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Risk assessment of debris flows in Songhe Stream, Taiwan

Ji-Yuan Lin [a], Ming-Der Yang [b,*], Bo-Rung Lin [c], Ping-Sien Lin [b]

[a] Department of Construction Engineering, Chaoyang University of Technology, Taiwan
[b] Department of Civil Engineering, National Chung Hsing University, Taiwan
[c] Department of Civil Engineering, National Cheng Kung University, Taiwan

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ABSTRACT

Typhoon Mindulle was the most severe typhoon across the Tachia River watershed following the 921 Chi-Chi earthquake, and resulted in extremely high precipitation of 1431 mm that induced many landslides, debris flows, and debris floods in affected areas. This paper analyzes the debris flows in the Songhe area induced by Typhoon Mindulle by employing a numerical model for debris flow simulation. The FLO-2D numerical program was adopted to simulate the flow conditions of debris flows in the Songhe area, including flow depths, flow velocities, and sediment depositions. Comparing the field data with simulation results, this paper defines an Index of Accuracy to examine simulation accuracy. Ignoring the influence of houses in the alluvial fans, the simulation accuracy was 79.3% and 61.4%, respectively for the First and Second Branches of the Songhe Stream. Considering the house effect in the Songhe area raised the simulation accuracy to 82.3% and 75.5%, respectively for the First and Second Branches. In addition, the simulation considering the hydraulic structures established after Mindulle was executed.

This study also adopted 24 h accumulated precipitation at various recurrence intervals (10, 100, and 500 years) to perform scenario simulation of debris flows. Based on the method of Swiss Disaster Degree Classification, consisting of influential intensity and occurrence probability parameters, this study classified the risk degree of hazardous debris-flow areas into three categories, including high, medium, and low. The proposed approach generates the risk distribution map that may be used for setting up a disaster mitigation strategy for the Songhe area.

1. Introduction

Taiwan is located on the edge of the East Asia continental shelf. The influence of mutual collision and compression between the Philippine Sea Plate and the Pacific Plate creates precipitous terrains and fractural stratums in Taiwan. Large-scale sediment-related disasters often occur in the mountainous area of central Taiwan, in which debris flow is the most serious one, particularly after the 1999 Chi-Chi earthquake. The 2001 Typhoon Toraji on the Chenyulan River, the 2004 Typhoon Mindulle on the Tachia River, the 2008 Typhoon Silaku on the Taruowan River, and the 2009 Typhoon Morakot on the Laonong River and the Chishan River have triggered debris flows. Most debris flow disasters have been reported in Central Taiwan (Hung, 1996; Liaw et al., 1999; Cheng et al., 2000; Lin and Jeng, 2000; Chen and Su, 2001; Lin et al., 2002).

In the summer of 2004, the Mindulle event resulted in 33 fatalities, and 12 persons were missing due to heavy floods caused by intensive rains in Central and Southern Taiwan. Typhoon Mindulle brought record high rainfall, resulting in debris flows in many villages in Central Taiwan, such as the Songhe area beside the middle reach of the Tachia River (Figure 1). The debris flows caused significant damage to downstream villages. Fig. 2A shows the debris-flow deposition in Songhe Village and the First (left) and Second (right) Branches of the Songhe Stream flowed into the Tachia River. Fig. 2B shows one of the several ruined houses submerged by debris, Fig. 2C shows the residential area beside the stream before and after the event, and panels D and E on Fig. 2 show that the debris flow ran into a three-story house and deposited debris up to 5 m high. These photographs also show that the debris flow occurring at Songhe is a stony-type debris flow instead of the muddy viscous debris flow.

The Council of Agriculture in Taiwan has identified 1552 creeks as hazardous debris-flow creeks according to two criteria, natural environment and damage potential to downstream villages (Soil and Water Conservation Bureau, Council of Agriculture, 2009). Avoiding or mitigating debris-flow disasters is an important issue for the government and the public. This research applied the FLO-2D model to simulate debris-flow and generate a risk map as a reference for disaster control planning. The grid-based input and output structure of FLO-2D favors the combination with a Geographic Information System (GIS) application; therefore, recent studies have adopted GIS-based approaches to assess debris-flow and landslide hazards (Gupta and Joshi, 1990; Dai and Lee, 2002; Lin et al., 2002; Lin

* Corresponding author. Tel.: +886 4 22840440; fax: +886 4 22862857.
E-mail address: mdyang@dragon.nchu.edu.tw (M.-D. Yang).

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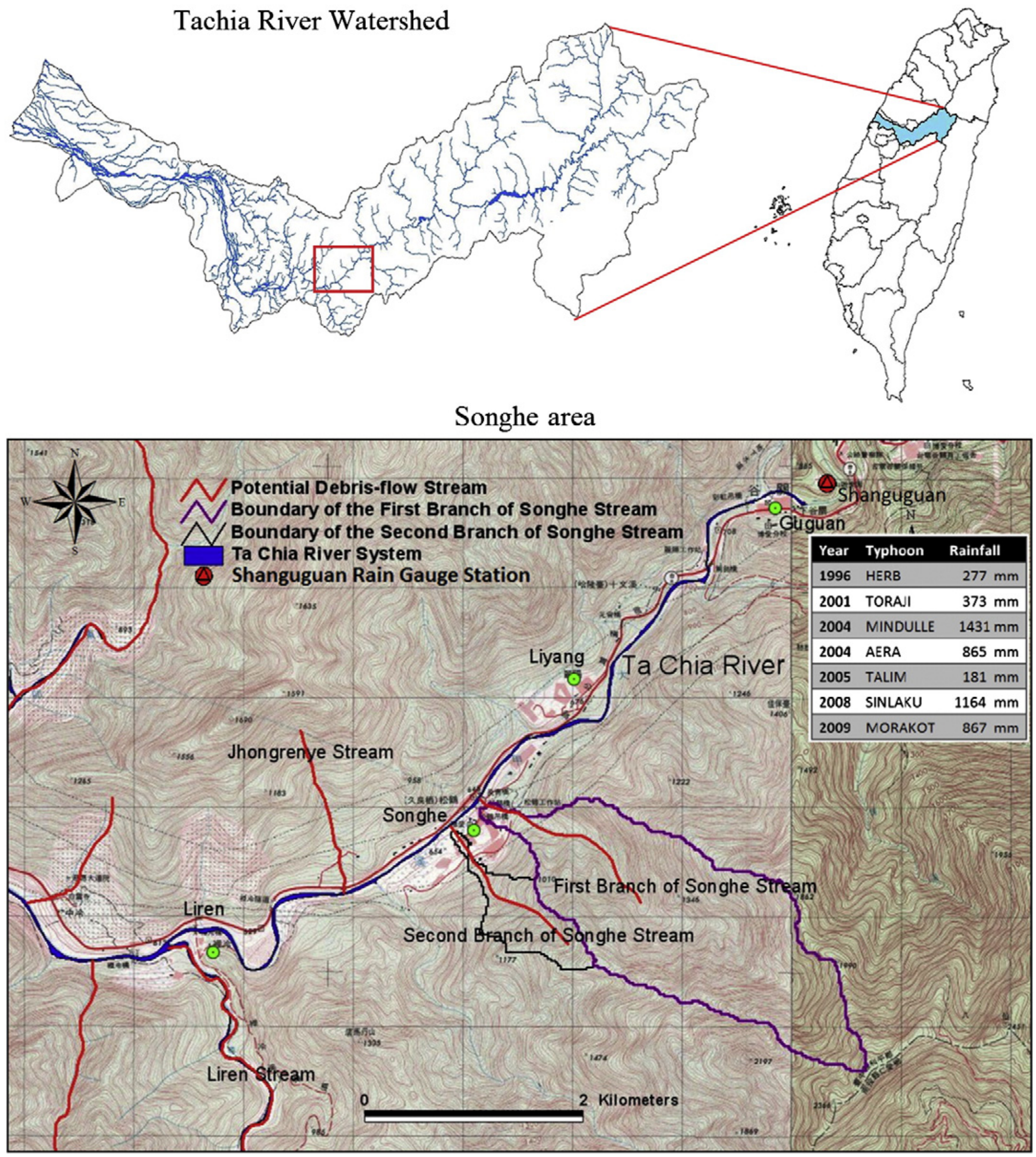

Fig. 1. Location and historical precipitation of Songhe Village and Songhe Stream basin.

et al., 2003; Zhou et al., 2003; Lin et al., 2006). One significant advantage of GIS over the traditional field investigation and mapping methods is its capability of processing large amounts of data layers and displaying spatial assessment results (Lin et al., 2002).

