Effects of Landslide and Forest Fire on Rainfall Threshold to Induce Bedload Discharge in Watershed in Republic of Korea

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In Korea, there are six sites that are using hydrophone (Japanese pipe microphone) developed in Japan. In this study, the rainfall threshold for the occurrence of bedload events was analyzed in forest disaster sites and control site. As a result, the total rainfall amount and the peak rainfall intensity among the rainfall characteristics were analyzed to be the best representations of bedload events. The difference between the bedload events and the rainfall threshold was clear in control site (normal forest), landslide site and forest fire site. In the control site, the rainfall threshold of bedload events was high, while the rainfall threshold of bedload events was low in the landslide and the forest fire site. In the forest fire site, the rainfall threshold of the bedload events was found to be higher after three years of forest fire damage. Therefore, an urgent soil erosion control work seems to be required to prevent the second damages in damaged forests.

Key words: bedload event, bedload monitoring system, forest disaster, hydrophone, rainfall threshold

1. INTRODUCTION

Recently, disaster management is important because natural disasters frequently occur due to global climate change, and disaster types have increased [*O'Brien et al.*, 2006]. Korea has four distinct seasons as it is located in the mid-latitude of the Northern Hemisphere and has cool-temperate climate. Also, it's dry and strong wind blows in spring and fall while most of rainfalls in summer because of the East Asian monsoon and continental climate. Though annual average rainfall is 1,200 mm or more, more than 60% falls in from June to September.

Such unique pattern causes two major forest disasters in Korea; landslide and forest fire. Forest fires do significant damage in spring. Over the past five years, on annual average, 486 forest fire cases occurred, damaging 593 hectare of forests on annual average. In 2017, there reported 692 cases, damaging 1,479 hectare of forests. The high temperature of forest fire changes the physical and chemical properties of the soil, and the plant was lost.

Therefore, soil erosion easily occurs due to the exposure of the hillslope, and the probability of occurrence of landslide and debris flow increased [*Lee et al.*, 2004; *Shin et al.*, 2013]. Also, the annual average of landslide-damaged areas keeps growing: it was 231 hectares in the 1980s, 349 hectares in the 90s, and 713 hectares in the 2000s [*KFS*, 2013].

In the case of Korea, various erosion control works have been carried out to rehabilitate forest disasters such as landslide and forest fire. Cases in point are constructing structures (like sabo dam), and planting vegetation. Related monitoring data such as the bedload discharge mechanism of the planning area are important for effective soil erosion work design and construction. Despite the fact that study on the bedload transport has continued for more than 100 years, there are still limitations in steep slopes such as mountain streams [*Tsutsumi and Laronne*, 2017]. Therefore, it is necessary to continue the study related to the bedload such as bedload transport, bedload discharge, bedload event, etc.

There are two types of methods to monitoring bedload transport; direct and indirect. Direct measurments for bedload transport is relatively accurate, though it requires human resources, time and cost, whereas the indirect method uses some hydrological data for calculation of the amount of sediment, which is less accurate, but more efficient in terms of human resources, time and cost. Besides, there are various monitoring methods related to the discharge of bedload from the watershed [*Itakura et al.*, 2005; *Arattano and Marchi*, 2008]. In the past, direct methods were used such as bedload and suspended load samplers.

Then, in Japan and Europe, we developed a device that can calculate the bedload discharge amounts using pulse and sound pressure when the soil collision [*Mizuyama et al.*, 2010; *Rickenmann et al.*, 2017]. Japan has developed hydrophone (Japanese pipe microphone) using acoustic sensors. Since hydrophone continuously monitoring changes in bedload events in watershed, it has the advantage of accurately analyzing the time of the occurrence of the debris flow in flood [*Uchida et al.*, 2018]. In addition, it can be important data to understand not only the bedload discharge amount but also the changes in the runoff in watershed characteristics and the mechanism of bedload transport due to rainfall characteristics.

Hydrophone developed in Japan was first installed in Korea in 2013. Since it is not possible to install hydrophone monitoring devices throughout the country, it was necessary to select representative monitoring sites. There are two objectives of monitoring. The first object is the test of effects of forest disasters on bedload discharge. So, we installed the system at watershed damaged by forest fire and landslide, and watersheds covered by undamaged forest. Second objective is the test of role of bedrock geology on bedload discharge. So, the systems were installed at three typical rock type areas in Korea, including igneous, metamorphic and sedimentary rocks.

