Advanced Hazard Information and Methods for Appropriate Evacuation during Sediment Disasters

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In Japan, recent sediment disasters have resulted in substantial damage. For appropriate evacuation to minimize damage, it is necessary to provide residents with suitable hazard information on a routine basis and to develop high awareness of disaster risks. Although numerical simulations are useful tools for obtaining advanced information, the associated systems are generally developed by experts with specialized knowledge and techniques. Consequently, non-expert residents experience difficulty understanding the input conditions and output results. Furthermore, the information that local governments and communities require to develop evacuation methods might be different from that received from researchers using simulations. To avoid this conundrum, we therefore presented our simulation systems to local government engineers and discussed examples of input and output data. The important factor was the simulation accuracy and reliability for applying to evacuation. Moreover, for providing information to local residents, we confirmed that the information for both the input and output data needs to be compared with the recorded or experienced rainfall or disaster events for intuitive understanding. To utilize numerical simulations as effective information, we applied the proposed simulation system to a village in Miyazu City, Kyoto Prefecture with three scenarios considering past disaster rainfall records. For secure high accuracy and reliability to the target site, we conducted field survey and observation, and estimated some suitable parameters, then run simulations. And we presented the results of our simulations on GIS, which better helps residents to be cognizant of the disaster risks.

Key words: sediment disasters, advanced hazard information, providing methods, evacuation, numerical simulations

1. INTRODUCTION

In Japan, recent sediment disasters have caused substantial damage. In August 2014, Tamba City, Hyogo Prefecture and Hiroshima City, Hiroshima Prefecture were affected by sediment disasters caused by heavy rainfall. Although the difference in the estimated volume of sediment displaced in the two disaster was not significant, the respective number of fatalities in Tamba was one. In Tamba, local governments and communities had been working together toward disaster prevention. Consequently, residents were highly aware of sediment disaster risks; during the rainfall, appropriate evacuation advice, namely, vertical evacuation instead of moving to a shelter at the time of the flood in the night, was effective and minimized the damage.

Therefore, for appropriate evacuation, it is necessary to provide residents with useful hazard information on a routine basis and to develop high awareness of disaster risks. In this study, aiming for appropriate evacuation against sediment disasters, we considered advanced hazard information and also useful means of providing such information.

2. STUDY OUTLINE

Since 2015, we have been conducting studies on sediment disaster risks and hazard information on several mountainside villages in Kyoto Prefecture, Japan. Not only have we been conducting field research and applying simulations, we have also been cooperating with local government engineers to discuss and search for effective information required for evacuation.

2.1 Simulation systems for advanced hazard information

Currently, most of the hazard information for sediment disasters, such as time and place, can be forecast using numerical simulations.

2.1.1 Outline of our recently proposed systems

We recently proposed a multi-hazard simulator (SiMHiS) based on the landslide prediction model and water and sediment runoff model in the watershed scale [*Yamanoi and Fujita*, 2017]. The system can spatially and temporally simulate the risk level of three multi-hazard categories: rainfall, landslide, and flood (see **Fig.1,** left). This system can provide a rough estimate of the time and magnitude of sediment disasters based on the rainfall condition; however, it cannot provide details of the flooding/deposition area and distribution.

We have also developed and applied a GIS-related debris flow simulation system called Hyper KANAKO [*Nakatani et al*., 2016]. Using this system and by setting specific debris flow scenarios, we can predict the details of the flooding/deposition area and the distribution and indicate which residential area is at risk (see **Fig.1**, right). However, users are required to set the specific input debris flow data, such as volume and time, due to the heavy rainfall.

2.1.2 Solving the problems affecting recent systems

We connected the two simulation systems in order to obtain advanced hazard information. When the initial rainfall data information is set, the system not only provides the occurrence time of sediment disasters but also indicates the flooding/deposition area and the distribution.

However, runoff process from rainfall to small basin such as 0.01-10 km^2 which faces debris flow risks in Japan is still not clear. Especially for large runoff event such as landslides and debris flows occur, the detail process is not clear but presumed that water and sediment seemed to move in large volume comparing to normal conditions. Applying runoff analysis such as SERMOW or other CommonMP tools, it can describe normal and small rainfall event and runoff, but usually underestimate large events. In basins with 5-10 km^2, empirically it is difficult to obtain runoff simulation results with peak discharge results larger than 10 m^3/s; though observed data show larger peak discharge. Therefore, for calculating rainfall, landslides, and runoff process in SiMHiS, parameters and input conditions must be estimated properly for the large rainfall event. To set suitable parameters, we need to acquire the target site information, such as recorded disaster data or with field survey and observations.