2. Research area

The study area was targeted at the First and Second Branches of the Songhe Stream, a tributary of the Tachia River having long, narrow watersheds with wavy terrains. The First Branch of the Songhe Stream originates at an elevation of 2381 m and drops more than 1700 m to 644 m at the outlet to the Tachia River near Songhe Village. The river course is approximately 4500 m long and has a watershed of 375 ha. The Second Branch of the Songhe Stream originates at an elevation of 1450 m and flows approximately 700 m down to the Tachia River. The river is nearly 1500 m long and has a watershed of about 50 ha.

Based on the Taiwan Geological Map (1:500,000) published by the Central Geological Survey, the stratum of the Songhe area is Paileng Formation and Terrace Deposit as shown in Fig. 3. Paileng Formation mainly consists of sandstones and slates and Terrace Deposit consists of deposit materials of debris flow (gravel, sand, and clay). Particle size investigation in field was executed at the sampling sites every 5 m on stream sections and every 10 m along the stream according to the Handbook of Soil and Water Conservation (Soil and Water Conservation Bureau, Council of Agriculture, 2000). The First Branch of Songhe Stream has d_{90} of 156.9 cm, d_{50} of 86.2 cm, and the deposited sediment materials consisting of 78.1% gravel, 20.4% sand, and 1.5% silt and clay indicates that a stony-type debris flow in the Mindulle event.

3. Method and verification

3.1. Data preprocessing

FLO-2D is a two-dimensional model to simulate debris flows and requires a digital elevation model (DEM), rheological parameters, and a defined input hydrograph (Hubl and Steinwendtner, 2001; Canuti, et al., 2002). The model applies the quadratic rheological model presented by O'Brien and Julien (1988), including yield shear stress, viscous shear stress, cohesive yield stress, and turbulent shear stress.

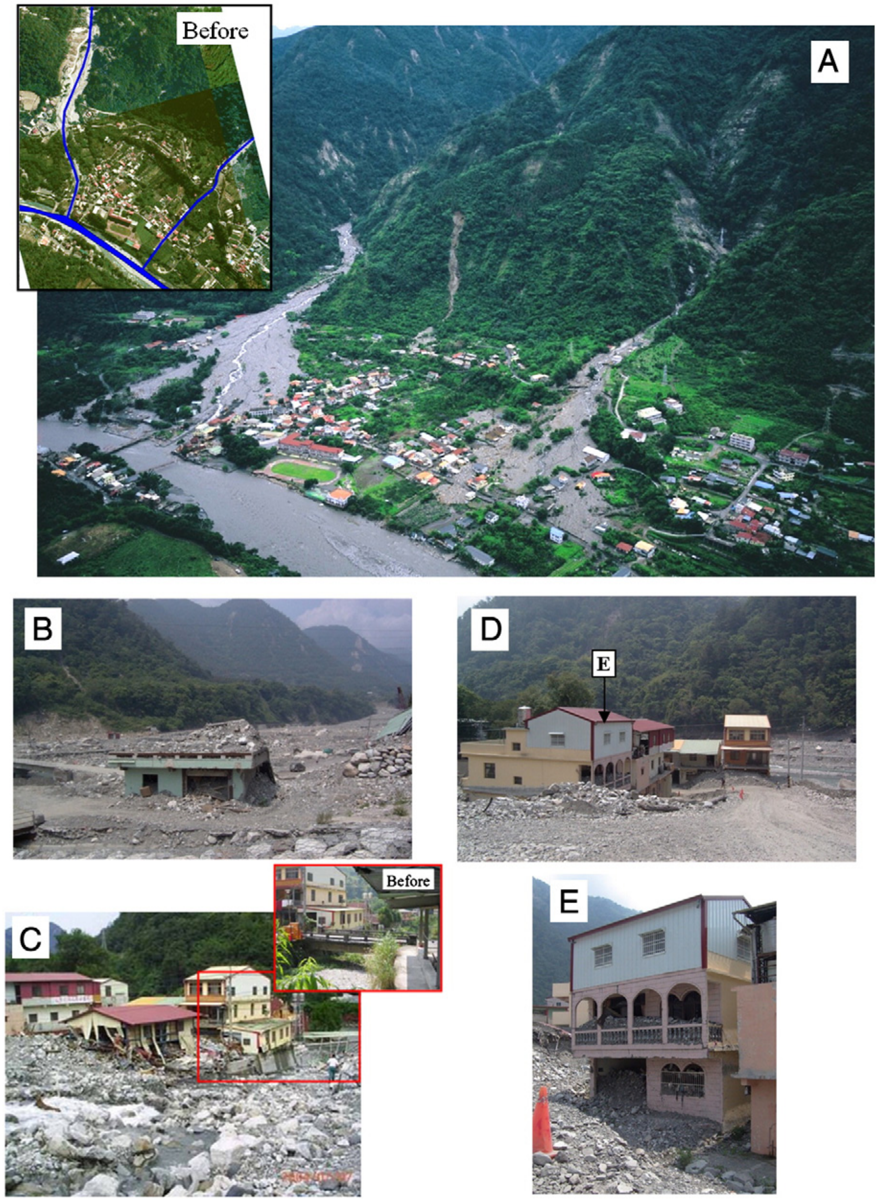

Fig. 2. Aerial and field photographs of Songhe debris flow.

It routes with the continuity equation and dynamic wave equation on the DEM grid system to generate simulation results (O'Brien et al., 1993; O'Brien, 2004). The debris flow rheology is modeled by a shear stress relationship written in slope form as (O'Brien, 2004):

$$S_f = S_y + S_v + S_{td} = \frac{\tau_y}{\gamma_m h} + \frac{K\eta u}{8\gamma_m h^2} + \frac{n^2 u^2}{h^{4/3}} \quad (1)$$

where S_f is the total friction slope, S_y is the yield slope, S_v is the viscous slope, S_{td} is the turbulent-dispersive slope, τ_y is the yield strength, γ_m is the specific weight of the slurry, h is the flow depth, K is the laminar-flow drag coefficient, η is fluid viscosity, u is flow velocity, and n is Manning's roughness coefficient.

Various parameters, including terrain information, rheological parameters, Manning's roughness coefficient, laminar-flow drag coefficient, were adopted in the following simulation as listed in Table 1. K is an empirical resistance parameter and has a proper value suggested by the FLO-2D user's manual (O'Brien, 2004), and n was empirically estimated by the grain size distribution according to outcrop (Soil and Water Conservation Bureau, Council of Agriculture, 2005). τ_y and η are two major parameters related to the flow sediment concentration (C_v) that can be decided as:

$$\tau_y = \alpha_2 e^{\beta_2 C_v} \quad (2)$$

$$\eta = \alpha_1 e^{\beta_1 C_v} \quad (3)$$

where α_i and β_i are coefficients defined by laboratory experiment (O'Brien and Julien, 1988), and were given by the capillary rheometer experiment in laboratory (Jan et al., 1997). This paper adopts the equilibrium concentration proposed by Takahashi (1991) to determine C_v based on the porosity of deposit sediments. However, the rheological parameters and the sediment concentration of debris flows remain highly uncertain. Proper values of sediment concentration (C_v) were discussed by several investigators such as Takahashi (1978), Canuti et al. (2002) who adopted C_v of 0.66 for FLO-2D simulation, and Hubl and Steinwendtner (2001) who adopted C_v of

