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POSSIBILITY OF EARLY WARNING FOR LARGE-SCALE LANDSLIDES USING HYDROLOGICAL AND SEDIMENT TRANSPORT OBSERVATIONS IN MOUNTAIN RIVERS

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ABSTRACT

Early-warning systems for sediment disasters are important tools for disaster risk reduction, achieving sustainable development, and ensuring livelihoods. In 2005, the Japanese government initiated a new nationwide early warning system for landslide disasters. The main methodology of the system involves setting a criterion for the occurrence of debris flows and slope failures based on several rainfall indices. However, these rainfall thresholds did not always work well and could not ensure early evacuation. We considered that the early detection of small-scale sediment movement, likes sediment discharge from streams, could be used effectively in early warning systems for large-scale landslides; however, the difficulties in directly monitoring traction processes, such as bedload and mass movements, has been widely recognized. Here, we propose a new observation method for monitoring bedload transport in mountain rivers using an acoustic method: the use of hydrophones, as proposed by Mizuyama *et alii* (1996). Moreover, we demonstrate the applicability of this method to clarify bedload dynamics in Japanese mountain rivers. Then, we argue that our new method offers the possibility of improvements in early warning systems of large-scale landslides using real-time monitoring systems for bedloads in mountain rivers.

Key words: *large-scale landslide, bedload monitoring, hydrophone, early warning system*

INTRODUCTION

In steep mountainous regions, landslides may include both soils and underlying weathered bedrock (e.g., Uchida *et alii*, 2010). The velocities and volumes of these landslides are often very high, and these large-scale landslides may form landslide dams and have serious impacts on human lives and infrastructure (e.g., Costa & Schuster, 1988). Thus, such landslides may cause serious damage. For example, a huge landslide killed more than 400 people at Shaolin Village, Taiwan, in 2009 (e.g., Shieh *et alii*, 2009).

Early warning systems for sediment disasters are important tools for reducing disaster risk, achieving sustainable development, and preserving livelihoods. In 2005, the Japanese government initiated a new nationwide early warning system for landslides disasters. The main methodology of the system involves the setting of a criterion for the occurrence of debris flows and slope failures based on several rainfall indices (e.g., Osanai *et alii*, 2010). Moreover, many previous studies have been conducted to clarify an appropriate rainfall threshold for the prediction of landslide occurrence (e.g., Caine, 1980; Guzzetti *et alii*, 2008; Saito *et alii*, 2010). These efforts are novel and have been proven to result in reduction of landslide disasters. However, the use of these rainfall thresholds did not always ensure early evacuation (e.g., Shieh *et alii*, 2009; Fujita *et alii*, 2010). Therefore, other monitoring systems have been proposed (e.g., Uchimura *et alii*, 2010; Fujita *et alii*, 2010).

Recently, several researchers have argued that several small-scale sediment movements can occur before large-scale landslide occurrence (e.g., Fujita *et alii*, 2010). Therefore, if we were able to detect these small-scale movements early, the information could prove useful in ensuring effective early warning systems for large-scale landslides. However, the difficulties in directly monitoring traction processes, such as bedload and mass movements, have been widely recognized.

Over the last few decades, research has been conducted into surrogate monitoring technologies, including acoustic (e.g., geophones, hydrophones) and seismic methods, for the monitoring of bedload transport (e.g., Rickenmann & McArdell, 2007; Gray *et alii*, 2010; Rickenmann *et alii*, 2012). Over the last decade in Japan, hydrophones (Mizuyama *et alii*, 2010); also referred to as "Japanese pipe system") have been applied widely to monitor bedload in mountainous rivers (e.g., Mizuyama *et alii*, 1996, 2003; Kanno *et alii*, 2010). Thus, the abundance of monitoring data has increased dramatically in recent years. However, since the results of acoustic measurements must be converted to bedload using empirical and/or theoretical relationships, calibration is still a key issue in the application of acoustic bedload measurements (e.g., Nakaya, 2009; Mizuyama *et alii*, 2010, 2011; Suzuki *et alii*, 2010). Recently, we proposed a new method for conversion of sound pressure data, collected by hydrophones, to rates of bedload transport (Suzuki *et alii*, 2010). In the present study, we conducted field bedload transport observations in Japanese mountain rivers to examine the applicability of hydrophones to (1) measuring the bedload transport rate, and (2) detecting small-scale sediment movements just after their occurrence.