2.2 Providing effective information

In general, numerical simulation systems are developed by researchers and experts with specialized knowledge and techniques. Consequently, non-expert residents experience difficulty intuitively understanding the input conditions and output results. Furthermore, the information that local governments and communities require to develop evacuation methods might be different from that presented by researchers using simulations.

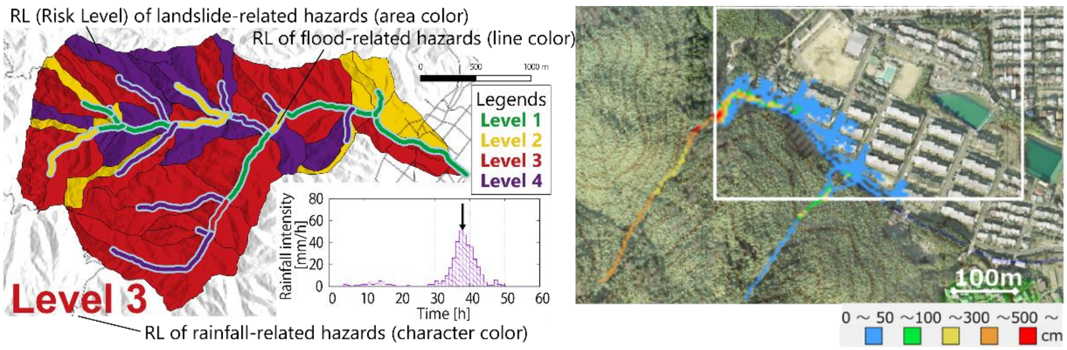

Fig. 1 Simulation results of Kyoto Prefecture (left: using SiMHiS, which considers multi-hazard; right: using Hyper KANAKO, which considers debris flow deposition)

Therefore, we presented our simulation systems to local government engineers in Kyoto Prefecture and in Miyazu City, and discussed examples of input and output data.

We obtained comments from the engineers. The important factor was the simulation accuracy and reliability for applying to evacuation. Moreover, for providing information to local residents, we confirmed that the information for both the input and output data needs to be compared with the recorded or experienced rainfall or disaster events for intuitive understanding (see **Table 1**).

To apply numerical simulations as effective information, researchers must consider the request, set input conditions, and improve the input and output to such an extent that it is sufficiently understandable for residents to realize the risk intuitively. Moreover, we have to consider the target recipients, such as local people, voluntary disaster prevention groups, and local government engineers, and provide information suitable for each standpoint and select the necessary information with appropriate style.

And for securing high accuracy and reliability to the target site, we need to acquire the target site information, such as rainfall, flow depth and discharge at the torrent and downstream site, sediment details such as size and thickness, flooding and deposition area and distribution. The preferable information is the recorded disaster or large rainfall event data, but those can't always be acquired except for the rainfall data. Especially, recorded discharge data in mountains torrent is few. But for accuracy verification, we must know those data somehow for considering the sediment disaster risk designated sites; in Miyazu City approx.600 and in Kyoto Prefecture approx.16,700 (on 2018 March). Therefore, when we don't have enough data for verifying, we can obtain data from field survey and observations. Although large-scale surveys and observations can get detail data but requires high cost, we tried to conduct with small-scale and get minimum requirement effectively in low cost. The minimum requirement seemed to be as following: rainfall data, discharge at basin or torrent downstream, sediment details.

3. STUDY TARGET: HATA RIVER

We conducted advanced simulation considering an effective provision method on Hata river, a local river administrated by Miyazu City, Kyoto Prefecture, Japan (see **Fig. 2**).

Table 1 Discussion results for providing effective information to residents

Data (input/output)	Comments
Rainfall (input)	Residents find it difficult to understand probable rainfall. The disaster scale can be understood using the records of past maximum rainfall or of rainfall during other disasters.
Flooding/deposition area or distribution (output)	Residents will realize the risks when the flooding/deposition area or distribution results of the recent disaster are compared with the past disasters results. Images or animation results on the GIS map will help residents realize the risks, but they might believe that the other scenarios may not occur.

