The Application of Monitoring and Early Warning System of Rainfall-Triggered Debris Flow at Merapi Volcano, Central Java, Indonesia

Teuku Faisal Fathani and Djoko Legono

Abstract The 2010 Mt. Merapi eruption has produced approximately 140 million m^3 of pyroclastic deposit, in which more than 10 million m^3 deposits are potential to move downstream through Boyong/Code River towards Yogyakarta City. The flow behavior of Code River may be affected by the presence of accumulated sediment at the upstream of the river (namely Boyong River). By rainfall trigger, this potential source can cause debris flow disaster that may contribute damage to the settlement areas in Yogyakarta City. This paper presents the application of monitoring and early warning system to mitigate the impact of debris flow disaster along Boyong/Code River as revealed by most adaptive, low cost, and collaborative-based technology. The real-time monitoring equipment consists of automatic rainfall recorder, automatic water level recorder, debris sensor, and interval camera. The system was developed by considering the community aspiration in determining the types and placement of monitoring equipment, and maintaining its sustainability. The information flow of the proposed early warning system has been introduced accordingly. The central station receives the results of the real-time monitoring and the information through radio communication from the focal points located along Boyong/Code River. Afterward, the warning alert is sent to focal points and the debris flow monitoring radio. This newly built system is expected to be integrated with the monitoring system of other volcanic rivers at Merapi Volcano.

Keywords Volcanic debris flow · Real-time monitoring · Early warning system · Community preparedness

T. F. Fathani (✉) · D. Legono
Department of Civil and Environmental Engineering, Universitas Gadjah Mada,
Jalan Grafika No. 2, Yogyakarta 55281, Indonesia
e-mail: tfathani@gmail.com

F. Wang et al. (eds.), *Progress of Geo-Disaster Mitigation Technology in Asia*, Environmental Science and Engineering, DOI: 10.1007/978-3-642-29107-4_13,

1 Introduction

Mt. Merapi is one of the most active volcanoes in Indonesia. It has a long history of frequent eruptions with avalanche type pyroclastic flows caused by collapsing lava mass. Mt. Merapi eruption induced pyroclastic, tephra, laharic flow, and debris flooding have often occurred with a cycle of approximately 9–16 years for larger scale flows and 1–3 years for smaller scale ones. During the eruption period, Mt. Merapi produces a large number of sediment volumes which can move downstream in various mechanisms, such as through natural flow by bed load transports and debris flows, and flow through human-related activities by sand mining (Wardoyo et al. 2010).

It was reported that the 2006 Mt. Merapi eruption (from April through October 2006) had produced approximately 8 million m^3 of sediment, which has high potential to move downstream towards the southern part of the mountain (Legono et al. 2008). Meanwhile, the 2010 Mt. Merapi eruption (from 25 October through 2 December 2010) produced approximately 140 million m^3 of pyroclastic deposit toward the southern and western part of the mountain (Legono et al. 2011a). Since then, the volcanic debris flow has caused severe damage to the inhabitants and residents living on the foot slopes. Figure 1 shows the Merapi volcano before and after 2010 eruption.

Due to 2010 Mt. Merapi eruption, a large number of sediment is deposited at the upstream of several volcanic rivers, hence the secondary disaster in term of rainfall-induced debris flow may occur in a long period. The presence of river bends also increases the possibility of inundation in some river flood plains in the city area or may create a new stream, causing significant damage to various infrastructures and settlements. Figure 2 shows the collapsed bridge at the west side of Mt. Merapi, while the damage on houses is shown in Fig. 3. These damages were due to the destructive power of rainfall-induced debris flow. Considering the large deposit accumulation in the upstream part of volcanic rivers, there is a necessity to monitor the hydraulic and hydrology parameters, which may be used to predict the occurrence of debris flow. The monitoring results can be used for both anticipating the debris flow disaster and developing the criteria of rainfall characteristics induced debris flow for early warning system. Therefore, both types of monitoring, i.e. historical and real-time, are very much needed.

