PROBABLE MAXIMUM FLOOD INUNDATION SIMULATION FOR RIVERS IN TOYAMA PREFECTURE, JAPAN

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ABSTRACT

The purpose of this study is to propose a countermeasure to promote early evacuation in areas where residents typically underestimate flood risks and experience fewer disasters. As one of the countermeasures, we examined whether it is possible to improve the presentation of hazard maps and to promote evacuations. This study proposes a new risk rank evaluation method using flood inundation simulation results. Two rivers, the Jinzu and the Jouganji River, were chosen, and Toyama City, which was inundated by the target rivers, was selected as the target area. A flood inundation model was applied to the target area to compute the flood inundation depth and velocity. Flood inundation simulations with several scenarios were analyzed in the computation. We simulated the worst-case flood inundation to demonstrate its effects to the local people. In addition, a new risk rank evaluation of the flood inundation that identified safe and unsafe areas was proposed to formulate a new flood hazard map in this study. Based on the results of the flood simulations, hazard maps consisting of only two colors (safe and unsafe zones) were created based on the new risk rank proposed in this study. We believe that the hazard maps that uses only two colors can have a strong impact on the residents, who underestimate the risks, and can promote evacuation in the event of a flood disaster.

Keywords: Flood inundation simulation, Risk rank evaluation method, Hazard maps, Jinzu river, Jouganji river

1. INTRODUCTION

Every year, severe water-related disasters occur in Japan due to typhoons and frontal rains. In July 2018, heavy rains were recorded over a wide area, especially in western Japan, and caused 224 casualties. While the evacuation behavior at the time of disasters is considered important, the percentage of those who evacuated during prior disasters was as low as approximately 0.5% of the residents who were advised early evacuation. At present, there is an improvement in the disaster information dissemination and warning system, but the flood associated risks are challenging for residents to realize, and thus, the awareness regarding flood-associated risks has been low. Therefore, this study examines a countermeasure to promote early evacuation of residents in areas who have been alerted regarding an impending disaster and have little experience of them. In particular, because the risks involving flood disasters are underestimated, disaster situations of multiple flood scenarios in Toyama City are reproduced by flood inundation calculations, and suggestions were proposed on how to demonstrate an easy-to-understand hazard map for promoting evacuation in advance. For the worst-case scenario, we simulated the probable maximum flood inundation to show what would happen under the worst case scenario.

2. STUDY AREA

The target area for this study was Toyama City, near the Jinzu and Jouganji Rivers in Toyama prefecture, Japan (**Figure 1**). The Jinzu River is 120 km in length and originates from Kaoredake, Gifu Prefecture (1,626 m asl) with a catchment area of 2,720 sq km. The Jouganji River is 56 km in length and originates from Kitanomatadake, Toyama prefecture (2,661 m asl) with a catchment area of 368 sq km.

The Jouganji River is the steepest river in Japan, with riverbed gradients of about 1/30 in the mountains and approximately 1/100 on the plains. The Jinzu River is also steep, with riverbed gradients of about 1/20 to 1/150 upstream, 1/150 to 1/250 midstream, and 1/250 to 0 downstream. It is important to consider these steep river segments when evaluating flood hazard since high-speed river flows can cause levee erosion and the occurrence of scours.