LESSONS FROM PAST DISASTERS

First, we compiled documentations of recent two disasters to test our hypothesis that if we were able to detect these small-scale movements early, the information could prove useful in ensuring effective early warning systems for large-scale landslides.

SHIAOLIN VILLEAGE, TAIWAN

Typhoon Morakot landed Taiwan at 7-Aug., 2009 and brought the heaviest rainfall in southern part of Taiwan. Cumulative rainfall amounts of this event exceed 2,500 mm. This heavy rainfall triggered many sediment disasters. Especially, in Shiaolin village, Kaoshung, County had a serious damaged by deep-seated catastrophic landslide. Many studies documented this disaster in detail (e.g., Shieh *et alii*, 2009; Fujita, 2010).

On 17:00LT and 21:00LT, 7-Aug., cumulative rainfall amount exceeded threshold values for the caution and warning of sediment disasters, respectively. However, the heavy rainfall was continued and the peak rainfall intensity. At 19:00LT, 8-Aug. the bridge No.8 was broken by sediment discharge from a tributary (Fig. 1). Moreover, at 6:00LT, 9 Aug. the bridge No.9 was broken by sediment discharge from another tributary. Then, huge deep-catastrophic landslide oc-

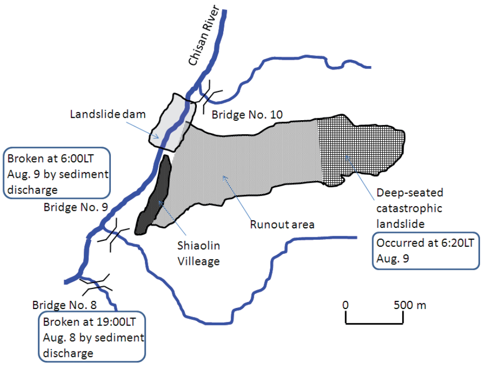

Fig. 1 - Schematic map of Shiaolin village, Taiwan describing locations and timing of deep-seated catastrophic landslide and sediment discharge triggered by typhoon Morakot, 2009. Location s and timings were compiled from Shieh *et alii (2009) and* Fujita *(2010)*

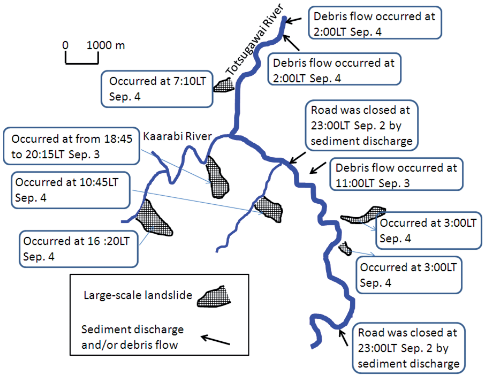

Fig. 2 - Schematic map of Totsugawa village, Japan describing locations and timing of large-scale landslide, debris flow and sediment discharge triggered by typhoon Tales, 20011. Location s and timings were compiled from the survey by Nara Prefecture and Yamada *et alii (2012)*

curred at 6:20LT, 9-Aug. A part of this landslide directly attacked Shiaolin village and induced landslide dam. Finally, the landslide dam breeched by overtopping erosion and triggered a flash flood. The Shiaolin village was completely destroyed by landslide and landslide dam and most of local people who lived in the village were killed by this disaster.

TOTSUGAWA VILLEAGE, JAPAN

Typhoon Tales landed Japan at 3 Sep., 2011 and brought the heaviest rainfall in central part of Japan. Cumulative rainfall amounts of this event exceed 1,500 mm. This heavy rainfall triggered many sediment disasters. Especially, in Kii Peninsula, including Totsugawa village, many deep-seated rapid landslides were occurred. Based on satellite image survey, we detected more than 50 large landslides, means that landslide areas were larger than 1.0 ha.