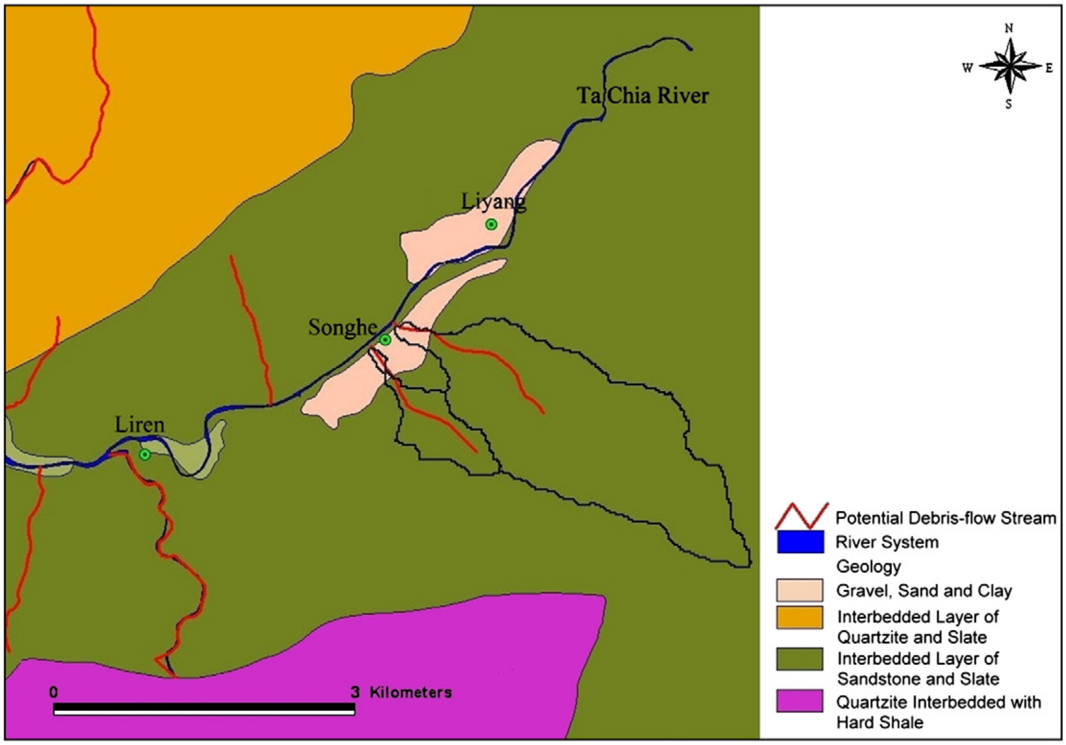

Fig. 3. Geological map of Songhe area.

0.5–0.6 for FLO-2D simulation. Most debris flows in Taiwan were induced by landslide and intensive rainfall so that the scale and damage power was greater than elsewhere in the world. In this paper, we consider the risk of debris flows from a conservation perspective and adopt a larger C_v value of 0.7.

GIS software, ArcView, was employed to process contour line, slope aspect, and slope gradient for basic analysis of the research area and then to output the elevation into a text file. For FLO-2D configuration of inflow and outflow points, this research used the inquiry function of GDS4.exe with the potential debris-flow river disclosed by the Taiwan Council of Agriculture as well as the river system network to acquire and overlay the locations of inflow and outflow, and to eventually input the FLO-2D configuration file of inflows and outflows. Total cumulative precipitation and cumulative rainfall percentage were also required for debris flow simulation. During the Mindulle Typhoon event, the total cumulative precipitation of 1431 mm, the maximum daily rainfall of 516 mm, and the maximum hourly rainfall of 94.5 mm were recorded at the Shanguguan rainfall station shown as Fig. 4.

3.2. Scenario simulation of Typhoon Mindulle event

Witnesses reported debris flow occurring at about 9 AM on July 3 that consents to Shieh and Hsu's findings (1993), occurring at the maximum rainfall intensity and ending in the following 2 h (see Figure 4). Therefore, we simulated the debris flow for 3-hour duration from 9 AM to 12 AM on July 3. The water discharge at the occurring time of debris flow was multiplied by a magnification coefficient bulking factor (BF) to perform the debris-flow simulation.

The simulation result of the alluvial fan overlapped on the possible influential range of debris flow in Fig. 5. The possible influential range of debris flow was determined by assigning the apex of influential range at the valley outlet where the slope is 10° and a maximum spreading angle of 105°, and the run-out boundary of debris flow was drawn at the slope contour of 2° that is officially defined by the Soil and Water Conservation Bureau shown (Soil and Water Conservation Bureau, Council of Agriculture, 2000).

Based on the aerial photograph of Songhe Village taken after Typhoon Mindulle in July 2004, the actual flooding range was estimated at about 8.86 ha and 4.19 ha for the First and Second Branches of the Songhe Stream, respectively. However, the simulated flooding range was approximately 10.08 ha and 13.80 ha for the First

Table 1
Adopted parameters of FLO-2D simulation.

Parameter	Value
Specific gravity (G_s)	2.7
Volume concentration (C_V*)	0.7
Laminar-flow drag coefficient (K)	2280
Manning's roughness coefficient (n)	0.0312
α_1	0.811
α_2	0.00462
β_1	13.72
β_2	11.24

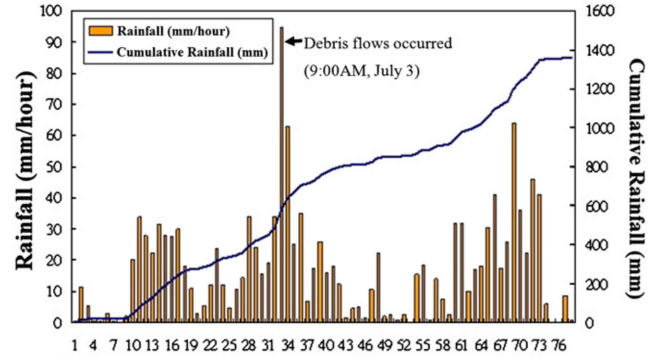

Fig. 4. Precipitation of Mindulle event at Songhe.

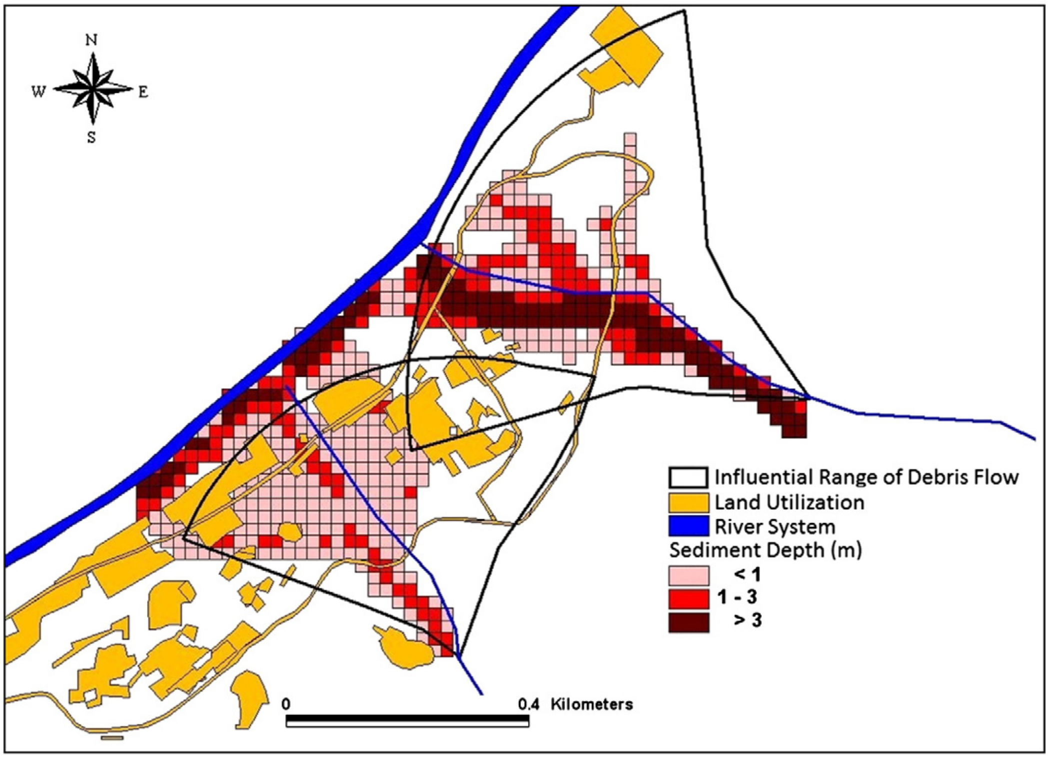

Fig. 5. Flooding range and depth of FLO-2D simulation neglecting houses for Mindulle event.

and Second Branches of the Songhe Stream, respectively. Overestimation was caused by excluding the effect of houses, because the ground resolution (20 m×20 m) of DEM with a Root-Mean-Square-Error (RMSE) of 4 m in elevation was not enough to identify the location and elevation of houses. House exclusion could cause a significant effect on the simulation because of ignoring the reducing effect of structures on the velocity of debris flow and the containability of debris sediments.