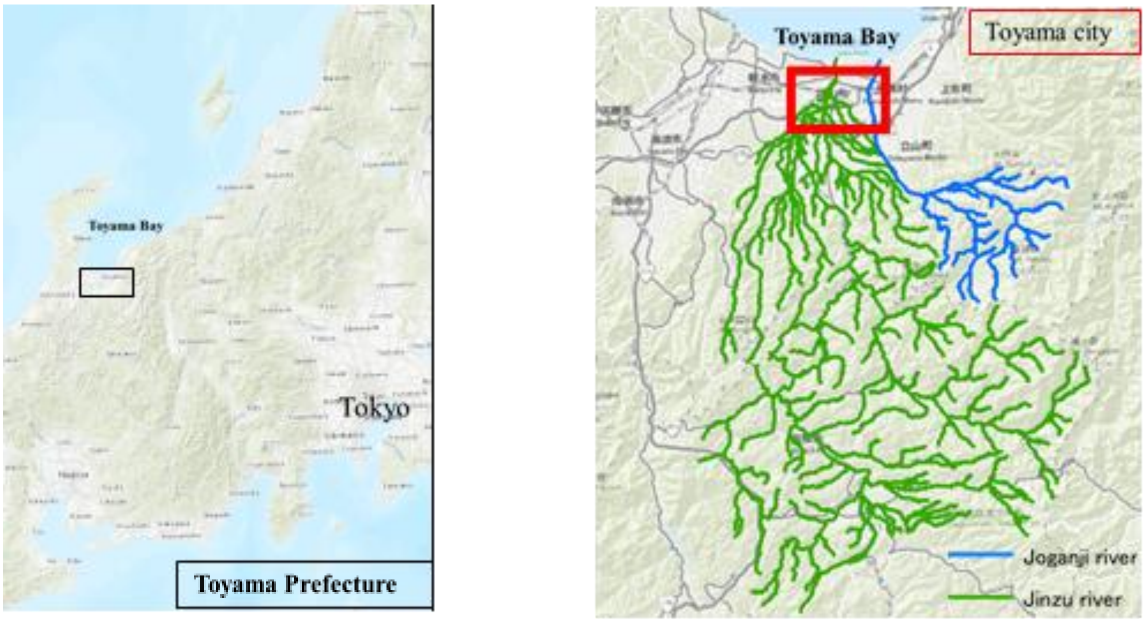

Figure 1. Location of Toyama Prefecture (left) and the study area (right)

3. METHODOLOGY

3.1. *Flood inundation model*

The flood inundation model comprised a hydrodynamic module of rivers and canal networks, and a flood inundation module of the floodplain. This model has been applied previously to several basins in Japan, as well as to Jakarta, Indonesia (Kure et al., 2008; Moe et al., 2016a, b, 2017; Priyambodoho et al., 2018).
Flood routes for rivers and canal networks were calculated using a continuous equation (1) and the Saint-Venant momentum equation for unsteady flow (2):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_l \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial(\alpha \frac{Q^2}{A})}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{n^2 gQ|Q|}{AR^{4/3}} = 0 \quad (2)$$

where Q is the discharge (m^3 s^{-1}), A is the cross-sectional area (m^2), q_l is the lateral inflow or outflow distributed along the x-axis of the watercourse (m^2 s^{-1}), n is the Manning's roughness coefficient, α is the momentum distribution coefficient, g is the acceleration due to gravity (m s^{-2}), R is the hydraulic radius (m), and h is the water level (m).

Unsteady two-dimensional flow equations, consisting of the following continuity and momentum equations, were solved numerically for the flood inundation simulations of the floodplains. The details of this numerical simulation have been described previously (Moe et al., 2016a).

$$\frac{\partial h}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=0 \quad (3)$$

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial x}+\frac{gp\sqrt{p^2+q^2}}{C^2-h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx})+\frac{\partial}{\partial y}(h\tau_{xy})\right]=0 \quad (4)$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+gh\frac{\partial \zeta}{\partial y}+\frac{gq\sqrt{p^2+q^2}}{C^2-h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy})+\frac{\partial}{\partial x}(h\tau_{xy})\right]=0 \quad (5)$$

where $C(x,y)$ is the Chézy resistance ($m^{1/2}$ s^{-1}); ρ_w is the density of water (kg m^{-3}); ζ(x,y,t) is the water elevation (m); τ_{xx}, τ_{xy}, and τ_{yy} are the components of effective shear stress (kg m^{-1} s^{-2}); p(x,y,t) and q(x,y,t) are flux densities (m^3 s^{-1} m^{-1}) in the x- and y-directions, respectively; h(x,y,t) is the water depth (m), and g is acceleration due to gravity (m s^{-2}).

The Manning roughness coefficients of the riverbeds were set as 0.04 for the different river sections, while those of the land surfaces were set as 0.06 for all floodplains during calibration.

3.2. *Dataset*

Cross-sectional data for the rivers in the target area were provided by the Toyama Office of Rivers and National Highways, Ministry of Land, Infrastructure, Transport and Tourism (MLIT). We used the J-FlwDir dataset (Yamazaki et al., 2018) to create a 30-m resolution digital elevation model (DEM). Its accuracy was verified using a 5-m resolution DEM obtained from the Geospatial Information Authority of Japan, MLIT. Predicted high flows of the target rivers were obtained from open reports published by the MLIT.