On 12:35LT, 2-Sep., local government and Japan Metrological Agency alerted the special warning of sediment disasters based on the rainfall threshold described by Osanai *et alii* (2010). However, the heavy rainfall was continued until the morning of 4-Sep. Around 23:00LT 2-Sep., national road was closed by rockfalls and sediment discharges from tributaries of Totsugawa river (Fig. 2). From 18:45LT 3-Sep. to 16:20LT 4- Sep. several deep-seated rapid landslides occurred and triggered serious damages in Totsugawa village, Japan (Fig. 2).

LESSONS FROM THE DISASTERS

Based on these two disasters, we can point our two issues about early-warning system for large-scale landslides.

Fig. 3 - Hydrophone in Bouzudaira Sabo Dam, Yotagiri River, Japan

(1) There were relatively long time lags (i.e., around one and half days in Shiaolin and Totsugawa villages) between the warning based on the rainfall thresholds and the occurrence of large scale landslide. It can be thought that since the current rainfall threshold for the warning against sediment disasters mostly determined by past ordinal-scale landslides and debris flows (Osanai *et alii*, 2010), the warning was much earlier than the occurrence of large-scale landslide.

(2) In both disasters, sediment discharge from relatively small tributaries occurred before the large-scale landslide occurrence. Moreover, the time lag between the occurrence of sediment discharge and large-scale landslide was relatively short, compared to the time lag between the warning and landslide occurrence.

These two issues supported our hypothesis suggesting that the information about small-scale sediment discharge could prove useful in ensuring effective early warning systems for large-scale landslides.

SEDIMENT DISCHARGE MONITORING METHODS

DEVICES

We used the type of hydrophone developed by Mizuyama *et alii* (1996, 2003, 2010), which consists of a pipe deployed across a riverbed (Fig. 3). The diameter of the pipe used was 48.6 mm, its length was 50 cm, and its thickness was 3 mm (Fig. 4). The pipe was fixed using a mortar mound. The height of the pipe from the surface of mortar mound was 12 mm, as shown in Fig. 4.

Vibrations of the air, generated by the collision of a sediment particle with the pipe, are detected by a microphone; these are amplified by a preamplifier and transmitted to a converter. The microphone and preamplifier were installed inside the pipe (Mizuyama *et alii*, 2010). The output of the preamplifier is a waveform, and we sampled output data at 100 kHz.

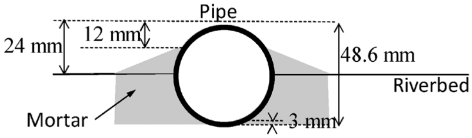

Fig. 4 - Schematic illustration describing cross section of hydrophone

CALIBRATION METHOD

We used the integrated sound pressure method proposed by Suzuki *et alii* (2010) to convert raw hydro-phone data to bedload transport rate. First, to reduce the electrical noise, we extracted circumferential frequency components using a band-pass filter [Step (2) in Fig. 5]. Sound pressure data correspond to the line connecting the local maximum points of the extracted data ("Filtered wave data" in Fig. 5), and we calculated the averaged sound pressures (*Sp*). Suzuki *et alii* (2010) confirmed the relationship between *Sp* and bedload transport rate, Qs, as follows:

$$Sp = \alpha\, Q\, sr \qquad (1)$$

$$R = f\,(N) \qquad (2)$$

where α is the proportionality coefficient, *R* is the detection rate, and *N* is the collision frequency. Equation (2) indicates that *R* is a function of *N*. The relationship between *R* and *N* can be obtained from experimental results under a wide range of conditions. However, the relationship obtained is unrealistic, because a tremendous amount of data is necessary for experimental accuracy. Therefore, Suzuki *et alii* (2010) proposed a method for estimating the relationship between *R* and *N* using numerical simulations, as follows ("Preparation" in Fig. 5).

