Critical Rainfall Thresholds for Hydrological Processes Leading to Debris Flow due to Torrent Bed Material Scouring

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In this study, we employ the 10-minute rainfall intensity and the effective rainfall with a half-life period most similar to the characteristics of torrent bed material water storage in the storage type model to calculate and evaluate the critical rainfall thresholds for hydrological processes leading to the generation of debris flow due to torrent bed material scouring. Critical rainfall thresholds for hydrological processes leading to debris flow since 2008 were effective rainfall of 41.2 mm and 10-minute rainfall of 6 mm for pipe flow without generating a debris flow, effective rainfall of 129.1 mm and 10-minute rainfall of 8 mm for a clogged pipe exit without generating debris flow, and effective rainfall of 126.8 mm and 10-minute rainfall of 19 mm for debris flow generation. These results suggest that a pipe flow has a small possibility of debris flow generation. For a clogged pipe exit, the amount of water stored in the torrent bed material meets the quantitative conditions required to generate a debris flow, indicating that a 10-minute rainfall of 19 mm or more may increase the possibility of a debris flow occurrence.

Key words: debris flow, hydrological process, rainfall indices, critical rainfall threshold

1. INTRODUCTION

Generation and development process of debris flow has not been revealed as yet. As a study on debris flows due to torrent bed material scouring, it suggested that torrent bedmaterial saturated due to rising groundwater level and debris flow occurred using hydraulic model experiments [*Takahashi*, 1977]. Field observations have been conducted in Japan and overseas in recent years [*Suwa et al.,* 1989 ; *Imaizumi et al.,* 2002 ; *M.Berti et al.,* 2005 ; *Jeffrey A.Coe et al.,* 2008 ; *C.Gregoretti et al.,* 2008 ; *Mizutanii et al.,* 2008 ; *Hayami et al.,* 2013 ; *Imaizumi et al.,* 2016].

In these previous studies, it suggests that debris flow occurs even if torrent bed material is not saturated or sediments are scoured due to surface flow. But there are still many unclear points on the process of generation of debris flow.11 Debris flows due to torrent bed material scouring occurred at the Nishinokaito River of Mount Fujiwara in Inabe City of the Mie Prefecture, Japan between 1999 and 2012. Our hydrological observations including runoff of subsurface flows from the torrent bed material, aim to reveal the mechanism of hydrological processes (pipe flow, clogged pipe exit, and debris flow) leading to debris flow and to propose a method to predict the timing and magnitude of debris flow. Due to high-intensity rainfall, hydrological processes including pipe flow and clogged pipe exits induce debris flow at the Nishinokaito River. The authors studied affected and non-affected areas by the occurrence of hydrological phenomenon using the RBFN (Radial Basis Function Network) method [*Yamada et al.*, 2017]. However, the relationship between the occurrence of hydrological phenomenon and the values of soil moisture index or effective rainfall using the storage type model based on actual discharge data are not elucidated. We employ the 10-minute rainfall intensity and the effective rainfall with a half-life period most similar to the characteristics of torrent

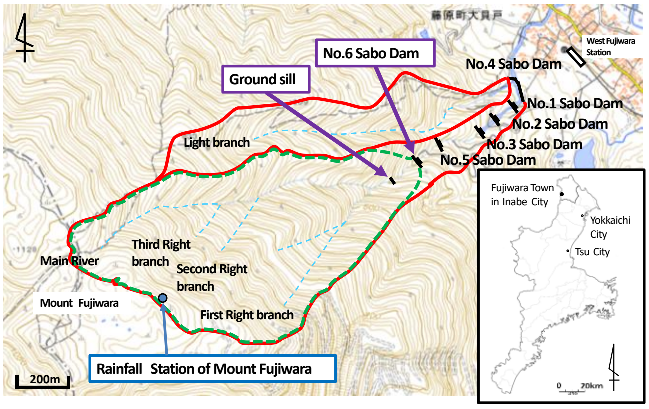

Fig.1 Location of the Nisinokaito river

(Dotted areas show study area.)

bed material water storage in the storage type model to calculate and evaluate the critical rainfall thresholds for hydrological processes leading to the generation of debris flow due to torrent bed material scouring.