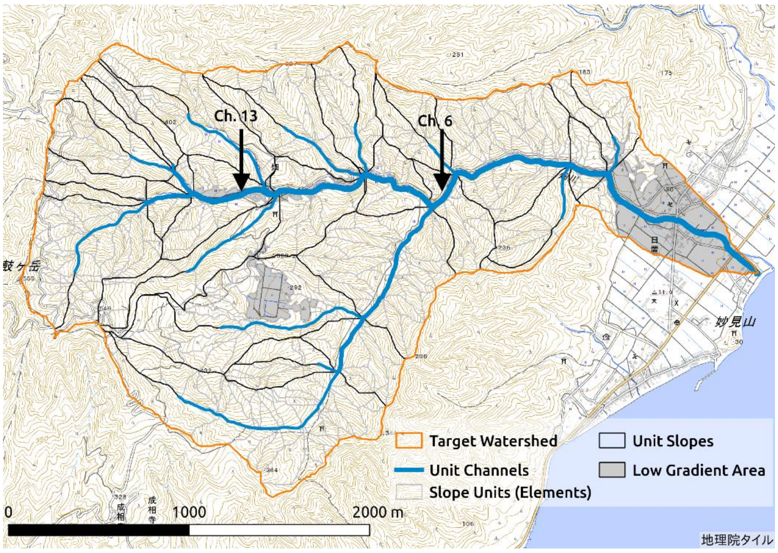

Fig. 2 Map of the simulation target watershed

3.1 Outline of Hata river

The Hata river watershed is 5.4 km^2. A residential area is located in the center of the watershed and is fully covered by the sediment disaster prone areas set by Kyoto Prefecture. Therefore, evacuation to the outside area of the watershed is important for the people when large-scale rainfall events that trigger flooding occur. There is only one road leading to the outside from the watershed, and it is quite close to the river, which has a high potential risk of overflowing its banks. Here, there weren't recorded discharge data at the downstream of torrent and basin at large rainfall, disaster event, or in small rainfall event.

In this study, we considered three sediment disaster scenarios due to heavy rainfall. Taking into account the provision of effective information for evacuation from simulations, we considered actual large rainfall events that recently occurred in Kyoto and other places.

3.2 Observations and field survey for setting simulation parameters

Runoff characteristics, such as depth of the soil layer and hydraulic conductivity, are very important for quantitatively estimating the rainfall runoff process. However, verification is difficult in small watersheds without discharge data, especially in a river managed by a local government. Therefore, we conducted a simple and low-cost observation utilizing a time-lapse camera (Brinno, TLC200) and identified the runoff parameters using the observed and field survey results.

The installation of the time-lapse camera is shown as Ch. 6 in **Fig.2**. The camera took one picture every 10 minutes, except at nights and in low-light conditions. **Fig.3** shows the pictures taken during a target flood event that occurred September 17–18, 2017. The water level during the event was estimated via visual observation of representative pictures. The large boulder, with a height of approximately 1.2 m, at the center of the picture was utilized as an indicator for the water level estimation. However, because the peak of the flood occurred during the night, no pictures were obtained for that even. Therefore, we estimated the peak water level value from the trace mark of the flood. From the sediments distributed on the large boulders by the flow, we estimated the maximum water depth as approximately 1.2 m.

Following estimation of the water level, we estimated the water discharge using Manning's formula (eq. 1), where n is the Manning's roughness coefficient, A is the cross-sectional area of the flow, S is the wet perimeter, and I is the slope of the hydraulic grade line-which seemed to be assumed being equal

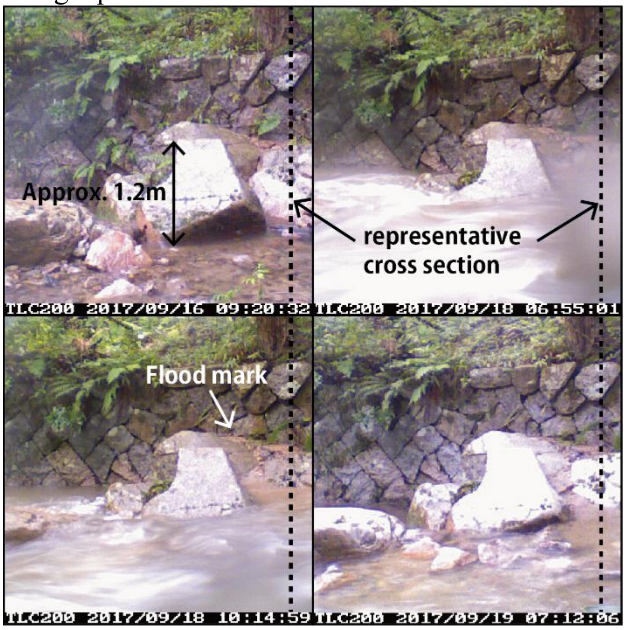

Fig. 3 Observed photo of the flood event that occurred on September 17–18, 2017, taken by Brinno TLC200 (A: One day before the event, B: During the event, C: Recession period of the event, D: One day after the event.)