There are many factors that affect the bedload transport, but the most direct cause of bedload event in Korea is rainfall. Therefore, this study analyzed rainfall characteristics of bedload events in landslide site, forest fire site and control site as beginning level of bedload monitoring study using hydrophone. In addition, this study was carried out to investigate the effect of forest damage on the rainfall threshold of bedload events. The results of this study are expected to be used as basic data to prevent secondary damage such as forest disasters management in Korea.

Fig. 1 Site photos of the bedload monitoring sites (A: Control site, B: Landslide site, C: Forest fire site)

2. MATERIAL AND METHOD

2.1 Device for bedload monitoring

In Korea, a bedload monitoring system using acoustic sensors developed in Japan was introduced in 2013 [*Seo et al.*, 2017]. This equipment is called Japanese pipe geophone, Japanese acoustic pipe, Japanese pipe microphone, etc. However, recent study has called hydrophone or Japanese pipe microphone [*Uchida et al.*, 2018]. In addition to hydrophone, there are slot sampler, water - level gauges, current meters, rain gauges, turbidity meters and CCTV in the bedload monitoring systems (**Fig. 1**).

2.2 Method of bedload monitoring

The hydrophone was installed in the spillway of the sabo dam and was expressed by the colliding number and the sound pressure that occur when the particles hit the steel pipe.

The slot sampler can be weight using the load cell sensors. It is also used for hydrophone calibration. The operation's principle of the hydrophone device installed in Korea was considered to be general because there are many precedent studies such as *Mizuyama et al.* [2010; 2011].

2.3 Study sites

The purpose of this study is to investigate the characteristics of bedload events in Korea's representative forest disaster sites through bedload monitoring. We selected one site for each of the typical forest disaster like landslide and forest fire sites in Korea. And for comparison, one site of the no disasters forest was selected as a control site (**Fig. 2**). **Table 1** shows the basic characteristics such as the watershed area of the study sites.

The bedload monitoring system was installed in the spillway of the sabo dam in downstream of each watershed.

2.4 Selection of effective data

In this study, the monitoring data for three sites were used for three years from 2014 to 2016, and data of missing such as machine defect were excluded from the analysis. Rainfall data were obtained from the tipping - bucket rain gauge at the downstream of each watershed (**Figs. 1**C and **2**). We thought rainfall measurements were appropriate because the watershed area was small and open terrain. In addition, rainfall more than 1 mm per hour was selected as effective data for the analysis of bedload events and rainfall characteristics, and the same rainfall event was considered when rainfall persisted.

We analyzed the characteristics of rainfall when bedload transport started. The starting point of bedload transport was regarded as the time when the change of the load-cell or hydrophone pulse (ch. 1024) started. This study applied the most sensitive channel because it is a study of rainfall thresholds at which bedload transport starts.

Table 1 A general situation of study sites

	Control site	Landslide site	Forest fire site
Monitoring started year	2014	2014	2014
Watershed area	142 ha	283 ha	25 ha
Country rock	Igneous rock	Igneous rock	Igneous rock
Forest physiognomy	Mixed Forest	Mixed Forest	Mixed Forest
Age class	6	5	4
Occurrence date	-	2012	Mar. 2013
Affected area	-	> 0.1 ha [a]	10 ha
Remarks	Non-damage	Small slope failure every year	Reforestation in Apr. 2014

[a] Recovery area at the time. So, it was estimated to be at least that much.