2. METHODS

2.1 Study area

The basin upstream of the No. 6 Sabo Dam (**Fig. 1**) has an area of 0.75 km^2, a flow path length (horizontal distance from the No. 6 Sabo Dam to the summit) of approximately 1.8 km, and a mean gradient of 24.3°. The geological setting is mainly composed of Paleozoic and Mesozoic lime rocks. Outcrops of calcareous breccia, which are mixed in the top layer of riverbed, are re-consolidated by rainfall. In 2010, the Kuwana Construction Office of Mie Prefecture conducted a boring investigation at the middle reach of the Nishinokaito River (an upstream area 250 m from the No. 6 Sabo Dam). The results revealed that a debris flow with a thickness between 5 m to 20 m is deposited at the riverbed. The main component of the sediment is sand and sub-granular gravel, which is a few centimeters in size. Some parts also contain silt and clay .

Although construction of the No. 6 Sabo Dam was completed in 2010, it became fully sediment-filled due to the 2012 debris flow and the river has not been dredged. Upstream of the No. 6 Sabo Dam has a thick layer of debris sediment between 5 m to 20 m. Thus, surface water is not permitted

Fig 2 Observation of subsurface flow discharge at drainage holes of the No.6 Sabo dam

except for heavy rainfall. Rainfall runs as a subsurface flow inside the riverbed sediment prior to discharging from drainage holes in the No. 6 Sabo Dam.

Observations of the subsurface water flow from right above the basin of the No. 6 Sabo Dam were conducted using the drainage holes of the dam. Between 2009 and 2011, an interval camera (KADEC21-EYEII) was installed at the lower of the No.6 Sabo Dam to record the subsurface flow conditions from the drainage holes such as water levels. In 2012 two ultrasonic water level gauges (SE-QT50U) were installed to monitor the water levels. One monitors two of the five drainage holes on the right and the other monitors the lowest left one (**Fig. 2**). It was difficult to install and maintain an ultrasonic water level gauge for the drainages located at the middle and upper levels;

hence, an interval camera (KADEC21-EYEII) was installed at the right wing of sub dam of the No.6 Sabo Dam.

The subsurface water levels at the middle and upper drainage holes were obtained by the imagery analysis of the flow from each drainage hole. Assuming a circular cross-section of drainage hloe, the water surface width of the subsurface water was read from the imagery. Then the water level was calculated using a geometrical relationship, which was subsequently converted into the discharge using the h–Q curve obtained by the authors previous study.

The hydrological phenomena related to the processes leading up to the debris flow such as pipe flow and the occurrence timing of pipe exit clogging were based on the authors' past observations (using imagery data obtained from the multiple interval cameras installed at approximately 150 m upstream from the No. 6 Sabo Dam) [*Yamada et al.*, 2017].

In August 2015, we also set an interval camera at the lower of the dam to observe of the night-time subsurface flow discharge from drainage holes of the dam.

2.2 The hydrological processes leading to debris flow in this study

A debris flow occurred at Nishinokaito river on September 2 to 3, 2008. A photo analysis of the hydrological process leading up to the generation of the debris flow showed an increase in discharge and turbidity of the subsurface flows from the cross-section of the torrent bed material (In this paper, this is defined as water spouting from pipe exits.) Due to clogged pipe exits, subsurface flows spouted from several places, and a cross-section of torrent bed material collapsed (excavation cross-section area for the Sabo Dam construction). These observations indicate that when subsurface flows spout, pipe flows occur within the torrent bed material. Therefore, these hydrological phenomena should be studied to elucidate the process for generating torrent bed scouring-induced debris flow at the Nishinokaito river [*Yamada et al.*, 2009].

In this study, the hydrological processes leading to debris flow were defined as pipe flow, clogged pipe exits, and debris flow, obtained by photo -analysis of our observation s conducted since 2008. By following the convention used in the previous study [*Yamada et al.*, 2009], "pipe flow occurrence" means a subsurface water spurt from the large pores (pipe holes) formed by gravel in the surface of riverbed sediment,

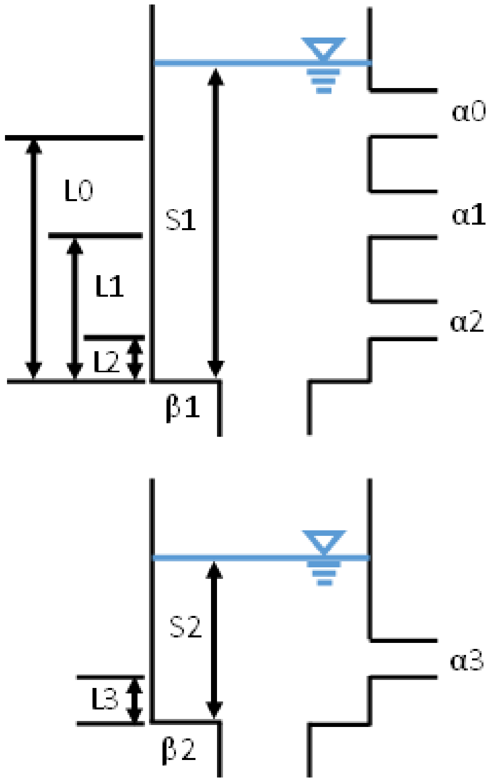

Fig 3 storage type model
(first tank and second tank)