2 Debris Flow at Boyong/Code River

The distribution of pyroclastic flow towards the southern part of Mt. Merapi appears dominantly in Boyong/Code River in which the 1994 Mt. Merapi eruption hit the upstream part of the river severely. Since then, several numbers of sediment control structures were built to ensure that Yogyakarta City would be sufficiently safe from debris flow disaster. There are 41 sabo dams provided with river training structures such as groundsills and retaining walls along Boyong River.

Fig. 1 Merapi volcano before the 2010 eruption

Fig. 2 Collapsed bridge due to the destructive power of rainfall-induced debris flow

The 2010 Mt. Merapi eruption is predicted to contribute more than 10 million m^3 pyroclastic deposits on the upstream (Legono et al. 2011a). By rainfall trigger, this potential source can cause debris flow occurrence that may contribute damage to the settlement areas at the surrounding Boyong/Code River in Yogyakarta City (Fig. 4). Although local communities in this area have been experiencing various flood disasters, such preparedness of flood disaster by means of debris flow is far beyond sufficient because such debris flow phenomenon is a very rare case. Such insufficient preparedness was found on 29 November 2010 afternoon, where the first flood after the 2010 Mt. Merapi eruption occurred. The flood carried various materials from fine sediment to coarse sand, but no boulder was found. The sediment was assumed to be originated from dust particles fallen in the catchment area of Boyong/Code River and accumulation of sediment in the upstream of Boyong/Code River (Fig. 5). In fact, local communities have initiatives to anticipate the debris flow disaster by identifying the debris occurrence at the upstream part of the river.

Fig. 3 Damage on houses near the volcanic river

Apparently, during the days after 29 November 2010, increase in rainfall intensity occurred, triggering a more intensive debris flow that caused significant damages in several infrastructures at some rivers (Pabelan River and Putih River). Fortunately, no casualty was reported. However, the damage of important infrastructures such as roads, bridges, paddy fields, and settlements was very significant. A hyper-concentrated flow in Boyong/Code River occurred several times that made the local people evacuate themselves (Fig. 6).

3 The Characteristic of Rainfall-Induced Debris Flow

Rainfall plays an important role in contributing the possibility of massive soil mass movement both in the form of debris flow and landslide. In many occurrences of debris flow or landslide, rain contribution can be in the form of heavy rain (commonly expressed in rain intensity, in mm/h), or relatively long rain (which is expressed in time unit of hour). Depending on the characteristic of soil mass movement, usually defined as soil mass stability (function of mass density, shear strength characteristic, soil water content, soil embankment shape, etc.), the rain intensity and duration will trigger the process of debris flow occurrence.