In this method, a uniform random number, *rd(t)*, is given every one-millionth of a second, where *t* is the elapsed time (s). The threshold value, *Th*, is set at *Th* = *N/100000* for a given value of *N*. When *rd(t)* is lower than *Th*, an individual collision wave datum, which is obtained by preliminary field experiments [Step (5) in Fig. 5], is added to the wave data being produced. R is calculated from the data computed in this way using Eq. (1). The relationship between *R* and *N* is obtained when *N* is varied over a wide range. Thus, *R* decreases as *N* increases owing to the effects of sound wave interference ("Collision frequency–Detection rate relationship" in Fig. 5). Then, we determined the relationship between collision frequency and relative detection rate (Step (7) in Fig. 5).

Qs is expressed as

$$Qs = \frac{\pi d^3}{6} N \qquad (3)$$

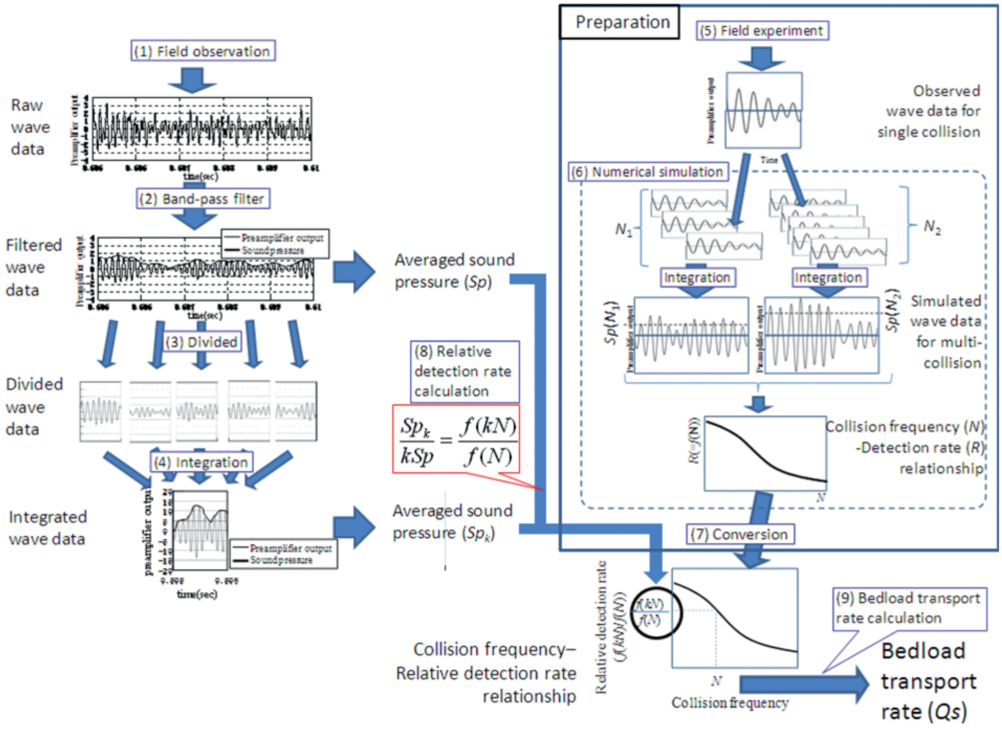

Fig. 5 - Schematic illustration describing the Integrated sound pressure method

where d is the mean diameter of the bedload. Substituting Eqs. (2) and (3) into Eq. (1), Eq. (4) is obtained:

$$Sp = \alpha \cdot \frac{\pi d^3}{6} N \cdot f(N) \tag{4}$$

It is impossible to obtain Qs from Sp using Eq. (4) alone, because there are two unknown variables: N and d. Here we imagined larger bedload condition. We defined the ratio of observed bedload to imagined bedload as k. So, according to Eqs. (1) and (4), if N increases k times without any increase in d, the following equation can be obtained.