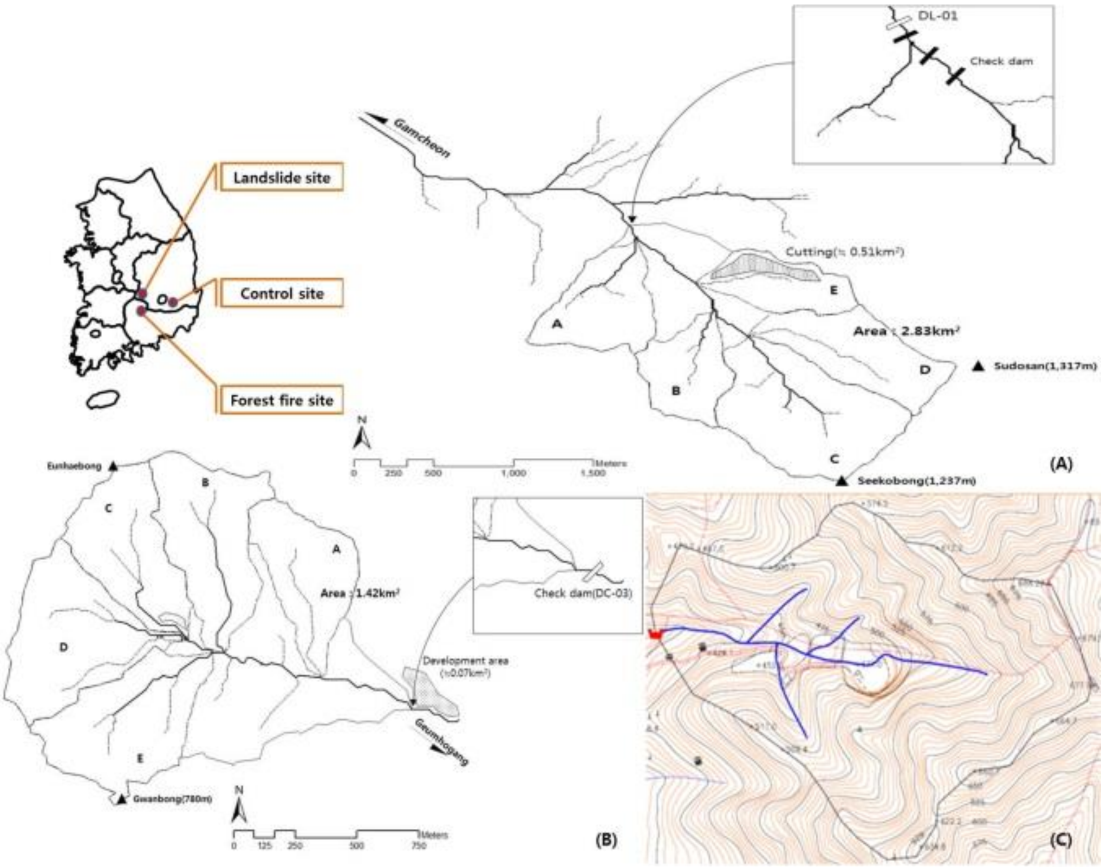

Fig. 2 Location of the study sites (A: landslide site, B: control site, C: forest fire site, Blue triangle: location of bedload monitoring system)

For the analysis, data from control site (Non-bedload events - 69, Bedload events - 19), landslide site (Non-bedload events - 41, Bedload events - 15), and forest fire site (Non-bedload events - 24, Bedload events - 31) were used.

Badoux et al. [2012] showed the rainfall threshold of bedload events (large, small) using rainfall intensity and rainfall duration. Similarly, in this study, the analysis showed that total rainfall amount and peak rainfall intensity were used to characterize rainfall condition to induced bedload discharge. So, for bedload events, we clarified the total rainfall amount and peak rainfall intensity until the start of bedload discharge. While, for non-bedload events, we used the total rainfall amount and peak rainfall intensity of given rainfall event.

3. RESULT AND DISCUSSION

3.1 Relation between bedload events and rainfall threshold

The total rainfall amount and peak rainfall intensity were plotted for bedload events and non-bedload events at the all sites. **Fig. 3** shows the relationship between total rainfall amount and peak rainfall intensity for the bedload events and non-bedload events in each study site. The difference rainfall threshold to induce bedload discharge between control site (no disaster forest), landslide site and forest fire site were clear. In all sites, when the rainfall condition was smaller than that of red line, most of events did not produce bedload events. In contrast, once rainfall magnitude exceeded red lines, most of events induced bedload discharge.

The rainfall threshold (red line) in the forest disaster sites (landslide, forest fire) was smaller than that of the control site. So, the rainfall threshold (red line) for control site in X and Y axes are 28 mm and 16 mm/hr, respectively. While, those in landslide site and forest fire site were 18 mm – 5 mm/hr and 5 mm – 4 mm/hr, respectively. The rainfall threshold in forest fire site was smaller than that of landslide site.