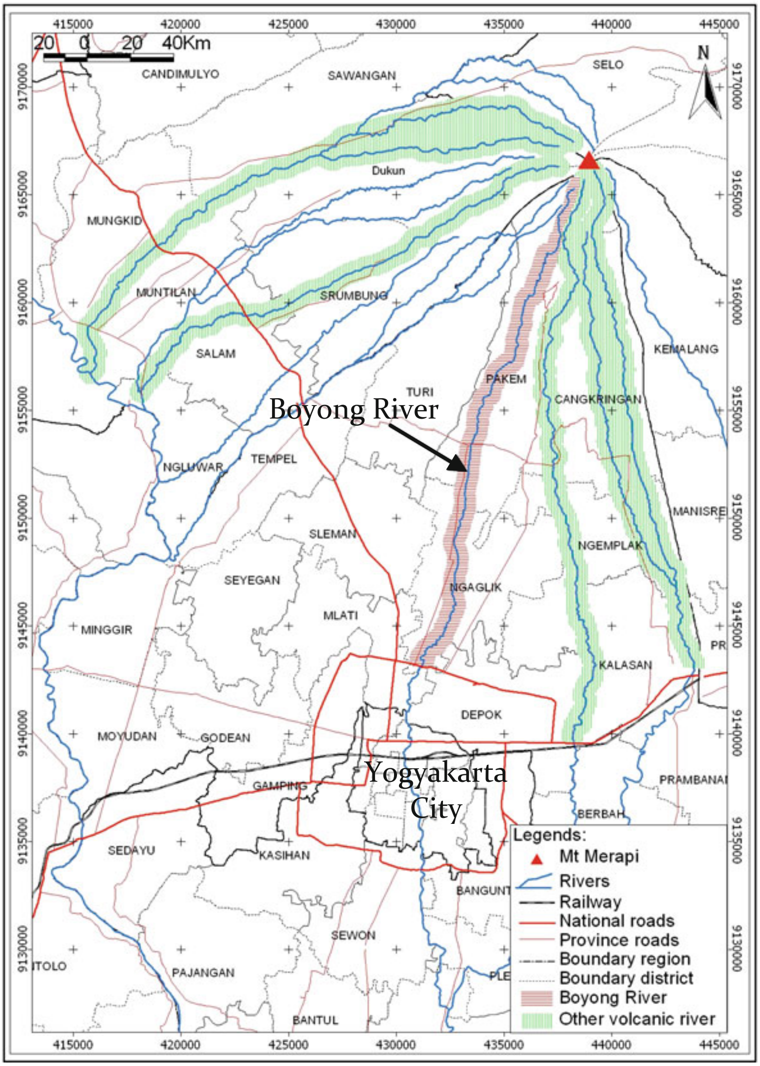

Fig. 4 Volcanic rivers toward southern and western part of Mt. Merapi which have potential impact of debris flow. Boyong River is directed toward Yogyakarta City and change the name to Code River

Three different approaches might be used to develop criteria of debris flow occurrence as described by MLIT (2004), i.e. based on the information of relationship between the rainfall intensity and rainfall accumulation, rainfall intensity and antecedent rainfall, and rainfall intensity and the soil moisture. As an illustration, before 2010 Mt. Merapi eruption, the criterion used as a sign of possibility of debris flow occurrence in the upstream of volcanic rivers at Mt. Merapi area was rainfall with intensity of 25 mm/h (Takahashi 1991) or 50 mm/h with the duration

Fig. 5 Upstream condition of Boyong River: Sabo dam BOD4 on 14 January 2011

of more than 2 h (Legono et al. 2008). However, at the present, after the 2010 Mt. Merapi eruption, the criterion changes due to the position of the sediment, in which instability increases significantly due to a large number of very loose granular materials forming a very steep slope formation upstream. Such condition may cause debris flow occurrence even in rainfall intensity of less than 50 mm/h and duration of less than 2 h. Based on two events on lahar flow occurrence at Kali Putih on 9 January and 23 January 2011, the rainfall intensities at upstream were 9 mm/h for 2 h duration and 40.9 mm/h for 2 h duration.

In order to obtain historical and real-time information, the rainfall monitoring should show rainfall intensity value in mm/h. Similarly for debris flow, as the wave propagation of debris flow is very fast (e.g. 3–5 m/s order), the monitoring of water elevation in stream should have very high accuracy, e.g. at 1.00 cm, with a reliably short frequency, e.g. every 10 s, particularly if such equipment is dedicated for the development of early warning system.

As the flow monitoring system will be transferred into discharge information (in volume units per unit time), the rating curve establishment, which represents the correlation between the water depth and the discharge, should be conducted and updated periodically. The necessary calibration is a part of “rule of thumb” of each system development; therefore, it is an obligatory requirement.

Fig. 6 Downstream condition of Code River: Jogoyudan area in the Yogyakarta City on 30 November 2010

4 Early Warning System Against Debris Flow

At the moment, the development process which considers reliable sustainability is the involvement of community participation in a form of highly local self-assessment, planning and action (Wisner 2006). In this development of debris flow early warning system, a collaborative-based process is introduced (Legono et al. 2011b). Although it is similar to community involvement process, the term "collaborative" is used to emphasize that community together with local government should be involved in solving a problem, i.e. debris flow early warning.

The collaborative-based debris flow early warning system of Boyong/Code River was developed with the following process.

(a) Public consultation meeting on Boyong/Code River debris flow (the people living along the Code River requested information on debris flow occurrence).
(b) Determination of key persons (hereinafter referred as focal point: FP) whose task is to receive the earliest news on debris flow phenomenon by SMS blasting.
(c) Construction and installation of integrated monitoring equipment (water elevation sensor, pendulum, camera interval) and its socialization to focal points.