Four external forces were used: the planned and expected maximum discharges of the Joganji River and the planned and expected maximum discharges of the Jinzu River. In this study, the probable maximum flood was considered the expected maximum discharge that could occur every 1000 years.

4. RESULTS

Flood inundation simulations were conducted for several scenarios. We performed a sensitivity analysis to evaluate whether the resolution of the 30-m DEM was sufficient for local flood hazard evaluations. Sample flood inundation simulation results obtained using DEMs with 5- and 30-m resolutions are shown in **Figures 2** and **3**, respectively. The 5-m resolution DEM yielded detailed inundation information for small-scale features, such as roads and paddy fields. However, the 30-m resolution DEM also simulated inundation depth and flood flow velocity reasonably well. Therefore, we decided to use the 30-m resolution DEM in subsequent simulations owing to its easy and rapid computation abilities.

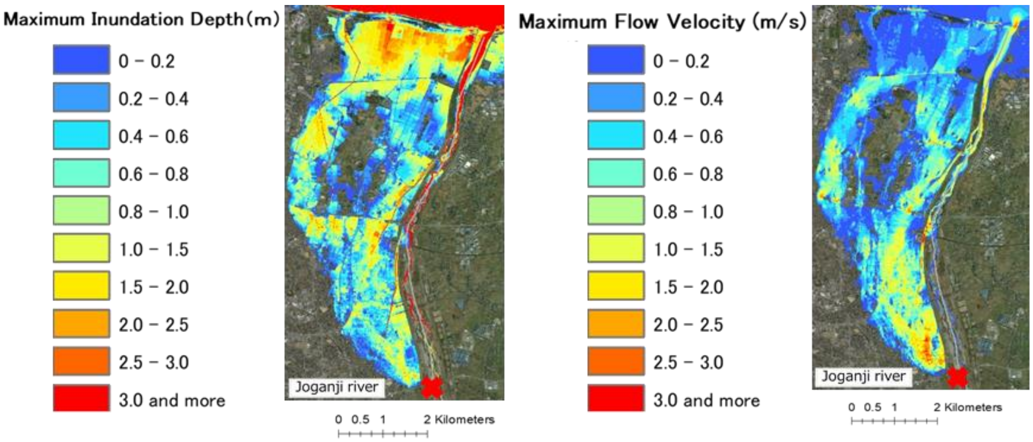

Figure 2. Maximum inundation depth (left) and flow velocity (right) simulation results obtained using a 5-m resolution digital elevation model (DEM)

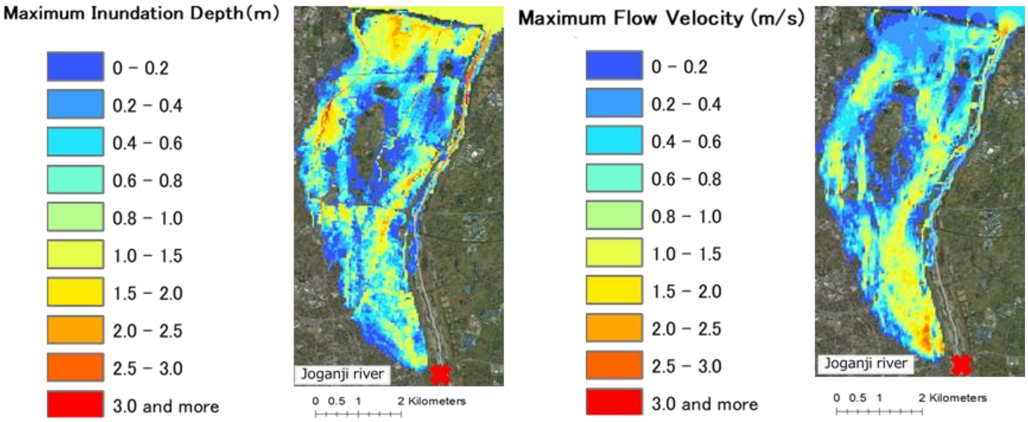

Figure 3. Maximum inundation depth (left) and flow velocity (right) simulation results obtained using a 30-m resolution DEM

Flood inundation calculations for multiple embankment breach scenarios were performed using a spatial resolution of 30 m with a low analysis load. The analysis results are shown from **Figure 4** through **7** -

