A Study on Criteria of Warning and Evacuation for Large-scale Sediment Disasters Considering the Relationships with Sediment Movement and Damage

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In Japan, Sediment Disaster Warning Information pertaining to a debris flow and slope failures due to rainfall is provided to residents based on the criteria of rainfall between the occurrence and non-occurrence of such sediment disasters. Early warning information system for large-scale sediment disasters has not yet been established, and the criteria that must be met to trigger warning have not yet been established. In this study, to estimate suitable criteria of warning and evacuation for large-scale sediment disasters in Japan, we examined and clarified the relationships among sediment movement, damage, and return period of rainfall causing large-scale sediment disasters by conducting a statistical analysis of 22 previous large-scale sediment disasters. We found that 1) large-scale sediment disasters may occur during rainfall events with a 30 to 50 year return period, and 2) longer rainfall return periods, as recorded in long-term rainfall indices (more than 24 hours), may indicate imminent large-scale sediment movement and demand attention as indicators of large-scale sediment disasters.

Key words: criteria, early warning information, large-scale sediment disaster, rainfall

1. INTRODUCTION

In Japan, Sediment Disaster Warning Information (SDWI) predicting a debris flow and slope failures due to rainfall is disseminated by both by prefectural governments and the Japan Meteorological Agency (JMA) [*Japan Meteorological Agency*, 2017a; *Osanai et al.*, 2010]. However, SDWI does not predict the scale of sediment disasters [*Japan Meteorological Agency*, 2017b]. Several previous studies on early warning information have focused on rainfall conditions predicting the occurrence or non-occurrence of landslides (i.e. *Keefer et al.*, [1987], *Baum and Gobt* [2010], *Osanai et al.*, [2010]). In contrast, few studies have been conducted on the relationships among sediment movement, damage (which are related to the scale of sediment movement, location of houses, population density and facilities to prevent sediment disaster), and rainfall. Warning and evacuation criteria for large-scale sediment disasters, e.g., multiple and/or simultaneous deep-rapid landslides [*Hayashi et al.*, 2013] and debris flows [*Nishi et al.*, 2014], which can result in large numbers of causalities and/or significant property damage, have not been fully established.

Regarding the receptivity to, and recognition of, early warning information by residents, such information currently does not effectively promote evacuation [*National Institute of land and infrastructure management and Tsukuba University* 2012; *Ministry of Land, Infrastructure Transport and Tourism*, 2013]. Ministry of Land, Infrastructure Transport and Tourism (MLIT) has therefore proposed a graded warning information linked with the actions that should be taken by residents to ensure their safety [*Ministry of Land, Infrastructure Transport and Tourism*, 2013]. Moreover, *Ushiyama* [2014] indicated that graded warning information is easier for residents to understand than public early warning statements. Although the JMA extensively disseminates Emergency Warnings regarding extreme weather conditions to individual prefectures [*Japan Meteorological Agency*, 2017c], to date no early warning information system for large-scale sediment disasters has been established.

In this study, we analyze the relationships among sediment movement, damage, and the return period of rainfall events causing sediment disasters to estimate suitable criteria of warning and evacuation for large-scale sediment disasters.

2. METHODS

Fig. 1 illustrates our research methods. We first evaluate the scale of sediment disasters regarding 22 previous rainfall-triggered sediment disasters, which are selected by literature search (i.e. *Japan Sabo Association* [2015]), in Japan based on the Sediment Disaster Scale [*Hayashi et al.*, 2015]. For the 22 disasters, we specify triggering rainfall which may contribute to cause sediment disaster and evaluate its return period respectively. Then we statistically analyze the relationship between the scale of sediment disaster and the return period of triggering rainfall. Finally, based on the results of this analysis, we estimate suitable criteria of warning and evacuation for large-scale sediment disasters.

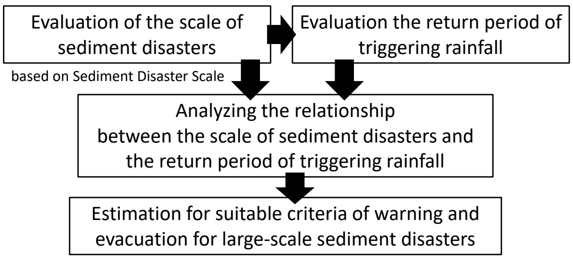

Fig. 1 Research methods

2.1 Evaluation of the scale of sediment disasters based on Sediment Disaster Scale

Of the 22 disasters, 17 were evaluated the scale of sediment disasters by *Hayashi et al.*, [2015] and *Hayashi et al.*, [2016]; we evaluate additional 5 disasters based on the Sediment Disaster Scale (SDS; *Hayashi et al.*, [2015], **Table 1**, SDS ≥ 3, from 1961 to 2014). SDS classifies sediment disasters into five categories using two indices - one that pertaining to sediment movement, "Sediment Movement Magnitude" (SMM; *Uchida et al.*, [2005]), and one that related to damage, "Damage Level" (DL; *Kojima et al.*, [2009]). SMM is calculated using Eq. (1):