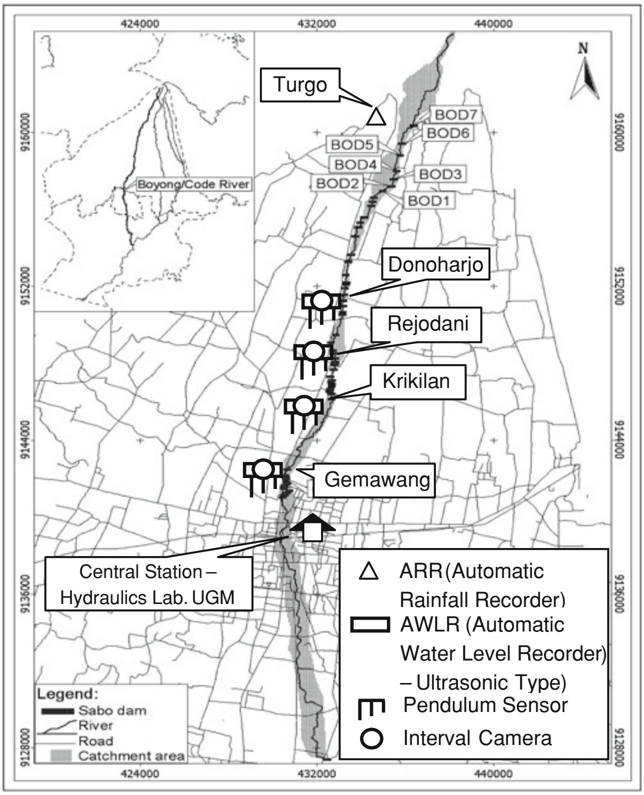

Fig. 7 The proposed location of the instrument for debris flow monitoring and warning system at Boyong/Code River

Figure 7 shows the proposed location of the instrument for debris flow monitoring and early warning, i.e. one real-time Automatic Rainfall Recorder (ARR) at Turgo, four sets cross-sectional monitoring system (comprising one real-time Automatic Water Level Recorder-AWLR, one real-time debris sensor, one interval camera) at Donoharjo, Rejodani, Krikilan, and Gemawang. A central station was set up in the Hydraulics Laboratory, Department of Civil and Environmental Engineering of Universitas Gadjah Mada which further addresses in maintaining the sustainability of the system.

Figure 8 shows the information flow of the proposed early warning system. Rainfall station in Turgo and cross-sectional monitoring system in four locations along Boyong River will transmit the result of real-time monitoring to the central station. In addition, the central station also receives information through radio communication from the focal points who monitor debris flow visually. After analyzing the received data, the central station then sends a warning alert to focal points located along Boyong/Code River and to the debris flow monitoring radio of 149.940 MHz. This warning can be sent automatically by the system or trigged

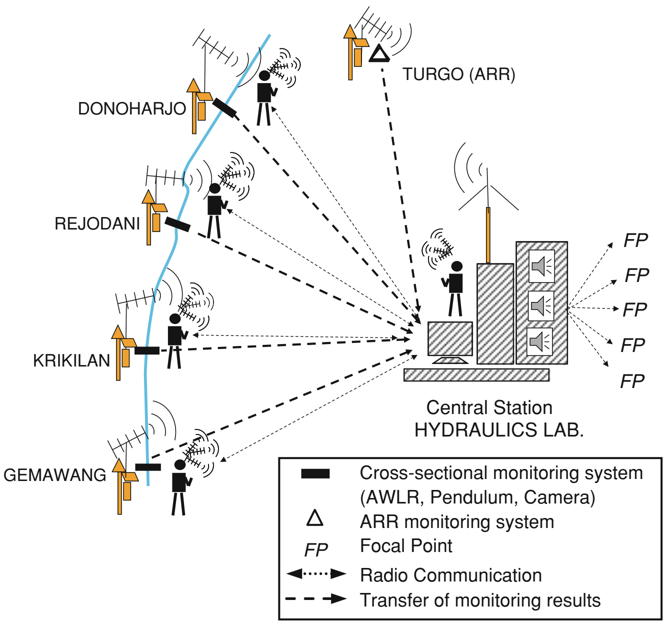

Fig. 8 Proposed information flow for monitoring and early warning of debris flow at Boyong/ Code River

manually by the operator. The system built in Boyong/Code River is expected to be integrated with the monitoring system of other volcanic rivers at Mt. Merapi area.