to the channel bed slope.

$$Q = \frac{1}{n} A^{\frac{5}{3}} S^{-1} I^{\frac{1}{2}} \quad (1)$$

The relationship between the observed water level (h) and A or S was estimated from the geometry of the representative cross-section shown in **Fig.4**. The location of representative cross-section is shown in **Figs. 3** and **5**. Furthermore, n was set as 0.04, and I was assumed to be 0.07 based on the longitudinal profile survey shown in **Fig. 5**. From **Fig.4** and field surveys and observed photos, normal river width seemed to be 2-3 m, and for the maximum flow depth time, the flow width was estimated approx. 10 m.

Applying this method, water discharge during the 2017/9/17-21 rainfall event was obtained as point plots in **Fig.6** and maximum water discharge was estimated at approximately 30 m^3/s.

4. CASE STUDY SIMULATIONS ON HATA RIVER

4.1 Calculation model and identification of runoff parameters on rainfall runoff model

As outlined in Section 2, *Yamanoi and Fujita* (2016) developed a SiMHiS (Storm induced Multi Hazard information System) that simulates a rainfall runoff, sediment production due to landslide, and sediment transport in a watershed.

The model comprises a landslide prediction model

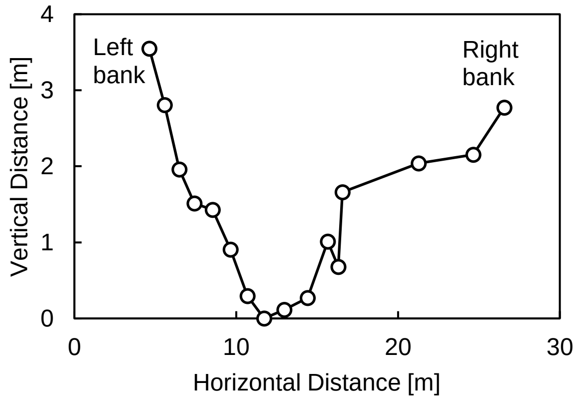

Fig. 4 Profile of the representative cross-section.

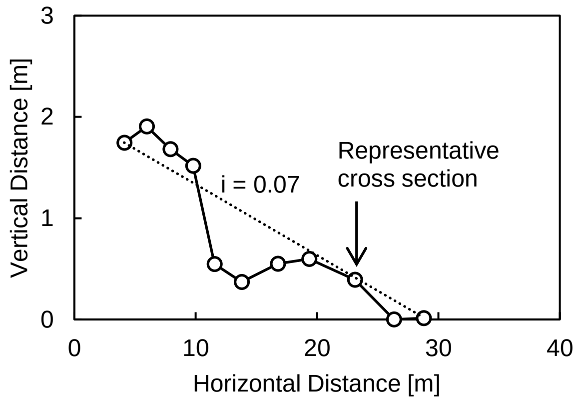

Fig. 5 Longitudinal profile around the observed channel.

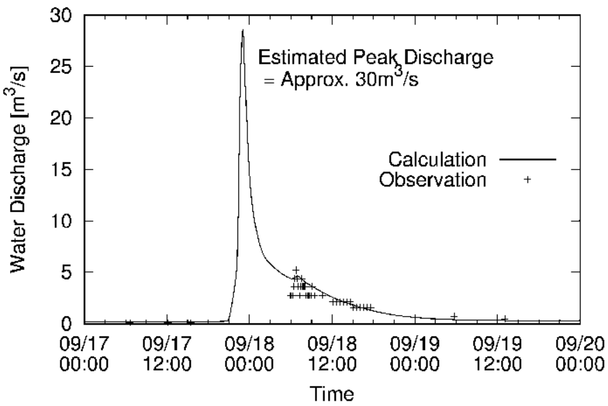

Fig. 6 Comparison between calculated and observed water discharge in the 2017/9/17–9/20 runoff event