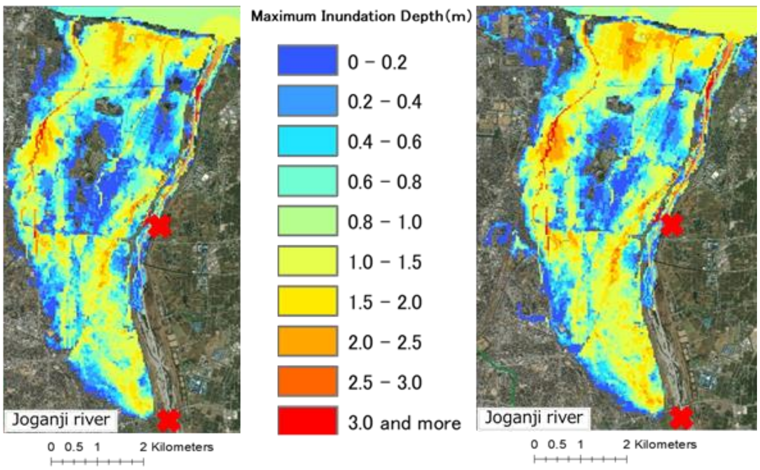

Figure 4. Maximum inundation depth using the planned (left) and expected (right) maximum discharges (24 hours after embankment break)

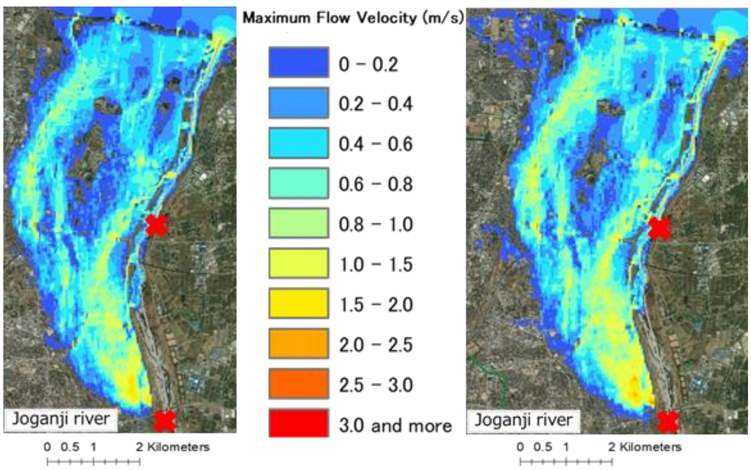

Figure 5. Maximum flow velocity using the planned (left) and expected (right) maximum discharges (24 hours after embankment break)

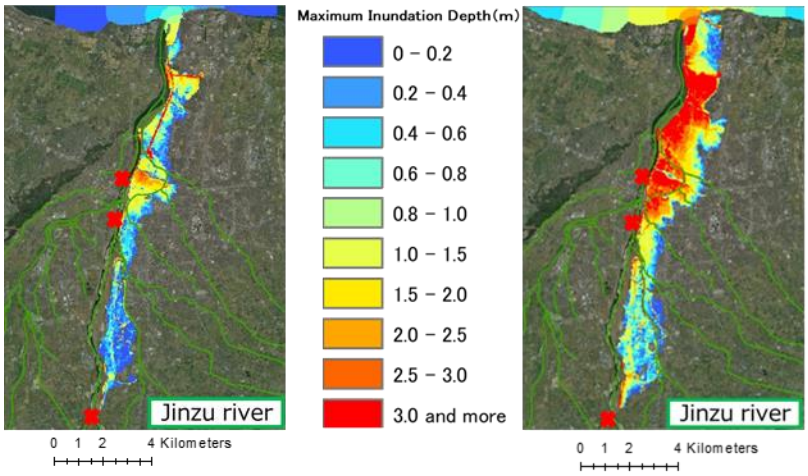

Figure 6. Maximum inundation depth using the planned (left) and expected (right) maximum discharges (24 hours after embankment break)