Table 1 Parameters of the storage type model

α0 (1/hours)	0.062			*L0* (mm)	160
α1 (1/hours)	0.024	*β1* (1/hours)	0.110	*L1* (mm)	60
α2 (1/hours)	0.007			*L2* (mm)	28
α3 (1/hours)	0.003	*β2* (1/hours)	0.087	*L3* (mm)	5

and "pipe exit clogging" indicates that a drainage exit clogs or subsurface water flow suddenly stops during torrential rainfall(pipe exit clogging would be induced by collapse of pipe walls during increasing subsurface flow in torrential rainfall[*Yamada et al.*, 2017].

2.3 Rainfall index

In this study, rainfall of the occurrence of each hydrological process was regarded as "rainfall of occurrence".
Both the 10-minute rainfall and the effective rainfall were employed as rainfall indices.

Storage type model (first tank and second tank) proposed by previous study [*Sano et.al.*,2015] was employed (**Fig.3**). This storage type model assumes the first tank is the surface flow layer and the subsurface flow layer, as indicated by a boring investigation of the local riverbed sediment [*Kuwana Construction Office of Mie Prefecture*, 2010] and the flow characteristics of subsurface water during torrential rainfall. Table 1 shows each parameter. The parameters were determined based on repeated trial and error to recreate the water flow amount of the effective rainfall events between 2012 and 2014 with a clear flow peak. (This is a total of 26 rainfall events.) Since the storage type model uses timescale parameters, each parameter for the flow coefficient (αn) and the permeability coefficient (βn) is 1/6 of its value to fit on a 10-minute scale.

We employ the 10-minute rainfall intensity and the effective rainfall and evaluate the critical rainfall thresholds for hydrological processes.

The effective rainfall was calculated by using Equation 1.

$$\boldsymbol{R}_{\boldsymbol{w}} = \sum \boldsymbol{a}_{\boldsymbol{1i}} \times \boldsymbol{R}_{\boldsymbol{1i}} \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \quad (1)$$

where R_w : effective rainfall, R_{1i} : 10 minute rainfall before *i* minute (*i*=10,20,30…), a_{1i} : Reduction coefficient before *i* minute, $a_{1i} = 0.5^{i/T}$, T : half-life period(minute)

To observe the changes in water storage of the first tank and to find similarities to the half-life period, we arbitrarily set 240, 300, 360, and 420 minutes for the half-life periods. To observe the changes in the water storage of the sum of the first and second tanks and to find similarities to the half-life period, we arbitrarily set 540, 600, 660, and 720 minutes for the half-life periods.

The half-life period of effective rainfall, which is equivalent to the changes in a tank's water storage in the storage type model (first tank and second tank) on a 10-minute scale was determined using the similarities between the water storage of each tank and the effective rainfall or the mean value of their absolute difference.

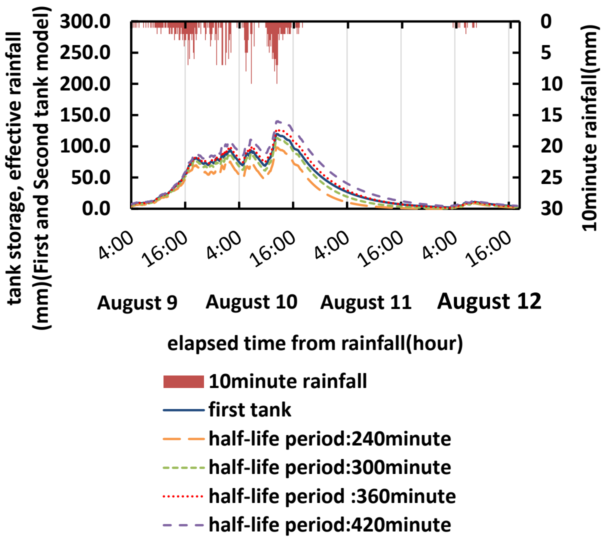

Fig.4 Half-life period of the effective rainfall equivalent to the first tank (Case on August 9, 2014)

