{u_x^2 + u_y^2}}{k^2} \quad (1)$$

Where, τ_x and τ_y are the tree resistance values per unit distance; u_x and u_y are the flow velocities in the x and y directions, respectively; h is the water depth; and k is the vegetation permeability coefficient. The vegetation permeability coefficient changes according to the tree growth conditions; studies have been conducted on the characteristics of this value⁹⁾. The present analysis did not have sufficient data on the river channel or tree growth conditions, hence the pre-flooding aerial photographs shown in **Fig.17** were used to simply determine tree locations in the river channel, and a value that reproduced the flood marks was uniformly set ($k = 10$ m/s).

(2) Analysis results

As shown in **Fig.18**, the analysis results reproduced the observed water-level characteristics, wherein the outer bank side values increased because of the river channel curvature near the Funaki Long Bridge and Sanyo Expressway, and the increasing water-level upstream of the Funaki station. **Figure 18** also shows energy loss gradients determined by integrating the tree resistance component (Eq. (1)) per unit area, and the bottom shear stress component at the peak water level by width integration. The tree resistance is predominant over the bottom shear stress, further downstream of Funaki Long Bridge. This corresponds to the locations where the water surface gradient becomes sharp and the water-level increase in the upstream direction, and where the tree-induced energy loss gradient is large. It can be observed that the tree growth downstream of the Funaki Long Bridge has an effect on the flood flow near the bridge. However, this analysis does not consider the influence of changes in the river channel, downed trees by flood flow, and overbank flows from the

Fig.17 Pre-flooding conditions near the Funaki Long Bridge (taken Nov. 2017) and vegetation distribution.

Fig.18 Water-level and tree resistance around the Funaki Long Bridge.

river. Further evaluations are required for quantitative assessment.

6. CONCLUSIONS

In this study, we evaluated the factors influencing the rise of water-levels using water-level data from the Nuta River basin, rainfall runoff analysis, and two-dimensional analysis of the flood flow. The major conclusions from this study are presented below.

- 1) The flood control functions of the Fukutomi and Mukunashi Dam on the Nuta River basin were

assessed using the observed water-level data. Water-level changes at the observation points that included the dam in the catchment area were clearly lower than those at other observation points. The results showed that controlling the dam discharge increased the water-level, verifying the flood-control functions of dams.

- 2) The rainfall runoff analyses showed that the peak flow rate at the Funaki point was at scale of the management plan discharge. Conducting the ideal special operations of storing up to the surcharge water-level after the second peak in the Mukunashi Dam would have had marginal effects for this flooding event.
- 3) Unsteady horizontal two-dimensional analysis using flow rates and observed water-level from the runoff analysis showed that tree growth directly downstream affected flood flow resistance near Funaki Long Bridge. Further quantitative assessments are required when considering changes in the river channel or levee overflow.

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