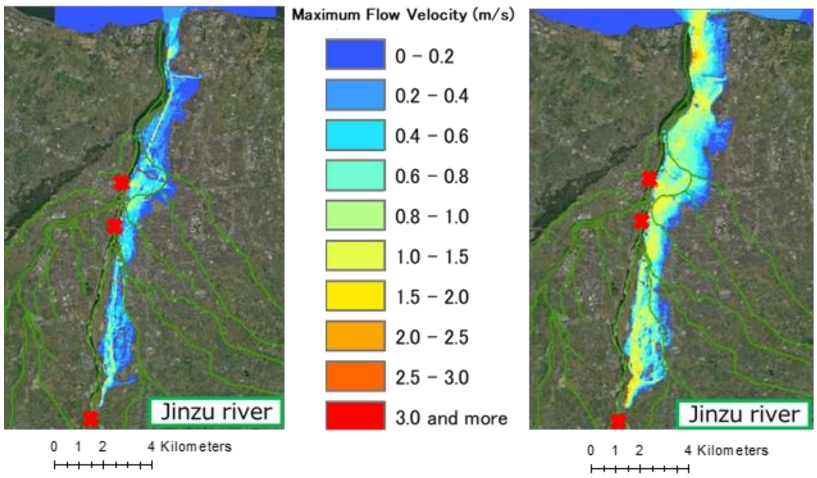

Figure 7. Maximum flow velocity using the planned (left) and expected (right) maximum discharges (24 hours after embankment break)

Figures 4 and **5** show that no inundation was simulated in the central part of the inundation area. Even if the expected maximum flow rate was used as an external force, the flood flow was blocked in these central areas because of the National Highway No. 8, which has high elevations. In addition, in the Joganji River, which is an alluvial fan, inundation can be observed in a wide area even during the flood inundation at the planned discharge sites (**Figure 4** and **5)**. Therefore, particularly, when the Joganji River was flooded, it was assumed that a several evacuees had to move to the evacuation sites in a short duration after the flood occurred.

To evaluate the flood inundation simulation results, we proposed a new method for ranking flood risks based on flood inundation depth, flow velocity, and hydrodynamic forces. For example, **Figure 8** shows two-stage flood risk zones, which are identified using the proposed method. People in the high-risk zone (red) require early evacuation prior to a flood event, whereas those in the low-risk zone (blue) may safely remain in their houses, perhaps move to the second or the third floor. This new risk identification method was developed based on the LIFESim (US Army Corp., 2004) and Floris (Rijkswaterataat, 2016) models, and is designed to encourage people who may underestimate flood risk to accurately assess their own risk and prepare for early evacuation

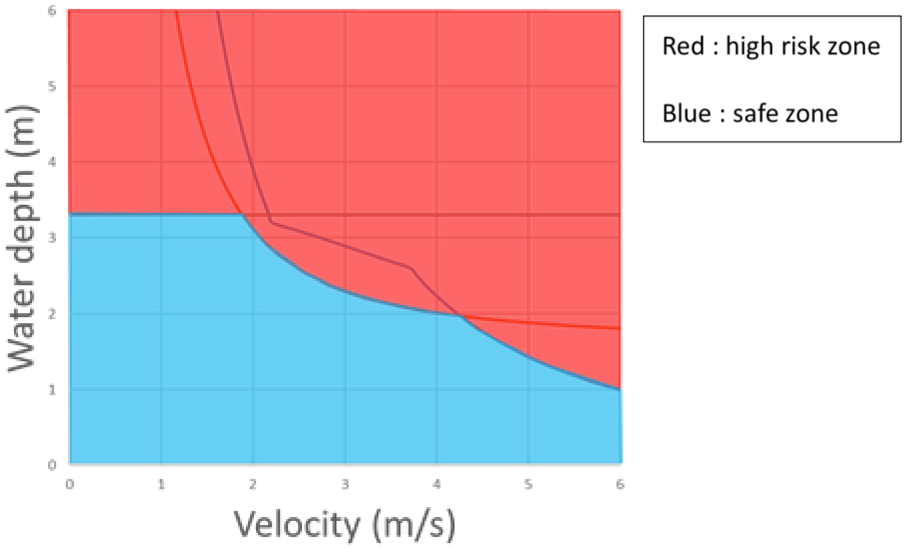

Figure 8. Two-stage flood risk identification. Red, high-risk zone; blue, safe zone

Next, this classification scheme was combined with the flood inundation simulation results to develop a new and user-friendly hazard map as shown in **Figure 9** below.