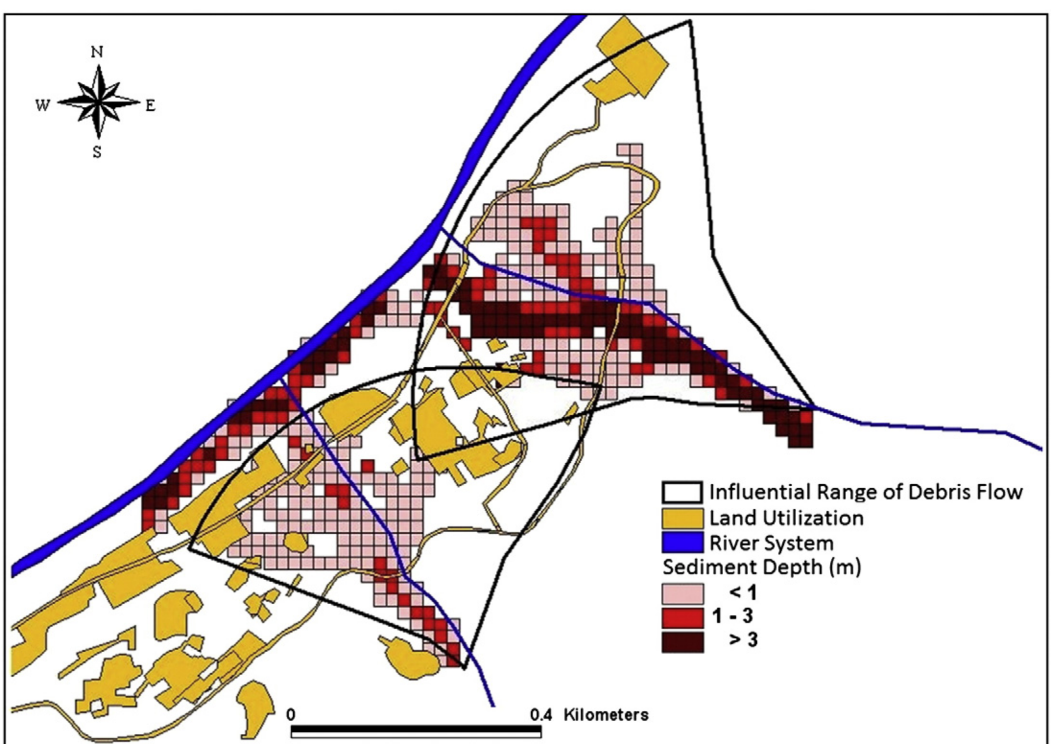

Fig. 6. Flooding range and depth of FLO-2D simulation considering houses for Mindulle event.

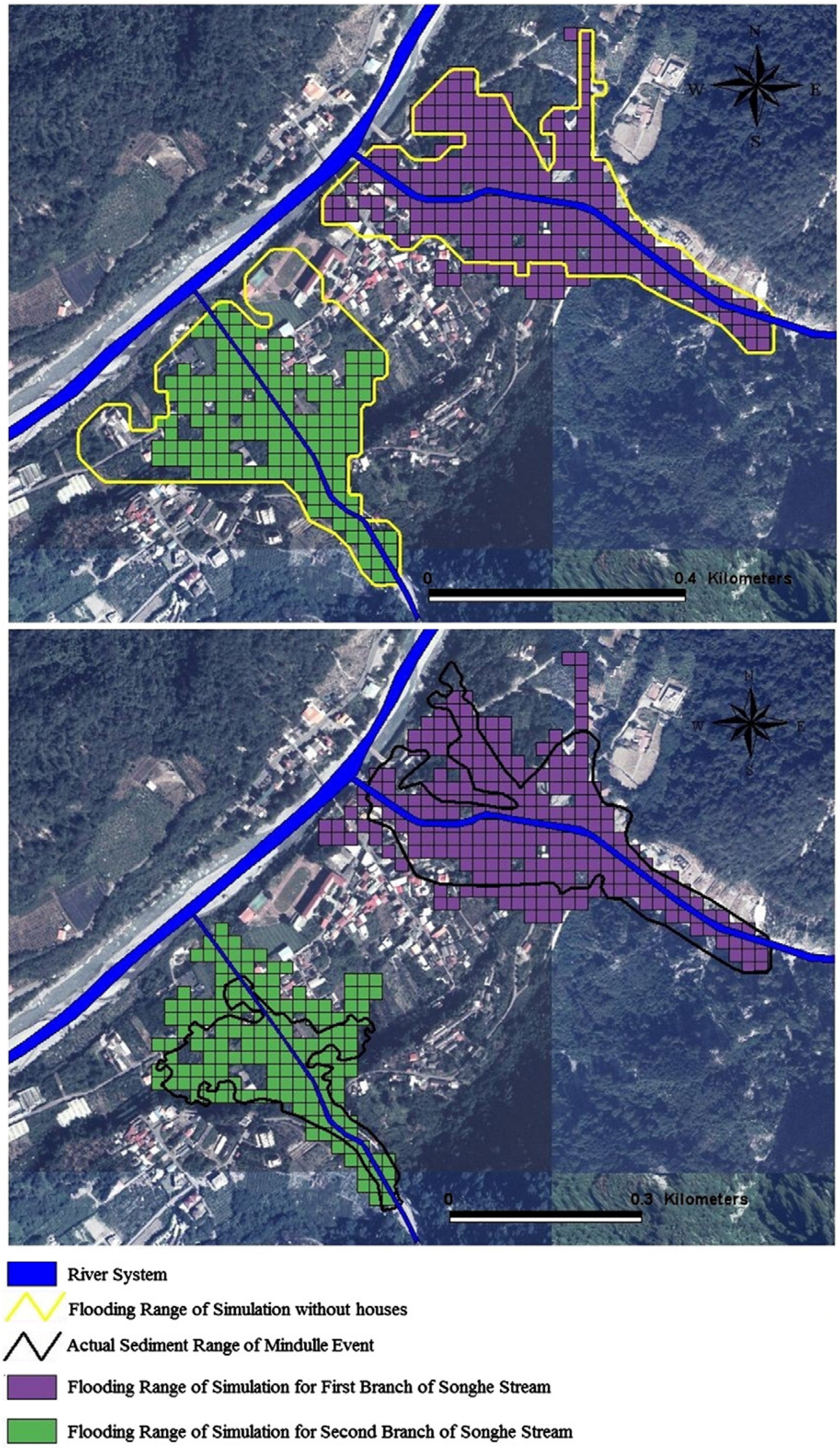

Fig. 7. Comparison of flooding range between simulation and actual deposition for Mindulle event.

3.3. Scenario simulation of Typhoon Mindulle event considering houses

To modify the FLO-2D simulation, the location and the elevation of houses in Songhe Village were manually added onto the elevation data according to the interpretation on the 2002 aerial photograph. Again, the simulation result of alluvial fan was overlapped onto the possible influential range as shown in Fig. 6. The simulated flooding range was 9.96 ha and 6.6 ha for the First and Second Branches of the Songhe Stream, respectively. By comparing the simulations without/

Table 2
Simulated area of Mindulle debris flood.