$$SMM = log_{10} \sum_{i=1}^{n} (V_i H_i) \quad (1)$$

where V is the volume of sediment movement (m^3), and H is the relative height (m). DL is calculated using Eq. (2):

$$DL = 0.69\, log_{10}\, x_1 + 0.16\, log_{10} \left(x_2 + x_3 + \frac{x_4}{3} \right) + 1.07 \quad (2)$$

where x_1 is the number of persons killed or missing, x_2 is the number of persons injured, x_3 is the number of houses totally collapsed, x_4 is the number of houses partially collapsed. SDS categories are defined as follows (excluding overlapping portions within the upper category):

SDS 1: SMM < 4.0 and DL < 1.0
SDS 2: 4.0 ≤ SMM < 6.0 or 1.0 ≤ DL < 1.5
SDS 3: 6.0 ≤ SMM < 8.0 or 1.5 ≤ DL < 2.0
SDS 4: 8.0 ≤ SMM < 10.0 or 2.0 ≤ DL < 2.5
SDS 5: 10.0 ≤ SMM or 2.5 ≤ DL

According to *Hayashi* [2017], multiple and/or simultaneous deep-rapid landslides and debris flows, which are typical disasters of large-scale sediment disaster, were are classified as SDS ≥ 3. Based on historical disaster records, most of sediment disasters included in SDS 1 and 2 were single debris flow and slope failure, which can be caused by daily rainfall exceeding 10 yr return period [*Ministry of Land, Infrastructure Transport and Tourism*, 1999 and 2012]. Therefore, we define large-scale sediment disasters as SDS ≥ 3.

2.2 Evaluation the return period of triggering rainfall

For the 22 sediment disasters, we evaluate the return period of "Triggering Rainfall" (hereafter "TR") that caused the disaster (**Table 1**) using AMeDAS (Automated Meteorological Data Acquisition System, operated by JMA) return period calculation program (hereafter "ARPCP") [*Public Works Research Institute*, 2003]. We defined TR as the rainfall index that had the longest return period of nine different rainfall indices (maximum 1 h, 2 h, 3 h, 6 h, 12 h, 24 h, 48 h, 72 h and total rainfall). Precipitation records for each sediment disaster are obtained from literatures of sediment disasters. The ARPCP can evaluate return period in 748 AMeDAS stations within nationwide AMeDAS stations (1302 stations, as of November 30, 2016), where can obtained yearly maximum value. For the sake of simplicity, we evaluate the return period of TR using the nearest AMeDAS station that can be evaluated by the ARPCP (hereafter "$AMeDAS_e$") from the rainfall observation station which written in the literature (hereafter "ROS_l"). The distance between $AMeDAS_e$ and ROS_l is always less than 30km; this may have led to the positive correlation between rainfall records of different rainfall observation stations (i.e. *Irasawa and Taguchi* [1996]).