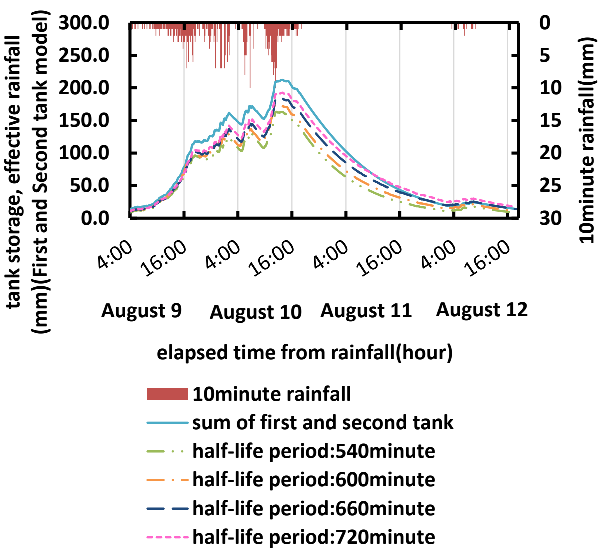

Fig.5 Half-life period of the effective rainfall equivalent to the sum of first and second tank (Case on August 9, 2014)

3 RESULTS

3.1 The correspondence of effective rainfall to the water storage of each tank in a storage type model

Figure 4 shows the correspondence of the effective rainfall to the water storage in the first tank and changes in half-life periods. A half-life period of 360 minutes for the effective rainfall was the closest to the changes observed in the first tank's water storage and its mean value of the absolute difference was also the smallest.

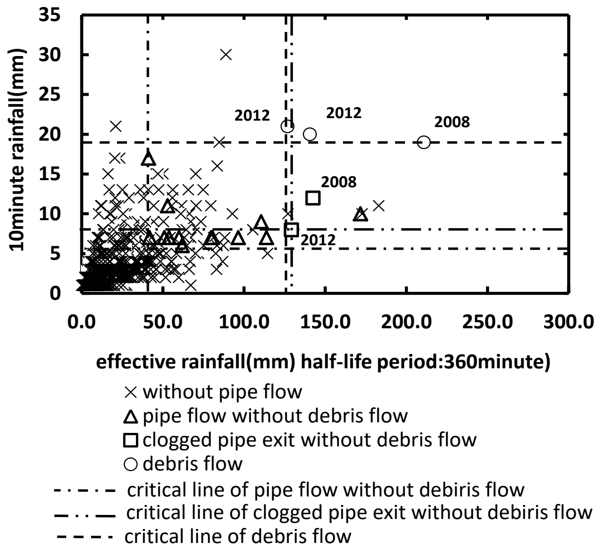

Fig6 Critical rainfall thresholds(effective rainfall with a half-life period of 360minutes) to generate a hydrological processes

Figure 5 shows the sum of the water storage of the first and second tanks as well as half-life periods of the effective rainfall. A half-life period of 720 minutes of the effective rainfall was the closest to the sum and its absolute difference was also the smallest.

It is assumed that first tank storage is closely related to hydrological processes leading to debris flow. Therefore, effective rainfall with a half-life of 360 minutes corresponding to the storage height of the first tank was employed.

3.2 The critical rainfall thresholds for hydrological processes leading to the generation of debris flow

Critical rainfall thresholds (effective rainfall with a half-life period of 360 minutes) for hydrological processes leading to debris flow since 2008 were effective rainfall of 41.2 mm and 10-minute rainfall of 6 mm for pipe flow without generating a debris flow, effective rainfall of 129.1 mm and 10-minute rainfall of 8 mm for a clogged pipe exit without generating debris flow, and effective rainfall of 126.8 mm and 10-minute rainfall of 19 mm for debris flow generation (**Fig. 6**). These results suggest that a pipe flow has a small possibility of debris flow generation. For a clogged pipe exit, the amount of water stored in the torrent bed material meets the quantitative conditions required to generate a debris flow, indicating that a 10-minute rainfall of 19 mm or more may increase the possibility of a debris flow occurrence.

4 CONCLUSIONS

1) Half-life period of the effective rainfall equivalent to the first tank and the sum of first and second tank were 360 minutes and 720 minutes, respectively.
2) Critical rainfall thresholds (effective rainfall with a half-life period of 360 minutes) for hydrological processes leading to debris flow since 2008 were revealed.
3) Possibility of debris flow generation during pipe flow is small, but a clogged pipe exit increases the possibility of debris flow generation with a 10-minute rainfall of 19 mm or more at the Nishinokaito River.

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