based on a water content indicator [*Chen and Fujita*, 2014], a sediment supply model that considers the deposition volume outside the river, and a rainfall and sediment runoff model [*Egashira and Matsuki*, 2000]. The landslide prediction model is a simplified model of the integrated landslide prediction model of rainfall-infiltration adopting Richard's equation, slope stability analysis depends on a simplified Janbu method, and a dynamic programming method to determine the critical slip surface [*Tsutsumi, et al.*, 2007]. The model calculates not only the time of landslide occurrence, but also the scale of the landslide mass volume. When a landslide occurs, the sediment supply model accumulates the produced sediment in unit slopes. The excess sediment is supplied to the channel when the cumulative volume exceeds the specific deposition volume of the unit slopes calculated from the topographical data. The rainfall runoff model employs a kinematic wave model considering a two-layer infiltration flow (layer A, surface erodible layer and layer B which is difficult to permeate water) and surface flow. Further, the sediment runoff model simulates the sediment transport as bed load and suspended load depending on the sediment transport equation considering heterogeneous bed material.

Firstly, we derived a parameter for the rainfall runoff model from the observed water discharge data of the September 17–18, 2017 flood event. We tried some calculation cases employing multiple parameters for the event. The parameters selected for this watershed are shown in **Table 2**.

Applying these parameters, the water discharge at Channel 6 was calculated as shown in **Fig.6**, which corresponds with the observed value from the time-lapse camera.

4.2 Evaluation of debris flow hydrographs caused from probable rainfall event

To set realistic scenarios of possible sediment disaster, it is important to know the scale of phenomena due to possible extreme rainfall events. Therefore, carried out calculations applying the three probable rainfall datasets shown in **Fig. 7**.

Case 1 is the actual rainfall data observed during Typhoon #23 in 2004 at Kamiseya station, which is located approximately 3 km north of the target area. This typhoon caused disasters such as flood, inundation, and sediment deposit due to debris flow to Miyazu City. According to the report from Miyazu City, the road to the Hata area was closed owing to river bank erosion along the main stream of the Hata river. Case 2 is the virtual rainfall data for a 400-year return period at the Maizuru weather station, Japan Meteorological Agency, which is located approximately 20 km south-east of the target area.

Table 2 Identified Parameters

Parameters	Values
Layer A depth, surface erodible layer [m]	0.1
Layer B depth, difficult to permeate water [m]	0.3
Initial Water Depth [m]	0.2
Hydraulic Conductivity of Layer A[m/s]	$6.0x10^{-3}$
Hydraulic Conductivity of Layer B [m/s]	$1.0x10^{-4}$
Manning's Roughness Coefficient of Slopes [$m^{-1/3}s$]	0.7
Manning's Roughness Coefficient of Channels [$m^{-1/3}s$]	0.3

Case 3 is the actual rainfall data obtained at the Susa weather station, which brought huge sediment and water-related disaster to Yamaguchi and Shimane Prefectures in 2013. This station is located far from the target area; however, the surrounding area has a Japan-Sea side climate pattern, which is similar to the target area.

The condition of the grain size distribution is shown in **Fig. 8**. The grain size distribution of the produced sediment was set from the sampling and sieving test in the target basin.

However, because measuring the ratio of the coarser materials such as cobbles and boulders via the sieving test is difficult, we assumed that the riverbed material in the exchange layer contains 50% boulders and cobbles. We also assumed that the entire deposition layer at riverbed consists of materials from field survey conditions with boulders and cobbles.

The calculated flow discharge in Ch. 13, the exit of the debris flow prone valley, is shown in **Fig. 9**. The calculated sediment discharge for the three cases are also shown in **Fig. 9**. The peak discharge of Case 3 is the largest among the three cases. And the sediment runoff volume was the smallest in Case 3 because the total rainfall was the smallest. Runoff of water and sediment seemed to correspond with input rainfall data. And in all 3 cases, peak discharge was larger than 10 m^3/s at torrent downstream describing relatively large runoff.

4.3 Debris flow simulations

As outlined in Section 2, we have developed and applied a GIS-related debris flow simulation system called Hyper KANAKO [*Nakatani et al.*, 2016]. The simulation method is based on the Takahashi model *[Takahashi*, 1991 and *Takahashi*, 2007] considering erosion/deposition due to equilibrium concentrations.