Although rainfall condition was the same, but the occurrence of sediment discharge was differed. For example, in **Fig. 3**, the orange line was also drawn under the same rainfall conditions at all three sites to clarify difference of occurrence of sediment discharge. In the control and landslide sites, even if the orange line was exceeded, there were both the bedload events and the non-bedload events. While, in the forest fire site, except for one rainfall condition, it was observed that the bedload events occurs when the orange line was exceeded.

These results indicate that the bedload started even in small rainfall condition in the forest disaster sites, suggesting that landslide and forest fire gave an impact on the rainfall threshold on bedload discharge. Moreover, the difference between landslide site and forest fire site indicates that effects of forest damage on rainfall threshold differed according to the types of damage and the affected area. Therefore, similar to previous studies by Johansen et al. [2001], Lee et al. [2004] and Seo et al. [2016], it can be thought that it is important that not only the prevention of direct damage caused by landslide and forest fire, but also the prevention of secondary damage such as soil erosion.

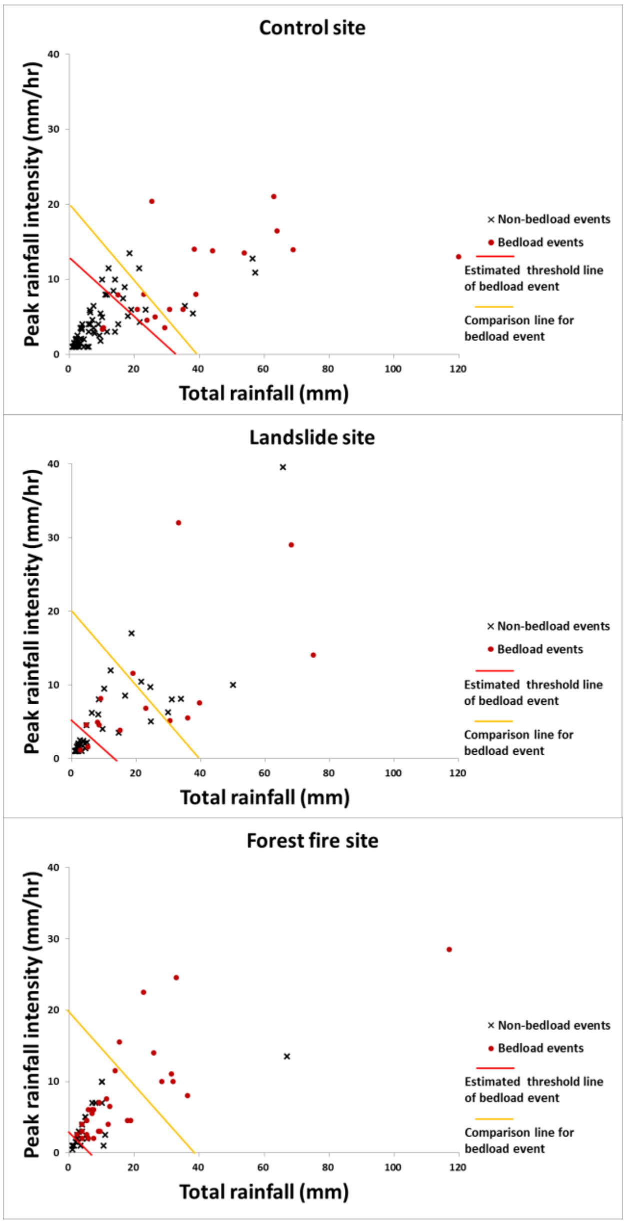

Fig. 3 Relation between the bedload events and rainfall condition in study sites

3.2 Annual changes of bedload events and rainfall threshold

In this chapter, bedload events and non-bedload events were marked by year to find out how long effects of landslide and forest fire disaster continue. In addition, the point of this study is the rainfall threshold to induce bedload discharge. So, we focused on this and lowered the graph scale (Total rainfall amount ≤ 40 mm, Peak rainfall intensity ≤ 15 mm/h). Because there were cases where data such as mechanical defects of the field monitoring system were missed, it was difficult to make a clear comparison of time series analysis such as annual change and seasonal change. However, the results of marking the annual change with available data were showed in **Fig. 4**.