Flooding Area (ha)	Simulation without houses		Simulation with houses	
	1st branch	2nd branch	1st branch	2nd branch
A_r	8.86	4.19	8.86	4.19
A_m	10.08	13.80	9.96	6.60
A_o	7.48	3.95	7.72	3.87
I_a	79.3%	61.4%	82.3%	75.5%

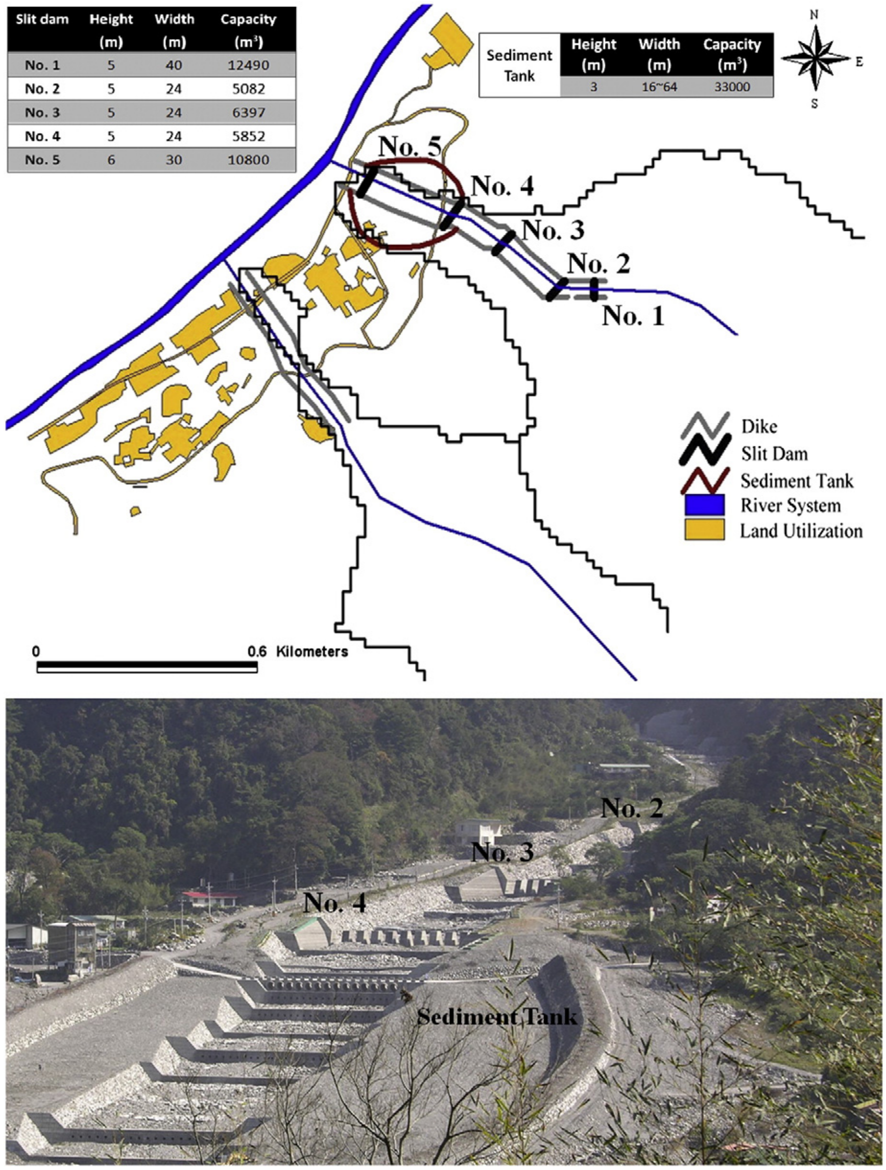

Fig. 8. Location and specification of hydraulic structures.

with houses during Typhoon Mindulle as shown in Fig. 7, there were a decrease of 0.12 ha and 7.2 ha in the flooding range for the First and Second Branches of the Songhe Stream that is the mitigation effect of the debris flow by houses. To quantitatively estimate the accuracy of such simulations, Index of Accuracy (I_a) was adopted to represent means of producer's and user's accuracies as:

$$I_a = \frac{\left(\frac{A_o}{A_r} + \frac{A_o}{A_m}\right)}{2} \times 100\% \quad (4)$$

in which A_r: actual flooding area, A_m: simulation flooding area, and A_o: coincided with the flooding area between actual and simulation flooding.

The values of A_o/A_r and A_o/A_m, which lie between 0 and 1, represent producer accuracy and user accuracy, respectively. To consider both omission error and commission error, the mean of A_o/A_r and A_o/A_m was considered to evaluate model validity. Table 2 lists the coincided flooding area between actual and simulation results as 7.48 ha (79.3%) and 3.95 ha (61.4%) for the First and Second Branches of the Songhe Stream when ignoring houses during the Mindulle Typhoon period. Once considering the effect of houses, simulation accuracy was enhanced to 82.3% and 75.5%, respectively. A precise survey of the location and elevation of houses to generate maps with better spatial resolution is suggested to produce higher simulation accuracy.

3.4. Scenario simulation of Typhoon Mindulle event considering hydraulic structures

In the aftermath of Typhoon Mindulle, the Soil and Water Conservation Bureau settled on a control plan for debris flow disasters, including five slit dams and one sediment retaining tank at the First Branch of the Songhe Stream and one sediment retaining tank at the Second Branch of the Songhe Stream, shown in Fig. 8 (Soil and Water Conservation Bureau, Council of Agriculture, 2005). To examine the effect of these hydraulic structures, the Mindulle flood event was rerun in FLO-2D to illustrate various outbreak situations, and the scale and flooding range of debris flow with the hydraulic

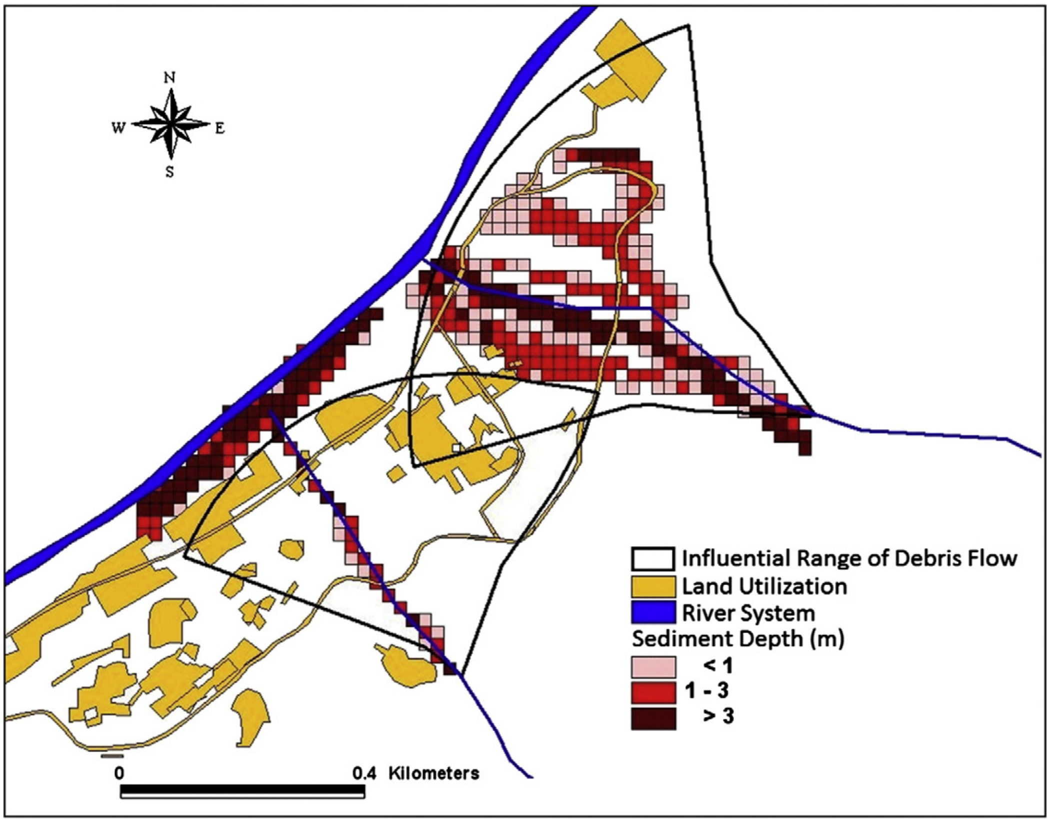

Fig. 9. Depth and influential range of FLO-2D simulation considering hydraulic structures for Typhoon event.