Table 1 List of sediment disasters evaluated SMM, DL, SDS and RPTR

Year	Name of disaster	Prefecture	SMM	DL	SDS category	Literature regarding SMM and DL	ROS_i	Literature regarding ROS_i	$AMeDAS_e$	The rainfall indices of TR	The amount of TR (mm)	RPTR
1961	Onishiyama	Nagano	9.05	2.45	4	*Hayashi et al.,* [2016] based on *Public Works Research Institute* [2010]	Iida	*Japan Meteorological Agency* [2017d]	Iida	24	354.4	410
1966	Ashiwada	Yamanashi	8.45	2.74	5	*Hayashi et al.,* [2016] based on *Oka and Katsurajima [1971], Sabo division of Yamanashi Prefecture* [1994]	Kawaguchiko	*Sabo division of Yamanashi Prefecture* [1994]	Kawaguchiko	1	68.2	45
1982	Nagasaki	Nagasaki	7.14	3.13	5	*Hayashi et al.,* [2016] based on *Egashira* [1983], *Mizuyama et al.,* [1985], *Nakano* [1982]	Nagasaki	*Public works department of Nagasaki Prefecture* [1983]	Nagasaki	6	432	110
1988	Kake	Hiroshima	6.18	2.23	4	*Hayashi et al.,* [2016] based on *Himegi* [1999], *Tochigi and Kaibori* [1989], *Tochigi et al.,* [1989]	Kake public works office	*Mizuyama et al.,* [1988]	Kake	6	238	140
1997	Hariharagawa	Kagoshima	7.18	2.22	4	*Hayashi et al.,* [2015] based on *Moriwaki et al.,* [1997]	Izumi	*Moriwaki et al.,* [1997]	Izumi	48	544	63
1999	Hiroshima and Kure	Hiroshima	6.63	2.34	4	*Hayashi et al.,* [2016] based on *Miura et al.,* [1999], *The committee for countermeasure against sediment disasters in Hiroshima Prefecture* [1999]	Uokiri-dam	*Sabo & Landslide Technical Center* [2000]	Kake	6	207.5	77
2003	Minamata	Kumamoto	7.48	2.09	4	*Hayashi et al.,* [2015] based on *National Institute for Land and Infrastructure Management and Public Works Research Institute* [2003]	Fukagawa	*National Institute for Land and Infrastructure Management and Public Works Research Institute* [2003]	Minamata	6	313	240
2003	Dazaifu	Fukuoka	6.68	1.27	3	*This study based on National Institute for Land and Infrastructure Management and Public Works Research Institute* [2003]	Futaba nursery home	This study based on *National Institute for Land and Infrastructure Management and Public Works Research Institute* [2003]	Dazaifu	6	258	170
2004	Izumozaki	Niigata	7.69	1.20	3	*Hayashi et al* ., [2015] based on *Noro et al.,* [2004]	Nagaoka	*Noro et al.,* [2004]	Nagaoka	24	231	51
2004	Miyama	Fukui	8.45	1.91	4	This study based on *Yao et al.,* [2005]	Miyama	This study based on *Yao et al.,* [2005]	Miyama	6	254	17,000
2004	Oyochi	Tokushima	8.78	1.28	4	*Hayashi et al* ., [2015] based on *Hiura and Sasahara* [2005]	Sawadani	*Noro et al.,* [2004]	Fukuharaasahi	48	1518	1,500
2004	Niihama	Ehime	7.67	1.60	3	*Hayashi et al* ., [2015] based on *Sabo & Landslide Technical Center* [2005]	Niihama	*Ministry of Land, Infrastructure Transport and Tourism* [2005]	Niihama	2	107	26
2004	Miyagawa	Mie	7.37	1.80	3	*Hayashi et al* ., [2015] based on *Hayashi et al.,* [2004]	Miyagawa	*Hayashi et al.,* [2004]	Miyagawa	1	110	67
2005	Mimikawa -shimado	Miyazaki	8.92	0.55	4	*Hayashi et al* ., [2016] based on *Public Works Research Institute* [2010]	Morotsuka	*Chigira* [2006]	Kuraoka	48	943	500
2006	Okaya	Nagano	6.46	1.93	3	*Hayashi et al.* , [2015] based on *Hiramatsu et al.,* [2006]	Tatsuno	*Hiramatsu et al.,* [2006]	Suwa	72	403	380
2009	Hofu	Yamaguchi	8.48	2.14	4	*Hayashi et al.,* [2015] *based on Hayashi et al.,* [2010]	Manao	*Ministry of Land, Infrastructure Transport and Tourism* [2009]	Hofu	6	229	310
2012	Kii peninsula	Nara, Wakayama, Mie	10.46	2.64	5	*Hayashi et al.,* [2015]	Kazaya	*Kinki regional development bureau of Ministry of Land, Infrastructure Transport and Tourism* [2013]	Kazaya	72	1302.5	2,200
2013	Tazawako	Akita	6.20	1.75	3	*This study based on Touhoku regional development bureau of Ministry of Land, Infrastructure Transport and Tourism* [2013]	Yoroibata	*This study based on Touhoku regional development bureau of Ministry of Land, Infrastructure Transport and Tourism* [2013]	Tazawako	6	231.5	960
2013	Izu-oshima	Tokyo	8.16	2.51	5	*This study based on The committee for countermeasure against sediment disasters in Izu-oshima island* [2014]	Oshima	*This study based on The committee for countermeasure against sediment disasters in Izu-oshima island* [2014]	Inatori	12	694.5	51,000
2014	Nagiso	Nagano	8.19	1.25	4	*This study based on Chubu regional development bureau of Ministry of Land, Infrastructure Transport and Tourism* [2014]	Nagiso	*This study based on Hiramatsu et al.,* [2014]	Nagiso	2	88	48
2014	Hiroshima	Hiroshima	8.01	2.75	5	*Hayashi et al.,* [2016] *based on Ministry of Land, Infrastructure Transport and Tourism* [2014]	Takase	*Ministry of Land, Infrastructure Transport and Tourism* [2014]	Higashihiroshima	2	166	750
2014	Tanba	Hyogo	7.85	1.31	3	*Hayashi et al* ., [2016] based on *Ministry of Land, Infrastructure Transport and Tourism* [2014]	Kitaokamoto	*Sakamoto and Uezono* [2014]	Kaibara	12	345	910