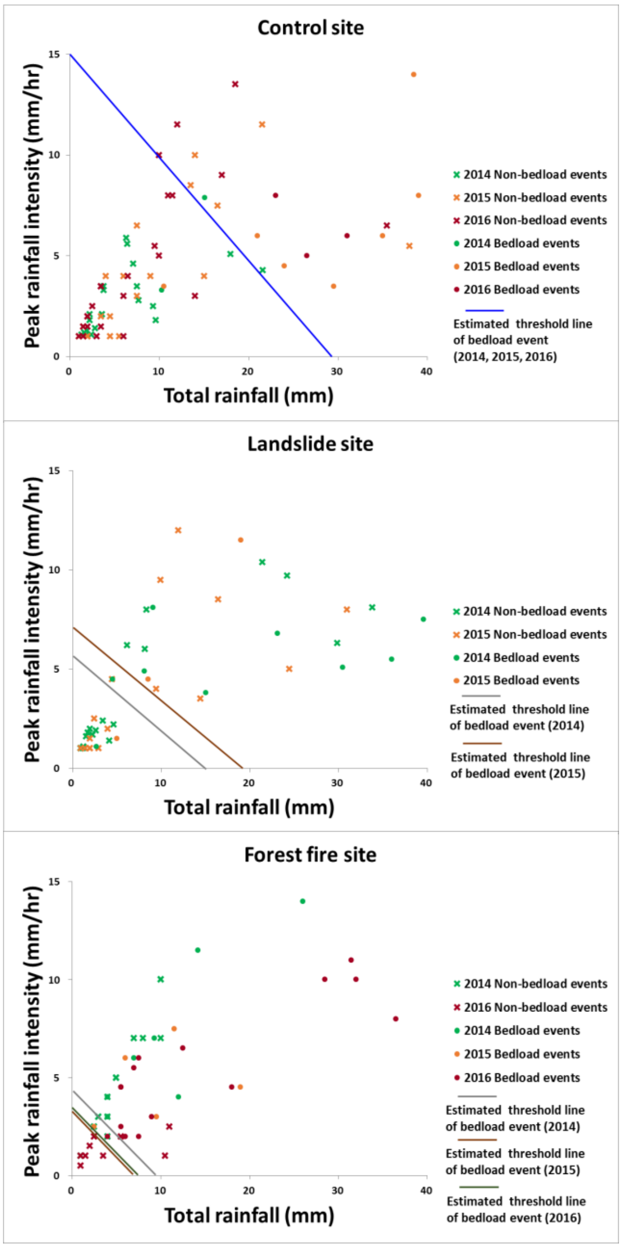

Fig. 4 Annual change of bedload events and rainfall threshold in study sites

Since the control site was a healthy forest without any forest disaster, there were no temporal change in rainfall threshold from 2014 to 2016 in control site.

The forest disaster sites were similar to the control site, the annual change in rainfall threshold in forest disaster sites. From this result, we considered that the effects of landslide and forest fire prolonged several years and effects of disaster on rainfall threshold did not change at least few years after the disasters.