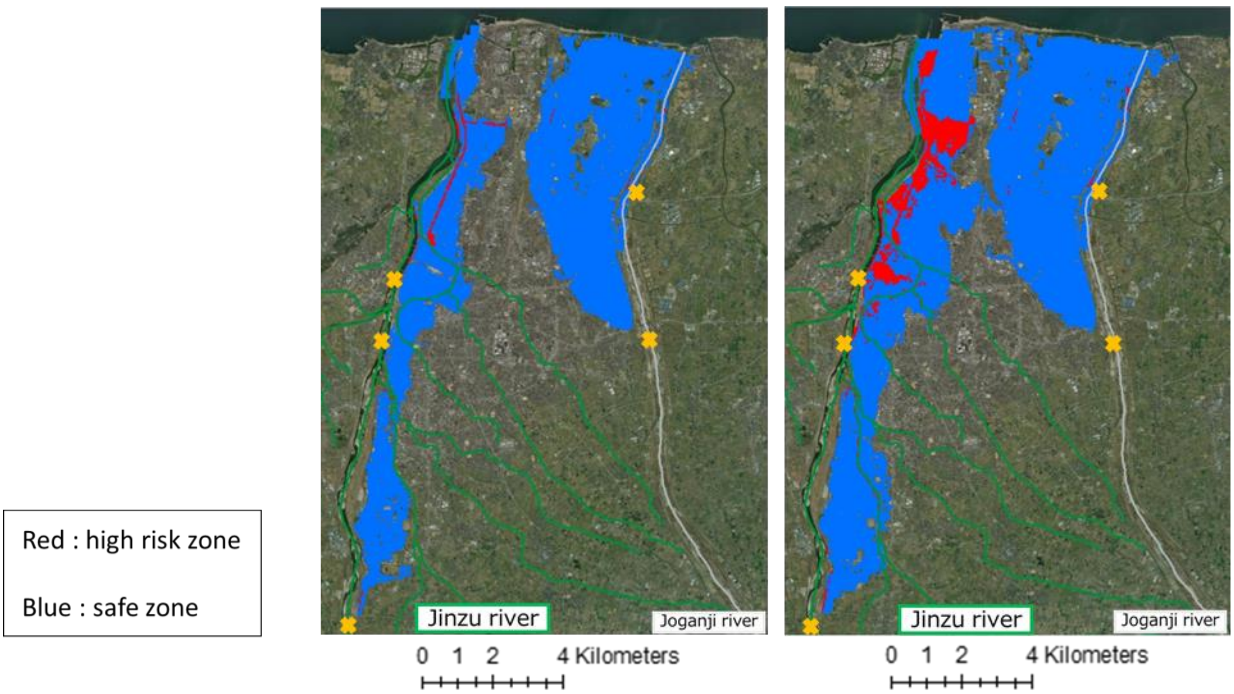

Figure 9. Two color hazard maps using two risk rank assessments. Red, high-risk zone; blue, safe zone. (the planned (left) and expected (right) maximum discharges)

The hazard map using the planned discharge shows vertical evacuation in most inundated areas, and the hazard map using the probable maximum flood discharge shows horizontal evacuation near the embankment break. As such, it is important for the residents to understand the risks, especially during maximum flooding cases.

However, in this study, only five cases of embankment breaks were considered; it is therefore necessary to create a hazard map considering more embankment break scenarios in future studies.

5. CONCLUSION

In this study, we applied a flood inundation model to the Jinzu and Jouganji Rivers in the Toyama prefecture, Japan. Flood inundation simulations were conducted for several scenarios. Sensitivity analyses comparing the DEMs with 5- and 30-m resolutions were conducted The 30-m DEM was selected owing to its accuracy and rapid computation.

Several flood inundation simulations were conducted including the probable maximum flood discharge to demonstrate the worst case effects. We also proposed a simple risk classification system based on flood inundation depth and flow velocity data. Formulating the hazard map in two colors using the risk rank evaluation method proposed above made it easier to understand the maps and could strongly impact the residents who underestimate the risk. In addition, advance evacuation in the event of a disaster is promoted. However, since the boundary between horizontal evacuation and vertical evacuation is not absolute, it is necessary to verify the risk rank method proposed in this study using a prior flood disaster event that led to the levee breakage and damages to houses due to the flood inundation, such as the damage caused by the Chikuma River during the event of the typhoon no. 19 in 2019.

6. ACKNOWLEDGMENT

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