structures. The elevation data input to FLO-2D was updated by adding the specification of hydraulic structure shown in Fig. 8. The debris-flow alluvial fan of scenario simulation considering the hydraulic structures was overlapped with the possible influential range of debris flow defined by the Soil and Water Conservation Bureau as in Fig. 9. The simulated flooding range was approximately 10.75 ha and 4.04 ha for the First Branch and Second Branch of the Songhe Stream, respectively. By overlapping the simulation considering the hydraulic

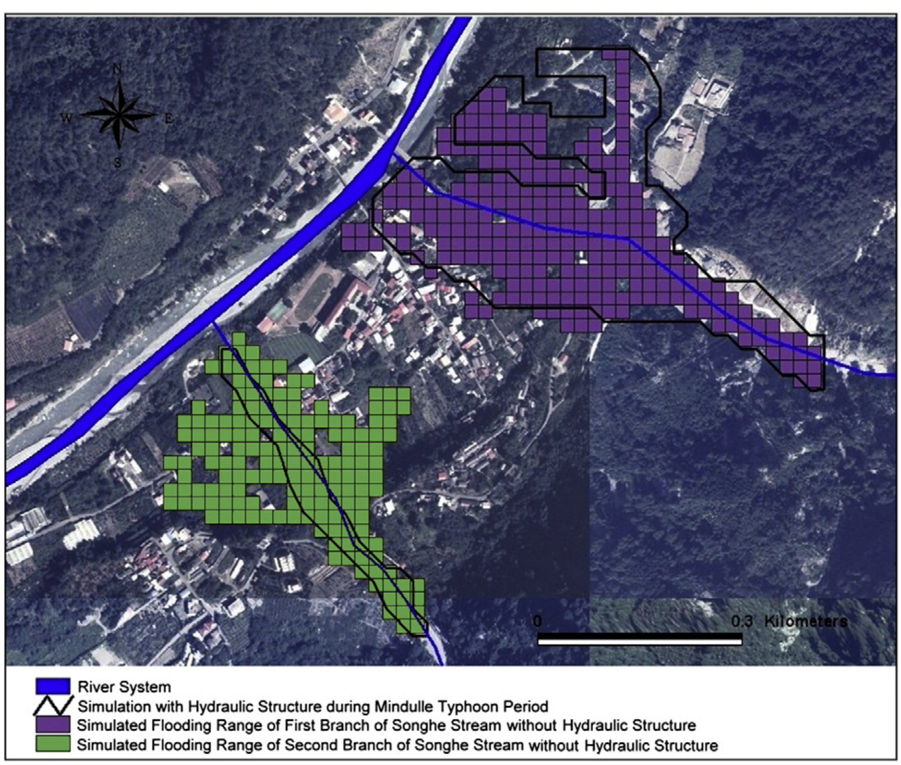

Fig. 10. Comparison of flooding range between simulation with/without hydraulic structures and actual deposition for Mindulle event.

Table 3
Sediment simulation of debris-flow alluvial fan of Songhe Stream.

Scenario		Maximum sediment depth (m)		Average velocity (m/s)		Average sediment depth (m)		Sediment area (m^2)		Sediment volume (m^3)	
House	Hydraulic structure	1st Branch	2nd Branch	1st Branch	2nd Branch	1st Branch	2nd Branch	1st Branch	2nd Branch	1st Branch	2nd Branch
Without	Without	10.26	5.77	4.94	0.90	2.4	1.04	100,800	138,000	241,000	143,000
With	Without	10.26	5.94	4.89	1.07	2.47	1.35	99,600	66,000	256,000	128,000
With	With	14.16	7.17	4.14	1.84	2.47	3.44	107,600	40,400	265,000	139,000

structures on the aerial photograph of Songhe Village (Figure 10), the lengthened and thinned simulated alluvial fan compared to the case without the hydraulic structures verifies the effect of the established sediment retaining tank.

Table 3 lists the simulation results of the debris-flow scenarios, including maximum sediment depth, average velocity, average sediment depth, sediment volume, and sediment area for the First and Second Branches of the Songhe Stream. The simulation with the hydraulic structure under the Mindulle rainfall proved effective by the sediment settling situation, particularly the Second Branch of the Songhe Stream. The average sediment depth and sediment area of the alluvial fan were enlarged after establishing dikes on both sides of the Second Branch serving as a sediment-retaining tank. However, overflow could occur at the turning point of the First Branch and turn into a spreading sediment on the right riverbank because of debris flow moving forward as a mass that needs more attention from engineers.

4. Assessment of risk degree

Risk maps of debris flow were generated based on four scenario simulations, including the Mindulle event, 10-year, 100-year, and 500-year recurrence intervals for Songhe Village after constructing hydraulic structures.

4.1. Generation of linear discharge hydrograph

To generate expected peak discharges, the rational formula is adopted as:

$$Q_p = \frac{1}{360} CIA \tag{5}$$

in which Qp: peak discharge (cms), C: runoff coefficient, I: design rainfall intensity for 10-year, 100-year, and 500-year recurrence intervals (mm/h), and A: area of watershed (ha), were employed to calculate peak discharge. Design of rainfall intensity can be decided based on Article 17 of the Technical Regulation for Soil and Water Conservation:

$$\begin{aligned} I &= (G - H\ \log T)\frac{a}{(t_c+55)^C} I_{60}^{25} \\ I_{60}^{25} &= \left(\frac{P}{-25.29+0.094P}\right)^2 \\ a &= \left(\frac{P}{-189.96+0.31P}\right)^2 \\ c &= \left(\frac{P}{-381.71+1.45P}\right)^2 \\ G &= \left(\frac{P}{42.89+1.33P}\right)^2 \\ H &= \left(\frac{P}{-65.33+1.83.P}\right)^2 \end{aligned} \tag{6}$$

in which T: recurrence interval (year), P: average annual precipitation (mm), 2163.8 mm at Shanguguan station, t_c: rainfall duration (min), and I_{60}^{25}: rainfall intensity for 25-year recurrence interval and 60-minute rainfall duration (mm/h).

Based on Article 18 of the Technical Regulation for Soil and Water Conservation, the runoff coefficient can be determined by two conditions: development level, such as undeveloped, developing, and developed, and terrain pattern, such as steep mountain, mountain ridge, hill/forest, flat farm, and non-agricultural land. The Songhe watershed was identified as an "undeveloped environment" "steep mountain" category (C value ranging from 0.75 to 0.9) and assigned C value of 0.8.

For the following analysis, the watershed areas of the First and Second Branches of the Songhe Stream were 375 ha and 54.48 ha, and I_{60}^{10} of 83.73 mm/h, $I_{60}^{100}$of 113.05 mm/h, and $I_{60}^{500}$of 134.18 mm/h were input. The resulting peak discharge for the First and Second Branches of the Songhe Stream with 10-year, 100-year, and 500-year recurrence at 69.79cms, 94.21cms, 111.82cms, and 10.14cms, 13.69cms, 16.25cms, respectively. To estimate the peak discharge of the debris flow, the peak discharge was multiplied by the bulking factor, $\frac{1}{1-C_v}$, to operate the triangular hydrograph based on 24 h.

The hour of maximum rainfall and the following 2 h were input as the precipitation condition for the debris flow simulation. Table 4 and Fig. 11 show the comparison result of such scenario simulations. The results were overlapped onto the alluvial fan to represent the possible influential range of debris flow. The officially defined alluvial fan did not consider the containability of the Tachia River so to over-estimates the affected area and is overly conservative from the land users' aspect.

4.2. Establishment of risk map for scenario simulation

Petarscheck and Kienholz (2003) processed hazard assessment and mapping of mountain risks in Switzerland. With reference to the Swiss Disaster Degree Classification (Garcia et al., 2004), this research classified the risk degree of hazardous debris-flow areas by the two parameters of influential intensity and occurrence probability into three degrees of risk (high, medium, and low) based on the harm to humans and the damage to houses. The Swiss method defines the intensity as the combination of sediment depth (H) and sediment depth (H) multiplied by velocity (V) to classify the influential intensity for flooding disaster. The disaster of mudflow and debris flow is more destructive than flooding; therefore, it is important to be more conservative in selecting influential intensity. This research classified the influential intensity of simulation by the maximum sediment depth and the maximum velocity as Table 5.