3.3 Seasonal changes of bedload events and rainfall threshold

There are four seasons in Korea: spring, summer,

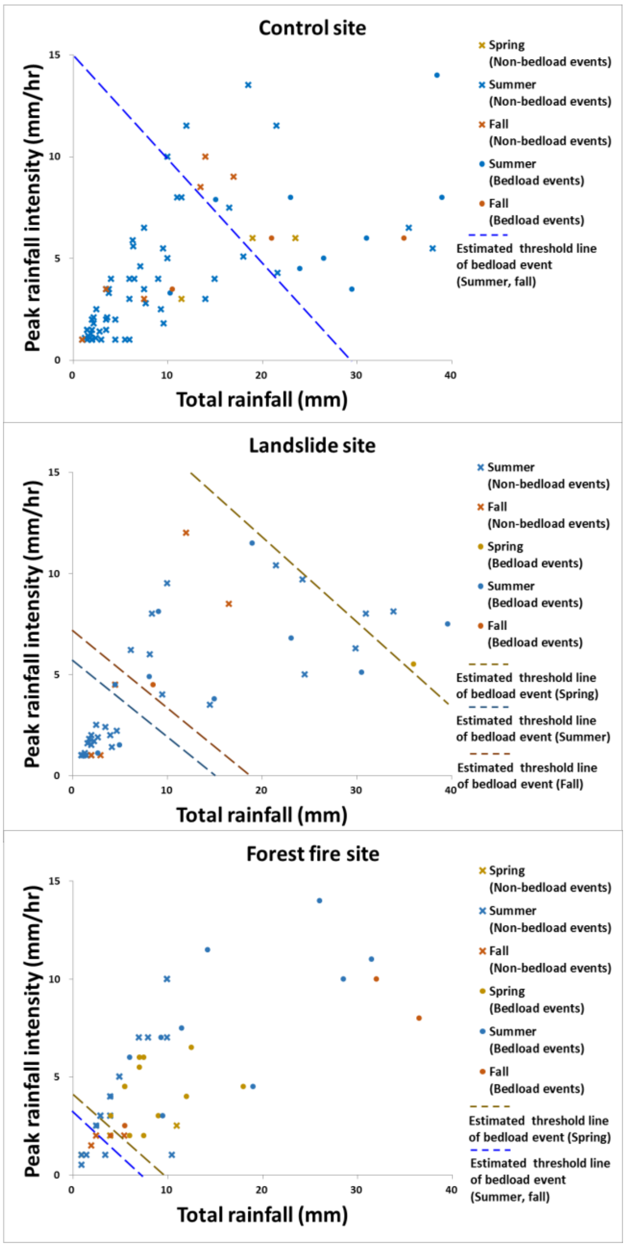

Fig. 5 Seasonal change of bedload event and rainfall threshold in study sites

fall and winter. In spring (Mar. to May) and fall (Oct. to Nov.), dry climatic conditions cause many forest fires. During the rainy season (Jun. to Sept.), which is often affected by heavy rainfall and typhoons in the summer, a landslide and debris flow occurs most of the time. Therefore, seasonal effects need to be considered to understand the threshold of bedload events and rainfall condition in Korea. For example, it can be thought that during the summer, since a lot of sediment yielded on damaged hillslope due to heavy rainfall, so, sediment deposition in riverbed might be increased. If so, rainfall threshold should become small. While, in summer periods, sediment discharge might be larger than sediment input from hillslope. In this case, the sediment availability should decrease, thus, rainfall threshold becomes large.

In **Fig. 5**, the bedload events and non-bedload events were marked according to each season. There is no clear difference in rainfall threshold in terms of seasons, regardless of forest disasters. This suggests that there is no seasonal change in sediment availability. Although there are several possible explanations about this result, it can be thought that the sediment transport capacity due to flood is no so large, thus, still a lot of unstable sediment caused by landslide and forest fire deposited in riverbed in forest damaged watershed. This well agrees with the prolonged effect of forest damage on sediment discharge argued in the previous section.

4. CONCLUSION

In Korea, there are six sites that are using a hydrophone (Japanese pipe microphone) developed in Japan. There are two objectives of monitoring. The first object is the monitoring of effects of forest disasters on bedload discharge. So, we installed the bedload monitoring system at watersheds damaged by landslide and forest fires, and watersheds covered by undamaged forest.

In this study, the rainfall threshold for the occurrence of bedload events was analyzed in forest disaster sites and control site. As a result, the total rainfall amount and the peak rainfall intensity among the rainfall characteristics were analyzed to be the best representations of bedload events. The difference between the bedload events and the rainfall threshold were clear in control site (no disaster forest), landslide site and forest fire site.

In the control site, the rainfall threshold of bedload events was high, while the rainfall threshold of bedload events was low in the landslide and forest fire sites. Compared with the control site, the forest disaster sites showed bedload events even in the low rainfall conditions of about 10 - 23 mm in the total rainfall amount and 11 - 12 mm/hr in the peak rainfall intensity. Therefore, it was thought that landslide and forest fire gave an impact on the rainfall threshold on bedload event. Especially, in the forest fire site, bedload events occurred even in the lowest rainfall conditions. In addition, it was found that most bedload events occurred when the rainfall condition exceeded the orange line.