Figure 9 shows the current warning system pursued by the community at surrounding Code River. The community living near the river has tried to carry out debris flow monitoring with the simplest way. Based on the previous experience, "caution" and "evacuation" elevation are marked on the river slope protection; hence, they can decide the right time to evacuate. The presence of integrated debris flow early warning system indeed helps the community to increase their awareness and preparedness in facing the disaster.

As shown in Figs. 7 and 8, the ideal version of early warning system against debris flow in Boyong/Code Rivers may comprise water level monitoring system at four locations, i.e. Donoharjo, Rejodani, Krikilan, and Gemawang, and provide with the pendulum type sensor to confirm the high degree of flow, i.e. the flow depth equal to 1.50, 2.25, and 3.00 m. In addition, one additional interval camera was also installed to confirm the flow occurrence visually. The sequence of alert should be arranged in such that the debris flow propagation time is sufficiently long to issue the warning that gives significant benefit to community, so that they have sufficient time to take necessary actions for evacuation.

Furthermore, the establishment of collaborative-based debris flow early warning system consists of the following process:

Fig. 9 Existing community warning alert in anticipating debris flow

(a) Installation of interval camera on the river side, accompanied by the local people (the installation was witnessed by the local people who are also members of an NGO, Jalin Merapi. At the same time, local people awareness and aspirations were studied).
(b) After the installation, the data on the river flow was collected for several days, and a collaborative review of the data was then conducted (the local people saw the benefits and asked for a higher specification, not the historical/logger type, but the real-time one).
(c) The development and installation of equipment were carried out taking into account community aspiration, at least types and locations (the local people showed the best location for the installation. Also, due to the necessity on the early debris flow monitoring, the local people avail facilities such as electricity accessibility and key-persons for the socialization of the equipment function and their maintenance).

Due to the insufficient budget, only the Automatic Rainfall Recorder (ARR) in Turgo and the Automatic Water Level Recorder (AWLR) in Rejodani were then established in the beginning of 2011. Figures 10 and 11 show some readings obtained from the installed ARR in Turgo and AWLR in Rejodani, respectively.

Automatic Rainfall Recorder (ARR) in Turgo recorded rainfall intensity every 6 min in the logger and then sent the data to the central station by radio telemetry. Rainfall intensity over 50 mm/h occurring between 14:00 and 16:00 PM on 13 May 2011 can be monitored from the website (Fig. 10). With this information, focal points should increase their awareness on the possibility of debris flow occurrence in the downstream.