The yearly occurrence probability of debris flow can be calculated through Eq. (7) by assigning m = 1, and then classifying it as high (greater than 10%), medium (between 10% and 1%), low (between 1% and 0.2%), or no risk (less than 0.2%).

$$P_m = 1 - \left(1 - \frac{1}{T}\right)^m \tag{7}$$

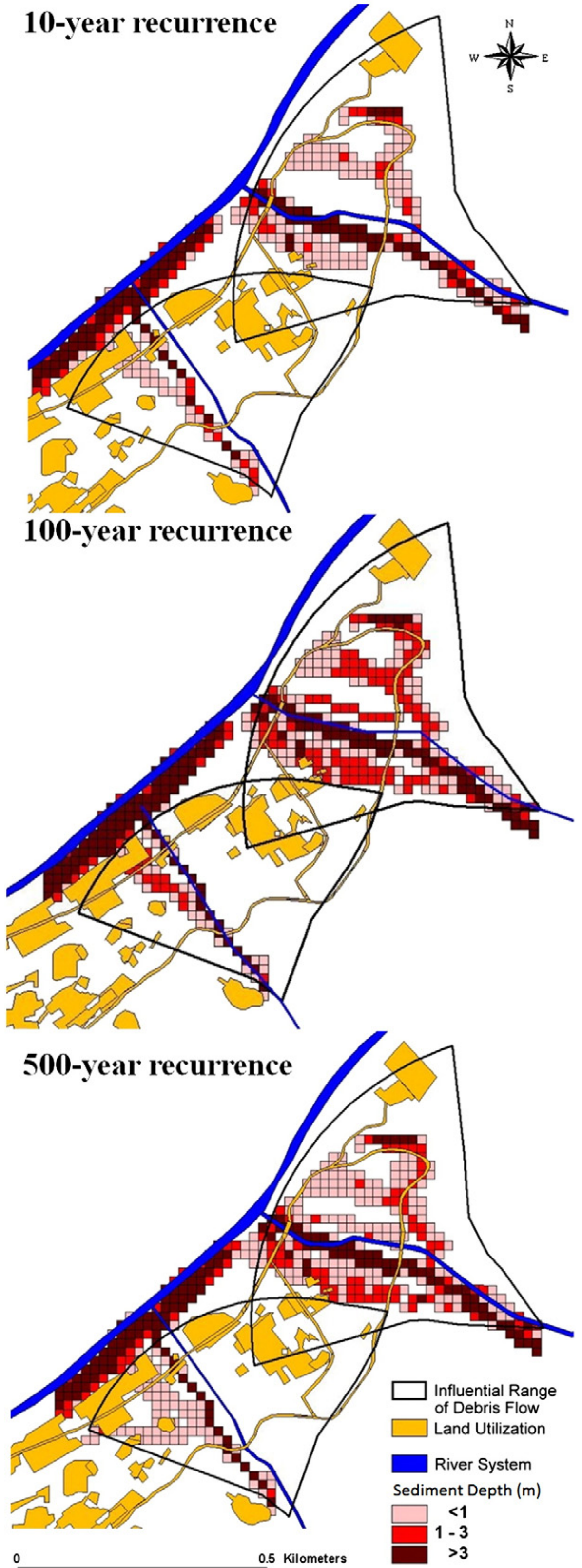

Fig. 11. Sediment depth of alluvial fan of FLO-2D simulation for various recurrence intervals.

in which P_m: occurrence probability during m years and T: recurrence year.

Subsequently, the risk degree can be subsequently classified by considering both influential intensity and occurrence probability as in Fig. 12. Based on the Swiss Disaster Degree Classification, this research created scenario simulations with 10-year, 100-year, and 500-year recurrence representing the occurrence probability of 10%, 1%, and 0.2% to become the risk maps of hazardous areas. According to the definition of risk classification in Table 5, the influential intensity of each scenario simulation was generated for Mindulle event as in Fig. 13 and various recurrence intervals as in Fig. 14. The highest risk was found in the river reach and at the relatively low sites within the alluvia fan. For the Second Branch, the hydraulic structure confines the debris inside the river reach and causes a sediment deposition at the outlet. Finally, an overall risk map of debris flow for Songhe Village was generated in Fig. 15 by maximizing the risk level of intensity with 10-year, 100-year, and 500-year recurrence according to Fig. 12. Most high risk areas of the Second Branch are transferred to the Tachia River, whereas many high risk areas remain in the downstream area of the First Branch. This risk map provides a reference for disaster control and land use planning in the future.

5. Conclusion

This research applied FLO-2D to simulate the occurrence situation of debris flow for Songhe Village and concludes the following points.

1. To consider both omission error and commission error, an index of accuracy (I_a) was proposed to represent the accuracy of FLO-2D simulation result and actual flooding range. For the First and Second Branches of the Songhe Stream, the accuracies of the simulation employing 20 m × 20 m DEM, which cannot identify location and height of houses, were 79.3% and 61.4%, and were substantially improved to 82.3% and 75.5%, respectively, by considering the house effect. A DEM with better resolution is believed more proper for debris simulation in the future work.
2. The simulation with the hydraulic structure, five slit dams and one sediment retaining tank at the First Branch of the Songhe Stream constructed after Mindulle, was proven effective by settling sediment according to FLO-2D simulation. However, it is noticeable that the overflow occurred at the turning point of the First Branch of the Songhe Stream because debris flow moves forward as a mass and needs more attention for further disaster mitigation.
3. According to the Swiss Disaster Degree Classification, the influential intensity with 10-year, 100-year, and 500-year recurrence was classified into high, medium, and low, and was shown in the risk map of debris flow for Songhe Village as a reference for authorized construction design and an evacuation plan for the public.

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Table 4
Simulation of debris-flow alluvial fan at 10-yr, 100-yr, and 500-yr recurrences for Songhe Stream.

Recurrence	Maximum sediment depth (m)		Average velocity (m/s)		Average sediment depth (m)		Sediment area (m^2)		Sediment volume (m^3)	
	1st Branch	2nd Branch	1st Branch	2nd Branch	1st Branch	2nd Branch	1st Branch	2nd Branch	1st Branch	2nd Branch
10-yr	13.02	8.13	4.60	2.53	2.52	3.29	80,800	57,600	203,828	189,404
100-yr	14.14	8.28	4.36	2.80	2.51	3.55	107,600	61,200	270,552	217,488
500-yr	14.60	8.44	4.57	2.69	2.59	3.00	114,800	73,600	297,384	221,016

Table 5
Influential intensity of mud flow and debris flow.

Influential intensity	Max. depth (m)	Operator	Max. depth max. velocity (m^2/s)
High	$H>1.0$	OR	$VH>1.0$
Medium	$0.2<H<1.0$	AND	$0.2<VH<1.0$
Low	$0.2<H<1.0$	AND	$VH<0.2$

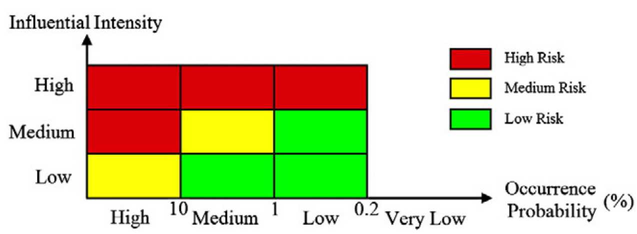

Fig. 12. Hazardous classification by occurrence intensity and occurrence probability.