3. RESULTS & DISCUSSION

Fig. 2 and **Table 2** show the relationship between the SDS category and the return period of TR (RPTR). For the upper value of RPTR (approx. from 960 to 51,000 yr), higher values of SDS category coincided with higher RPTR, average value and median value. However, for the lower value of RPTR (approx. from 30 to 50 yr), higher SDS category (e.g. 4 and 5) was not associated with higher RPTR.

We divided the rainfall indices of TR into two groups, short-term (ST, 1 to 12 h) and long-term (LT, more than 24 h) and then analyzed the relationships among SMM, DL and RPTR for each group separately using Spearman's rank correlation coefficient (SRCC) computed in R software (**Fig. 3** and **4**). As shown in **Fig. 3**, SMM and RPTR were not correlated in the ST group (SRCC = 0.11, P = 0.70); however, they were strongly positively correlated in the LT group (SRCC = 0.71, P = 0.09). As shown in **Fig. 4**, DL and RPTR had no correlation in the ST (SRCC = 0.08, P = 0.77) or LT group (SRCC = 0.29, P = 0.56). Because TR tends to cause large-scale sediment movement in LT cases (SMM ≥ 8.5, **Fig. 3b)**), it may modulate the relationships among SDS category and the upper, average and median values of RPTR (**Fig. 2**). In addition, Damage of any severity level may occur irrespective of RPTR, and thus may also affect the relationship between SDS category and the lower value of RPTR (**Fig. 2**).

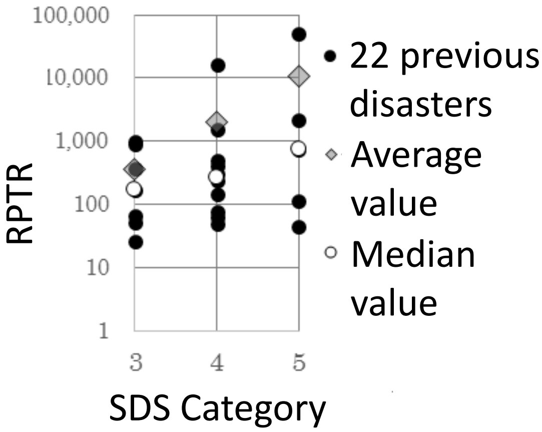

Fig. 2 The relationship between SDS category and RPTR, arithmetic average value and median value

Table 2 The upper, arithmetic average, median and lower value of RPTR and sample standard deviation for SDS categories (2 significant figures)

	3	4	5
Upper value of RPTR (yr.)	960	17,000	51,000
Average value (yr.)	360	2,000	11,000
Median value (yr.)	170	270	750
Lower value of RPTR (yr.)	26	48	45
Standard deviation (yr.)	410	5,100	23,000

Based on our analysis of the relationships among sediment movement, damage, and return period of rainfall events causing large-scale sediment disasters, we suggest for estimation of suitable criteria of warning and evacuation for large-scale sediment disasters as follows. 1) Large-scale sediment disasters may occur with approximately 30 yr and 50 yr of return period rainfalls in ST and LT, respectively (**Fig. 4**). Therefore 30 yr and 50 yr of return period rainfall can be criteria of warning and evacuation for large-scale sediment disasters in ST and LT, respectively. 2) In LT, longer return period of rainfall may cause large-scale sediment movement (**Fig. 3b)**). Therefore, if exceeding 50 yr of return period rainfall coincides with a prediction of intense rainfall, attention should be paid to it for the occurrence of large-scale sediment disasters.