In analysis of seasonal effects, rainfall events and bedload events were the most frequent in the summer, the rainy season of all sites. Also, the most bedload events occurred in the summer. Because many sediments yielded on damaged hillslope by heavy rainfall, and rainfall threshold was decreased due to increased sediment deposition in the riverbed.

Therefore, an urgent soil erosion control work seems to be required to prevent the second damages in forest disasters. It is expected that a larger database will increase the reliability of this result, and will help better understanding of the soil erosion control works and the bedload transportation mechanism.

REFERENCES

Arattano, M. and Marchi, L. (2008): System and sensors for debris-flow monitoring and warning, Sensors, Vol. 8, No. 4, pp. 2436-2452.

Badoux, A., Turowski, J. M., Mao, L., Mathys, N. and Rickenmann, D. (2012): Rainfall intensity–duration thresholds for bedload transport initiation in small Alpine watersheds. Natural Hazards and Earth System Sciences, 12, pp. 3091-3108.

Itakura, Y., Inaba, H. and Sawada, T. (2005): A debris-flow monitoring devices and methods biliography, Natural Hazards and Earth System Sciences, Vol. 5, No. 6, pp. 971-977.

Johansen, M.P., Hakonson, T.E. and Breshears, D.D. (2001): Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands, Hydrological Processes, No. 15, pp. 2953-2965.

KFS (Korea Forest Service) (2013): 2013 Main business plan detail (in Korean).

Lee, C.W., Lee, C.Y., Kim, J.H., Youn, H.J. and Chol, K. (2004): Characteristics of soil erosion in forest fire area at Kosung, Kangwondo, Journal of Korean Forest Society, Vol. 93, No. 3, pp. 198-204 (in Korean with English abstract).

Mizuyama, T., Hirasawa R., Kosugi, K., Tsutsumi, D. and Nonaka, M. (2011): Sediment monitoring with a hydrophone in mountain, International Journal of Erosion Control Engineering, Vol. 4, No. 2, pp. 43-47.

Mizuyama, T., Laronne, J.B., Nonaka, M., Sawada, T., Satofuka Y., Matsuoka, M., Yamashita, S., Sako, Y., Tamaki, S., Watari, M., Yamaguchi, S. and Tsuruta, K. (2010): Calibration of a Passive Acoustic Bedload Monitoring System in Japanese Mountain Rivers, U.S. Geological Survey Scientific Investigations Report 2010-5091, pp. 296-318.

O'Brien, G., O'Keefe, P., Rose, J. and Wisner, B. (2006): Climate change and disaster management, Disasters, Vol. 30, No. 1, pp. 64-80.

Rickenmann, D., Antoniazza, G., Wyss, C.R., Fritschi, B. and Boss, S. (2017): Bedload transport monitoring with acoustic sensors in the Swiss Albula mountain river, Proceedings of the International Association of Hydrological Sciences, No. 375, pp. 5-10.

Seo, J.P., Jung, Y.G., Lee, K.H., Lee, C.W., Kim, D.Y., Uchida, T. and Iuchi, T. (2017): Current condition and future challenges of sediment transport monitoring system in Korea, Japan Society of Erosion Control Engineering, Vol. 69, No. 5, pp. 71-74 (in Japanese with English abstract).

Seo, J.P., Lee, C.W., Kim, D.Y. and Woo, C.S. (2016): Estimating of annual sediment yield at mountain stream in fire/landslide damaged forest by using terrestrial LiDAR spatial analysis, Journal of Korean Society Hazard Mitigation, Vol. 16, No. 6, pp. 219-227 (in Korean with English abstract).

Shin, S.S., Park, S.D. and Lee, K.S. (2013): Sediment and hydrological response to vegetation recovery following wildfire on hillslopes and the hollow of a small watershed, Journal of Hydrology, 499, pp. 154-166.

Tsutsumi, D. and Laronne, J.B. (2017): Gravel-bed rivers (Processed and disasters), Wiley Blackwell, pp. 798.

Uchida, T., Sakurai, W., Iuchi, T., Izumiyama, H., Borgatti, L., Marcato, G. and Pasuto, A. (2018): Effects of episodic sediment supply on bedload transport rate in mountain rivers. Detecting debris flow activity using continuous monitoring, Geomorphology, doi: 10.1016/j.geomorph.2017.12.040.