4.3.1 Simulation conditions

We set the debris flow simulation target area as shown in **Fig.10** and applied the digital elevation model (DEM) landform data provided from Geospatial Information Authority of Japan (GSI).

The interval of the 1D simulation points was set as 5 m, with 181 simulation points, and the river width in the 1D area was set as 10 m. As shown in Section 3.2, normal river width seemed to be 2-3 m in Hata River. However, when debris flow occur, the flow width become larger due to erosion and high flow depth. And from the observation, the flow width

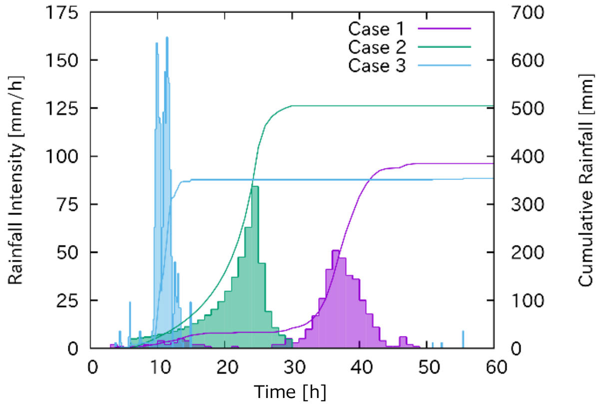

Fig. 7 Target rainfall events. Case 1 is the rainfall event during Typhoon #23 in 2004, observed at Kamiseya station, Kyoto Pref. Case 2 is the virtual rainfall data, which has a 400 years return period. Case 3 is the rainfall event observed in the Yamaguchi-Shimane sediment disaster in 2013 at Susa station, Yamaguchi Pref.

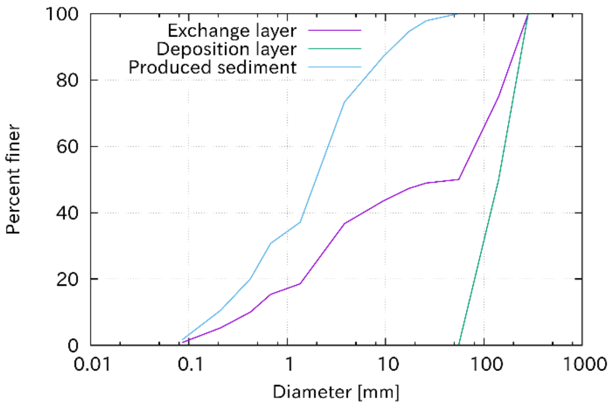

Fig. 8 Condition of the grainsize distribution of the material in the exchange layer, deposition layer, and produced sediment.

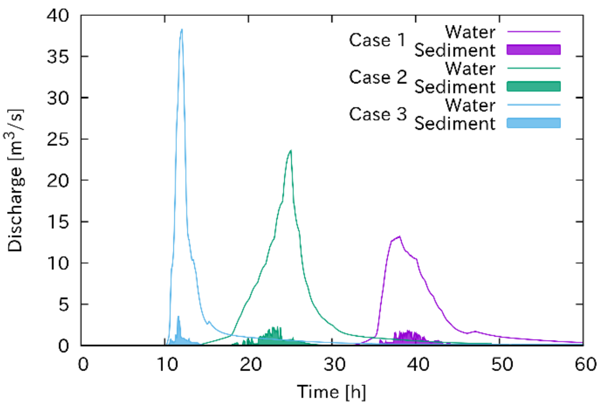

Fig. 9 Calculated water and sediment discharge in Ch. 13.

was estimated approx. 10 m at time of the maximum flow depth, we set 10 m width for initial condition. For the 2D area, we set a 10-m mesh, the same resolution as the input DEM data. Further, the 2D area range (flow direction × transverse direction) was set as (1240 m × 820 m).