Our suggestions is supported by the findings of several previous studies. Suggestion 1) corresponds to that JMA operates Emergency Warning based on exceeding 50 yr return period of Soil water index [*Okada et al.*, 2001], 3hr and 48hr rainfall [*Japan Meteorological Agency*, 2017e], which were mainly determined based on flood damage. *Saito et al.*, [2014] also found that large landslide events (>10^6 m^3) in Japan occurring from 2001 to 2011 were associated with greater-than 40 yr return period of rainfall events. Suggestion 2) correspond to findings of *Uchida and Okamoto* [2012], indicating that past multiple deep-rapid landslides in Japan, which are the major cause of large-scale sediment disasters, occurred when cumulative rainfall exceeded 600 mm within 48 hr and 72 hr. Based on these findings, and our own results detailed herein, we clarify approximate criteria of warning and evacuation for large-scale sediment disasters to establish graded early warning information.

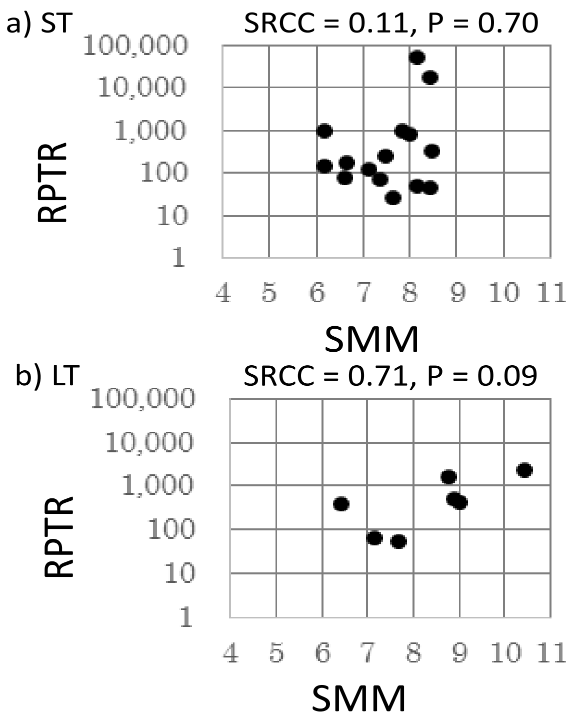

Fig. 3 The relationship between SMM and RPTR (a) in ST, b) in LT)

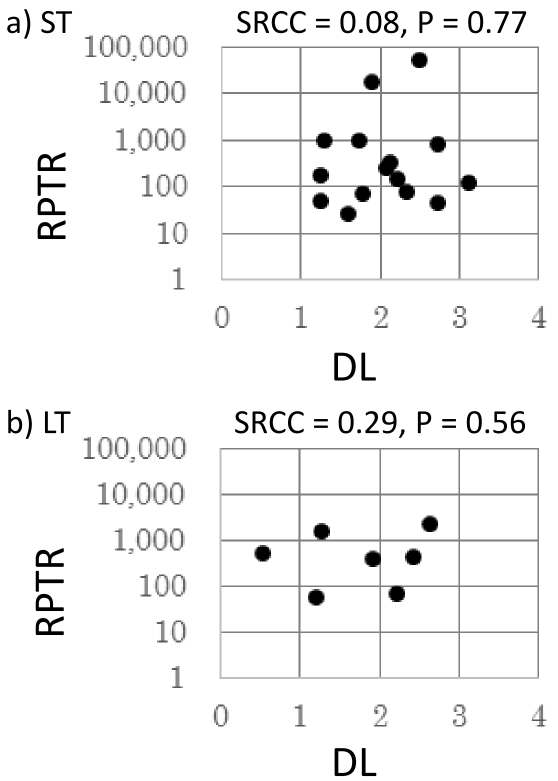

Fig. 4 The relationship between DL and RPTR in LT (a) in ST, b) in LT)

4. CONCLUSIONS

In this study, to estimate suitable criteria of warning and evacuation for large-scale sediment disasters, we analyzed and clarified the relationships among sediment movement, damage, and return period of rainfall causing large-scale sediment disasters (SDS ≥ 3), We found that 1) large-scale sediment disasters may occur with 30 to 50 yr of return period rainfalls and 2) longer return period of rainfall in LT may cause large-scale sediment movement (SMM ≥ 8.5); thus attention should be paid to it for the occurrence of large-scale sediment disasters.

Further examination is necessary to improve our study. Regarding evaluation for RPTR, the minimization of distances between where disaster occurred, rainfall observation station nearest where disaster occurred and evaluated rainfall observation station for RPTR improve the accuracy of RPTR evaluations. By increasing the number of reports on previous large-scale sediment disasters, future studies could help improve the general applicability of our method.

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