$$Sp_k = \alpha \frac{\pi d^3}{6} kN \cdot f(kN) \tag{5}$$

where Sp_k is the average sound pressure under the imagined k times larger bedload condition. Thus, from Eqs. (4) and (5), relative detection rate *(f(kN)/f(N))* can be calculated by the following equation:

$$\frac{Sp_k}{kSp} = \frac{f(kN)}{f(N)} \tag{6}$$

In the integrated sound pressure method, we divided the original observed wave data of the preamplifier output into k data [Step (3) in Fig. 5]; then, these k wave data were integrated into single wave data as the wave data of k times larger bedload condition [Step (4) in Fig. 5]. We assumed that the preamplifier output under k times larger bedload transport condition (vk(t)) can be described as follows.

$$vk(t) = \sum_{i=1}^{k} v_i(t) \tag{7}$$

where $v_i(t)$ is the preamplifier output of the i-th wave data. s the preamplifier output of the i-th wave data.

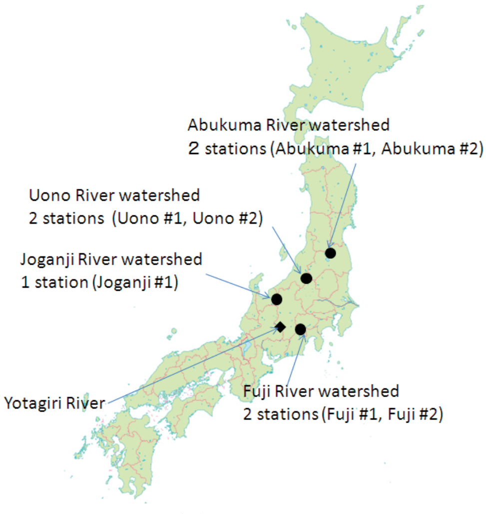

Fig. 6 - Location of observation stations

Using the integrated wave data produced using the observed preamplifier output and Eq. (6), we calculated the average sound pressure under the assumed k times larger bedload condition, Sp_k, and the relative detection rate, *f(kN)/f(N) (=Spk /kSp)* (Step (8) in Fig. 4). Based on the predermined relationship between collision frequency and relative detection rate, we were able to evaluate the bedload transport rate (Qs) from the observed Sp and calculated Sp_k (Step (9) in Fig. 4). We also evaluated mean diameter of bedload (d) based on this method.

INTENSIVE OBSERVATION

We conducted detailed measurements at Bouzudaira Sabo Dam in Yotagiri River in central Japan (Figure 6). The river has a drainage area of 42.7 km^2 and mean riverbed angle of 5.4°. Debris flows occur frequently at one particular tributary of Yotagiri River, Onboro-sawa, where unstable sediments are deposited on both the riverbed and surrounding hillslopes.

Bouzudaira Sabo Dam has a drainage area of 37.6 km^2 and is located at an altitude of 745 m a.s.l. The riverbed angle at Bouzudaira Sabo Dam is 2.3°; the width of the surface water is 50 m, and the median grain diameters of the riverbed sediments are around 3-5 cm.

A sediment flow observation system was installed at Bouzudaira Sabo Dam in 2000 (Ura *et alii*, 2002). Using this system, samples of river water can be obtained at three different heights (on the riverbed, and 50 and 100 cm above the riverbed). Therefore, the rates of bedload, suspended load, and washload can be observed directly (Ura *et alii*, 2002). We assumed that the rate of sediment transport at the riverbed was the same as the bedload transport rate.

INTERSITE COMPARISON

In 2010, the Sabo Department and Sabo Offices of the Ministry of Land, Infrastructure, Transport and Tourism of Japan initiated extensive monitoring of bedload transport in Japanese mountain rivers using hydrophones. Here, we have compiled some of these data, including data from seven observation stations in six watersheds (Fig. 6).

We evaluated transport rate using the integrated sound pressure method and hydrophone data. We calculated the dimensionless bedload transport rate (q_{s*}) using the following equations:

$$q_{s*} = q_s \Big/ \sqrt{(\sigma/\rho - 1) g d_r^{\,3}} \tag{8}$$

where is σ the unit weight of sediment and ρ is the unit weight of water, g is the gravitational acceleration, and d_r is the representative bedload diameter. We defined d_r as the grain sizes at which 60% of the sample is finer (d60). We used sample taken from riverbed sediments to define d_r.