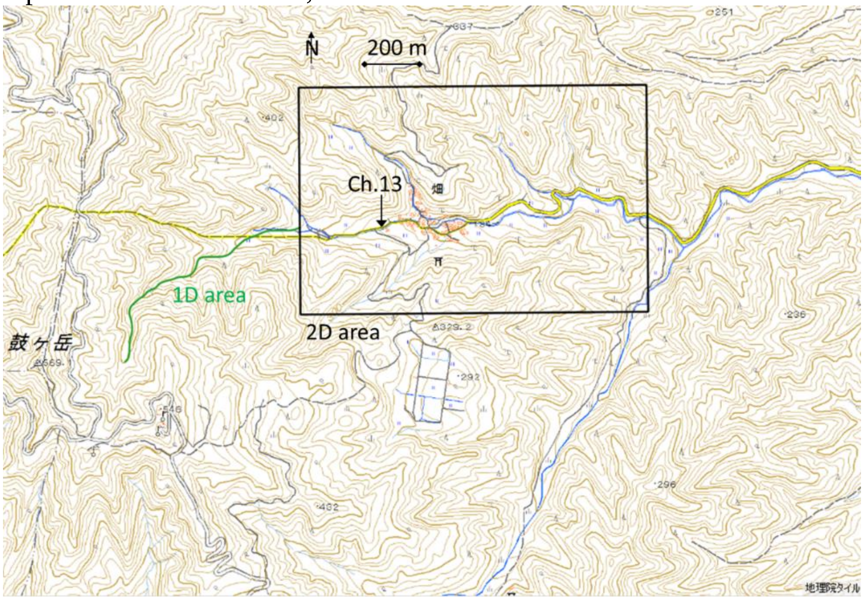

Fig. 10 Debris flow simulation target in Hata river

We did not set unstable soil in the 1D or 2D area for all cases.

To set the debris flow conditions, we applied the three scenarios, Cases 1-3, assumed from the large rainfall and actual disaster in Section 4.2. In the strict sense, discharges at the 1D upstream of the simulation target should be smaller from Ch. 13. However, in this study, we applied the calculated water and sediment discharge at Ch. 13, shown in **Fig. 9**, considering that the total amount of water and sediment supply should become as large when arriving at Ch. 13 during the debris flow event. This approach of using downstream discharge as the supplied condition in the upstream considering the total basin, is widely applied for debris flow studies and planning in Japan.

In the Hyper KANAKO system, debris flow simulation is applied using uniform grain size. In SiMHiS, focusing on sediment, it consider sediment product containing rather fine sediment from the slope and individual motion in river such as bed load rather large as set in **Fig.8** deposition layer. Hyper KANAKO is focusing on debris flow and fine particle such as produced sediment doesn't effect to the behavior if the ratio is small. In this target area, we checked the produced sediment and riverbed deposition layer, but we the mixed ratio is not clear and also hard to obtain. Therefore, we set a representative diameter as 0.2 m, the maximum diameter at the riverbed deposition layer from field survey and also representing stony debris flows occurred in Japan.

The other simulation parameters are shown in **Table 3**. The erosion and deposition coefficients

Table 3 Parameters applied for debris flow simulation

Parameters	Values
Time steps [s]	0.01
Diameter of material [m]	0.2
Mass density of sediment [kg/m^3]	2650
Mass density of fluid phase[kg/m^3]	1000
Concentration of movable bed	0.65
Internal friction angle[deg]	35
Coefficient of erosion rate	0.0007
Coefficient of deposition rate	0.05
Manning's Roughness Coefficient[$m^{-1/3}s$]	0.03

were set as 0.007 and 0.05, typical values for debris flow simulations in Japan (*Takahashi*, 2007). For the simulation time, we set different time durations owing to the **Fig. 9** results.

4.3.2 Simulation results

The simulation results for the debris flow trace, including data for the maximum flow depth and deposition thickness, are shown in **Fig. 11**. From the results, large flow depth and deposition thickness values such as 50-100 cm and 100-300 cm are found outside of the main channel. Flooding and deposition appear to arise when these debris flow scenarios occur. The areas in which flooding and deposition occur appear to be similar in all cases, with some areas showing large values that are different in each case. This occurs because not only is water discharge condition different but so are the condition of sediment discharge and the time series. Considering all cases, from upstream to section A, Case1-2 showed larger maximum flow depth. From section A to downstream, Case3 showed larger maximum flow depth and area showing large depth was wide.