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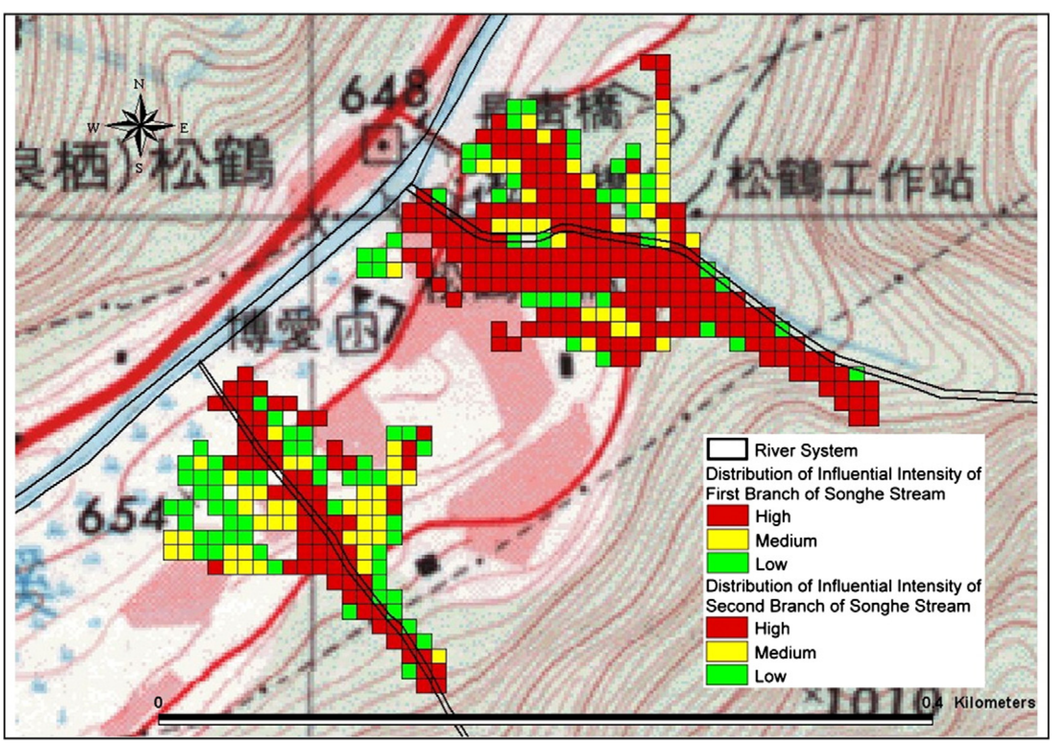

Fig. 13. Influential intensity of simulation during Mindulle event.

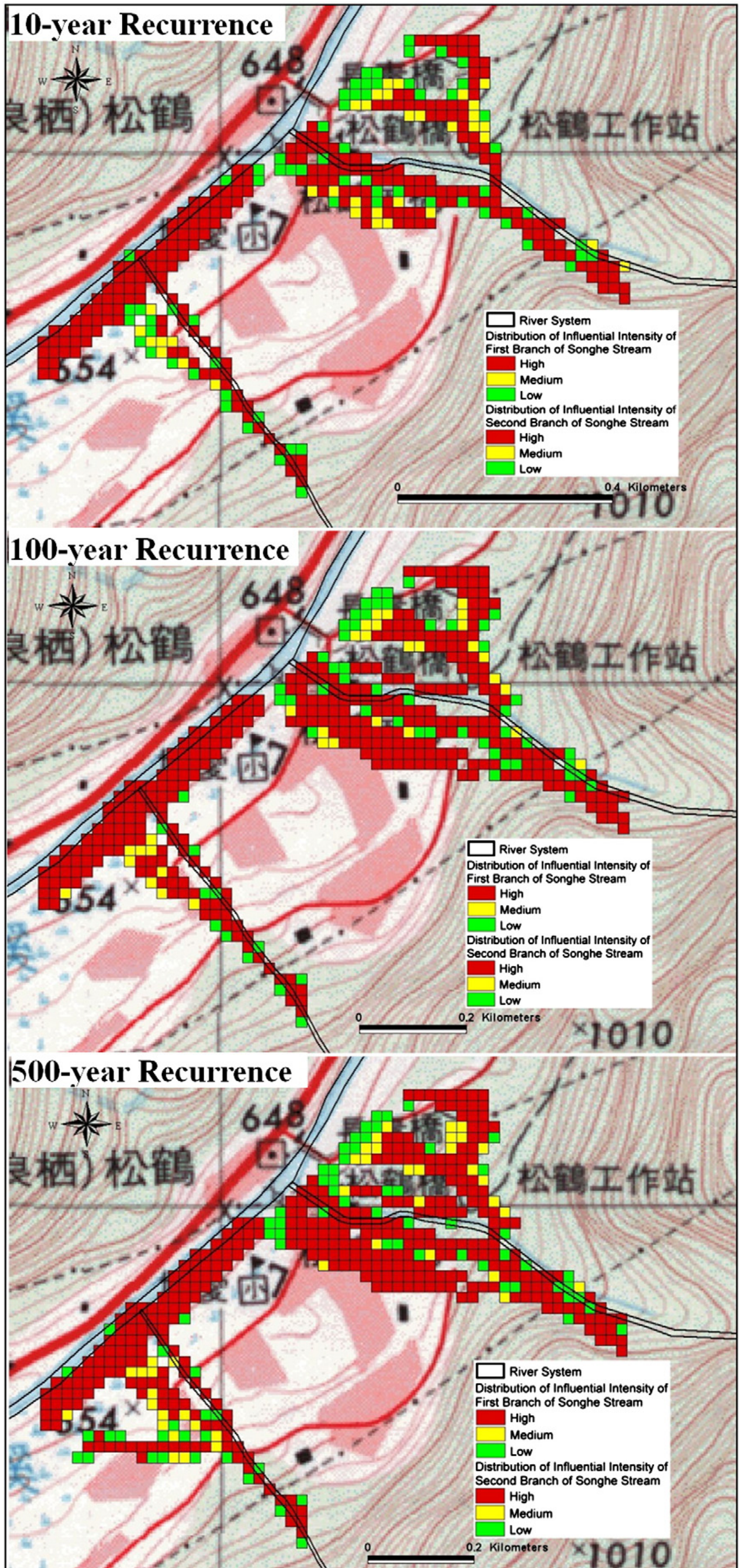

Fig. 14. Influential intensity of simulation for various recurrence intervals.

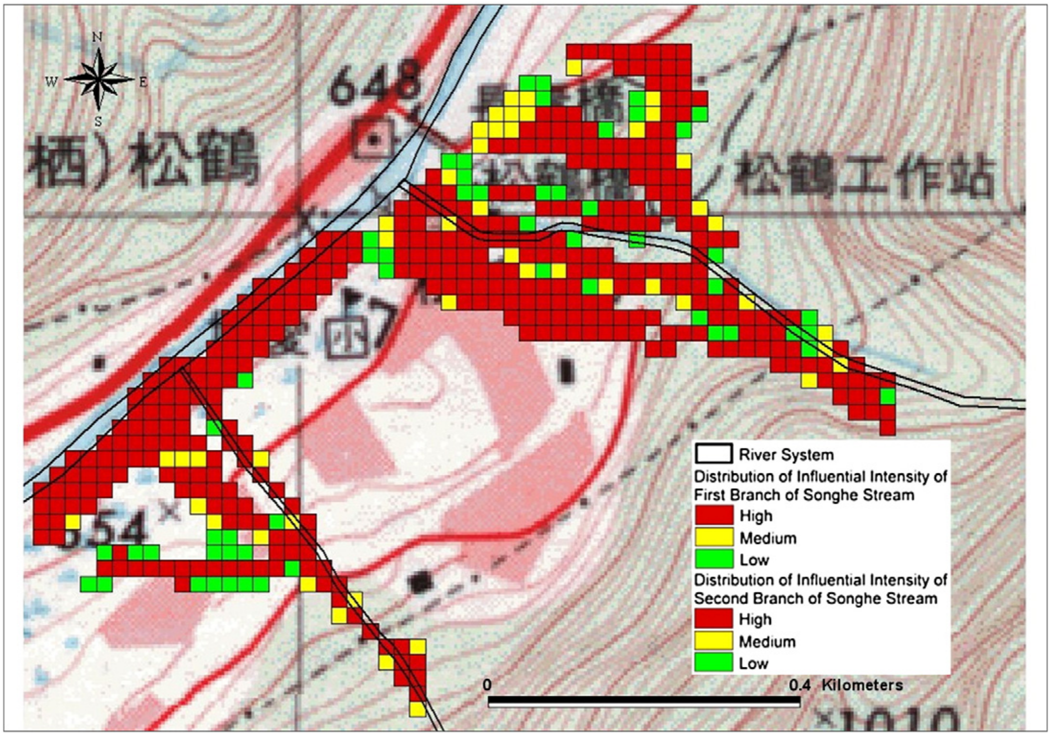

Fig. 15. Distribution map of risk degree of Songhe Village.