We also calculated the dimensionless bed shear stress (τ_*) using the following equation:

$$\tau_* = u_*^{\,2} \Big/ (\sigma/\rho - 1) g d_r \tag{9}$$

where $\boldsymbol{u}_*$ is friction velocity.

RESULTS

Here, we present the results of a storm triggered by Typhoon Roke (Fig. 7). Generally, the bedload transport rate evaluated by hydrophone agreed well with that observed by direct sampling. This suggests that the integrated sound pressure method is applicable for calibrating the output data of hydrophone preamplifiers to the volume of bedload transport.

Moreover, the bedload transport rate evaluated using the hydrophone exhibited complex characteristics of bedload transport. For example, the peak bedload transport rate occurred several hours earlier than the peak water level. Therefore, bedload transport during periods of rising water level was greater than that during periods of falling water level, assuming constant water level. Accordingly, we considered the hydrophone to be effective in clarifying the detailed dynamics of bedload transport in mountain rivers. Moreover, our results indicate that the bedload transport rate cannot be fully described under the assumption that sediment transport can be a capacity-limited system.

We evaluated temporal changes in mean bedload diameter using the hydrophone data (Fig. 8). Our results indicate that mean bedload diameter varied from around 1 mm to 10 mm, and increased with increasing bedload transport rate. Temporal variability in bedload diameter was particularly large during high-flow periods. We also compared mean bedload diameter evaluated using hydrophone data with the grain size distribution of bedload evaluated by direct sampling (Fig. 8). The results indicated that there was little difference in mean bedload diameter estimated using these methods. Therefore, we consider the hydrophone to be effective in clarifying the detailed dynamics of bedload transport, i.e., transport rate and particle diameters, in mountain rivers.

Various relationships have been determined (us-

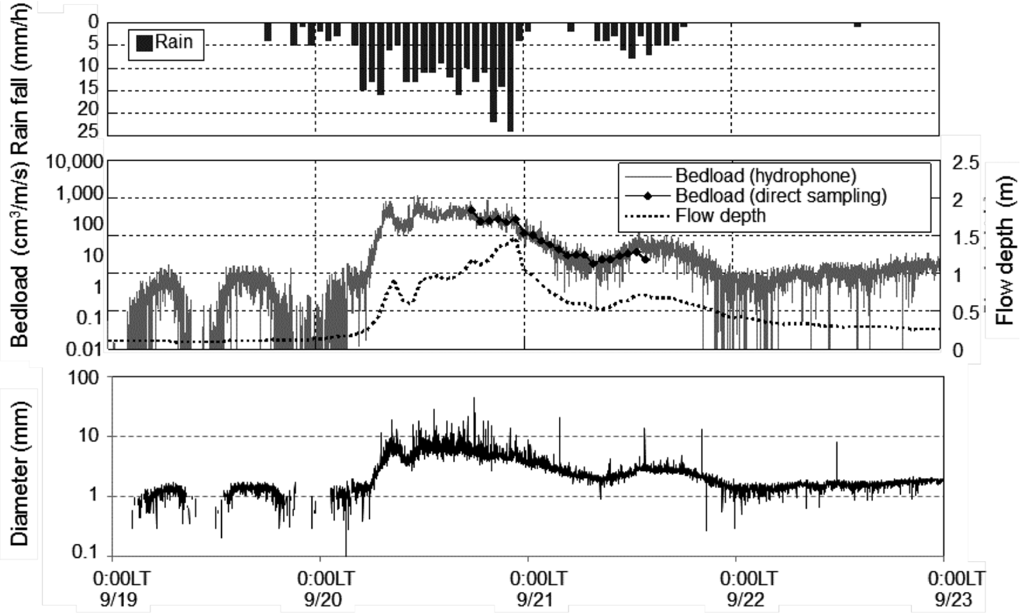

Fig. 7 - Hyetograph, water flow depth, bedload transport rate per unit width observed by both hydrophone and direct sampling, combined with temporal changes in bedload diameter evaluated by hydrophone during the storm triggered by Typhoon Roke, 2011