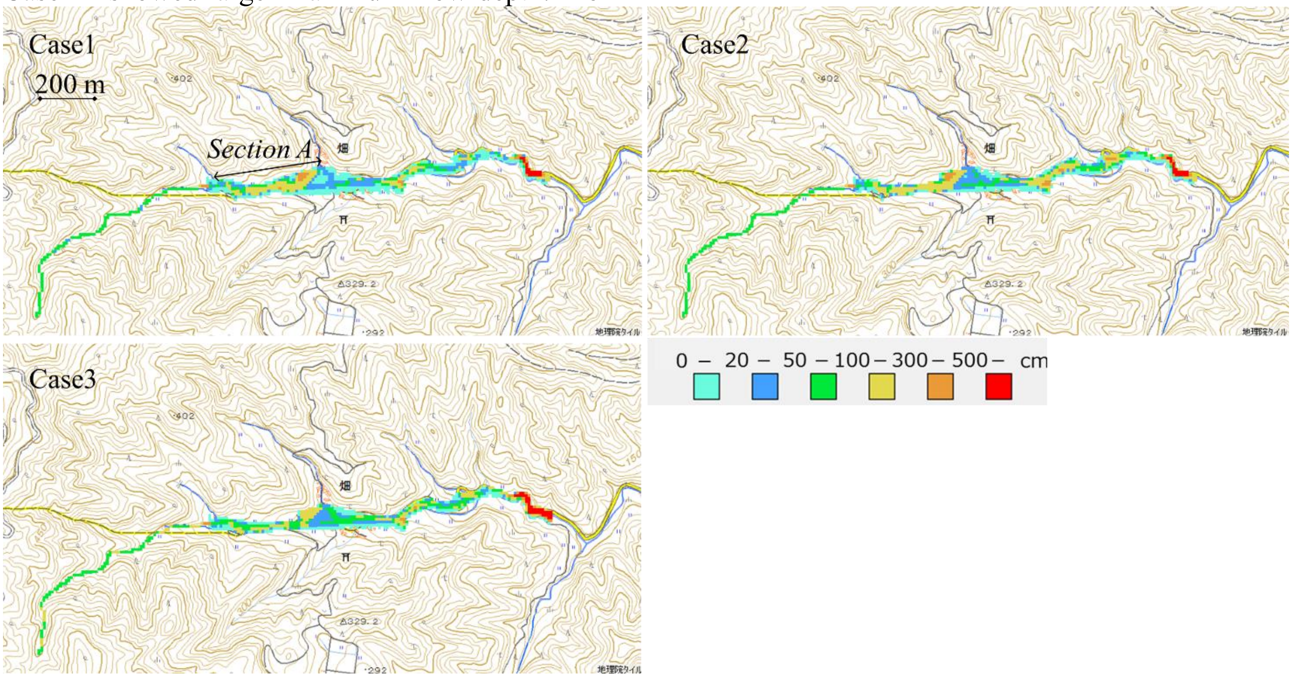

Fig. 11 Debris flow simulation results in Hata river; maximum flow depth and deposition thickness during simulation

For the Hata river target, we did not have information on past disaster results. As a result, we could not show the information together or compare them for effective information provision.

However, we indicated the results on the map in order to help residents become cognizant of the risks. Further, to avoid bias to one set of simulation results as the actual scenario, we utilized three realistic scenarios and showed the results for all three. The results will help residents to understand that even when the influence area due to debris flow is virtually the same, the area at risk of significant damage from flooding and deposition various according to the scenario.

On the other hand, using recent studies and method might show similar results to our proposed method. But our method have advantage on setting realistic continuous scenario from rainfall, sediment supplying, and debris flow verifying with field observed data.

5. CONCLUSIONS

In this study, with the objective of facilitating appropriate evacuation in the event of sediment disasters, we considered advanced hazard information and useful means of providing information to residents. In particular, in order to provide understandable and useful information to residents and local government engineers, we engaged in discussions and developed a set of scenarios based on recent disaster rainfall. Further, we combined two simulation systems to obtain advanced hazard information. By setting the initial rainfall data in the resulting system, we were provided with not only the occurrence time of sediment disasters but also indications of the flooding/deposition area and distribution. We conducted simulations on Hata river, Miyazu City, Kyoto Prefecture, Japan and considered three scenarios involving different levels of rainfall and also considered the target site conditions from field survey results. After running the simulations, we indicated the results on a map of the area to help residents become cognizant of the risks. Further, showing multiple scenario results helps residents to understand that even when the influence area due to debris flow is virtually the same the area at risk at significant damage from flooding and deposition varies for different scenarios.

The important factor was the simulation accuracy and reliability for applying to evacuation. Moreover, for providing information to local residents, we confirmed that the information for both the input and output data needs to be compared with the recorded or experienced rainfall or disaster events for intuitive understanding. For securing high accuracy and reliability to the target site, we found that conducting field survey and observation, and estimating some suitable parameters, then running simulations will be required.

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