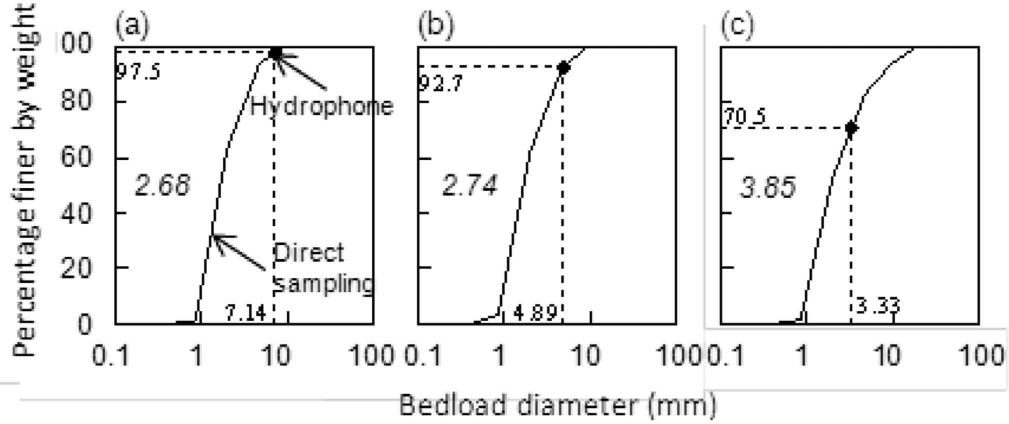

Fig. 8 - Mean bedload diameter evaluated by hydrophone (black circles) and bedload grain size distribution observed by direct sampling (solid lines) at (a) 18:00 LT Sep/ 20, (b) 21:00 LT, Sep/ 20, (c) 2:00 LT Sep/ 21, 2011. Numbers in italics represent mean bedload diameters (mm) evaluated by direct samplings

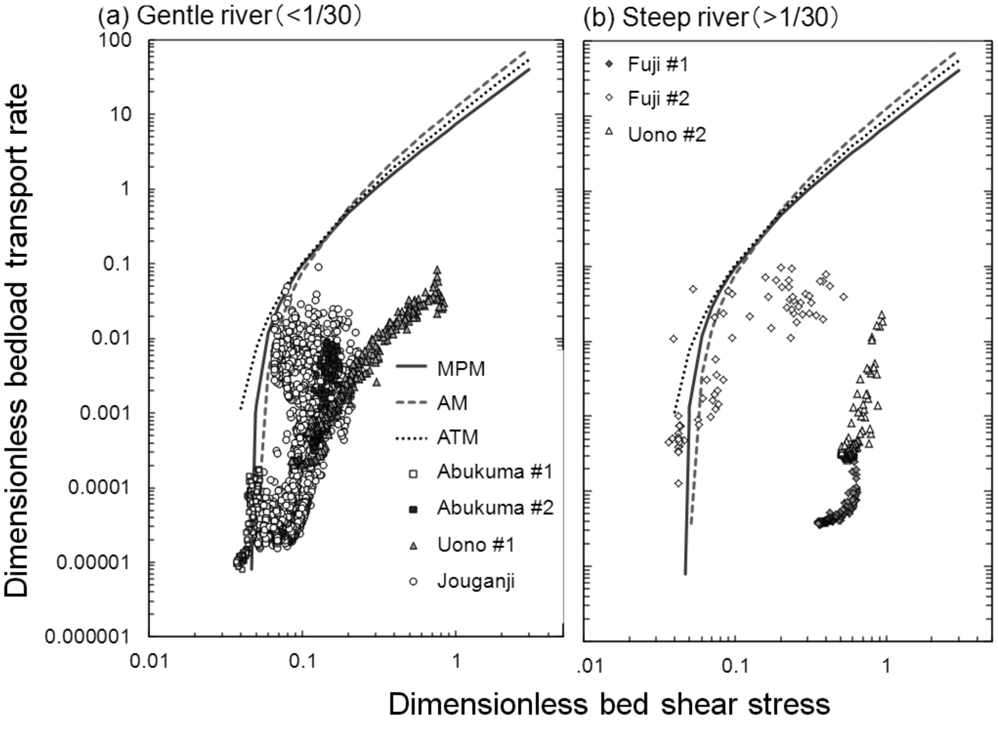

Fig. 9 - Relationship between dimensionless bedload transport rate evaluated by hydrophones and dimensionless bed share stress in mountain rivers of Japan: (a) gentle channel (gradient less than 1/30) and (b) steep channel. MPM, AM, and ATM indicate theoretical relationships between bedload transport rate and bed share stress proposed by M*EYER*-P*ETER* & M*ÜLLER (1948),* A*SHIDA* & M*ICHIUE (1972), and* A*SHIDA et alii (1978), respectively*

ing hydrophones) between dimensionless bed shear stress and dimensionless bedload transport rate in mountain rivers (Fig. 9). Furthermore, these relationships can vary temporally, even for the same station, e.g., Joganji #1 and Fuji #2 in Fig. 9. However, temporal variations in the relationship between bed shear stress and bedload transport rate were generally smaller than spatial variations.

At Abukuma #1 and Fuji #2, the relationship between bed shear stress and bedload transport rate was almost the same as theoretical relationships proposed by Meyer-Peter & Müller (1948), Ashida & Michiue (1972), and Ashida *et alii* (1978). In contrast, the bedload transport rate at Uono #2 and Fuji #1 was more than three orders of magnitudes smaller than the theoretical rate, assuming that representative bedload diameters as d60 of riverbed materials. However, in general, the bedload transport rate in gentle channels was close to the appropriate theoretical value.

DISCUSSION AND CONCLUSIONS

We have shown that use of a hydrophone and adoption of the integrated sound pressure method can evaluate bedload transport rate and bedload diameter successfully. In Yotagiri River, we observed preamplifier output at one-minute intervals using a data logger, and calibrated the data immediately after collection using a personal computer. Calibration according to the integrated sound pressure method took less than 1 min. Therefore, our system allows real-time monitoring of bedload transport rate and diameter.

While, based on the past disasters, it can be considered sediment discharge occurring in rivers near landslide areas just before the occurrence of large-scale landsliding (see Figs 1 and 2). Therefore, it is possible that our system could be used to obtain new information about sediment discharge before the occurrence of large-scale landslides (Fig. 10b). In the past disasters in Japan and Taiwan, there were relatively long time-lag between the waning based on the rainfall threshold and the lare-scale landslide occurrences (Fig. 10a). While, the time lags between sediment discharge and landslide occurrence were relatively short. So, these suggest that our system could contribute to improvements in early warning systems for large-scale landslides.

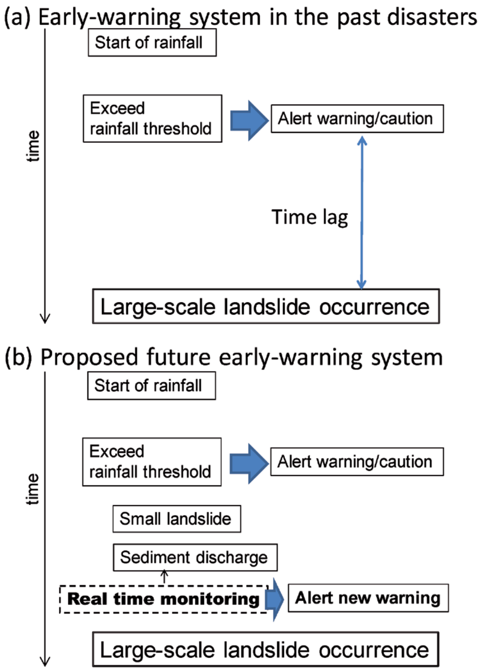

Fig. 10 - Schematic illustration describing early-warning system for large scale landslide

However, we feel that further research is necessary before the deployment of an early warning system that uses hydrophones. For example, it is important to clarify the types of changes in bedload transport that will occur owing to changes in sediment supply in upstream areas. Additionally, it is important to clarify the time lag between changes in sediment supply upstream and changes in bedload characteristics downstream.

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