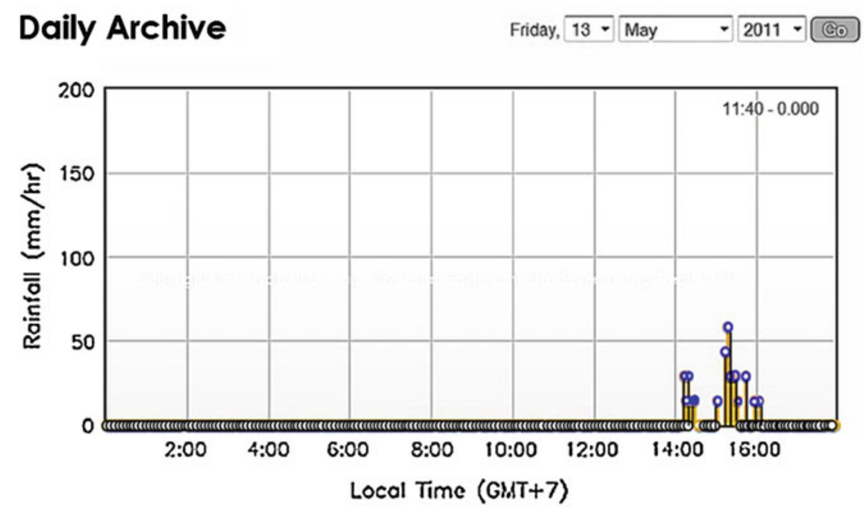

Fig. 10 Example of online reading obtained from Turgo ARR monitoring system

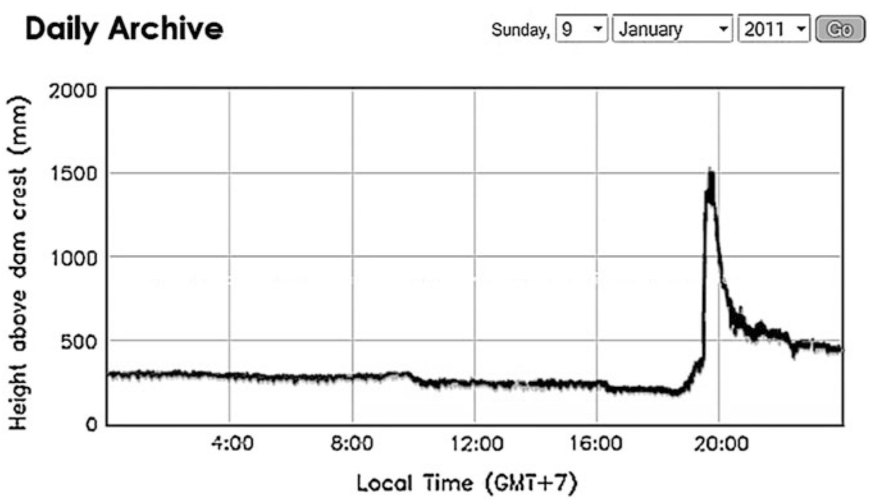

Fig. 11 Example of online reading obtained from Rejodani AWLR monitoring system

In Fig. 11, the rising of the flow monitored by the ultrasonic equipment every 15 s is shown real-time on the website. On 9 January 2011, the water elevation to dam crest rose from 39 to 130 cm in only 20 s. Further study should be carried out to determine the time needed for the debris to reach Yogyakarta City and the elevation of the flow in the downstream.

Figure 12 shows the cross-sectional monitoring system at Rejodani. Ultrasonic monitoring equipment, interval camera, and three different levels of pendulum are

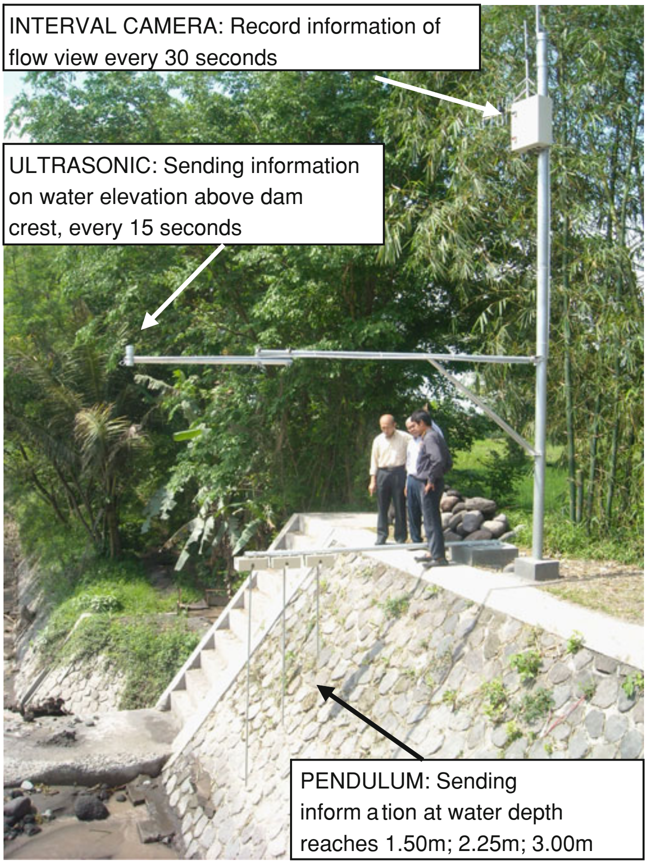

Fig. 12 Cross-sectional monitoring system at Rejodani

placed in one river cross-section. This system transfers the monitoring results regularly to the central station. The whole system was built by prioritizing most adaptive and least cost technology. Through this system, a debris flow monitoring system of Boyong/Code River for community at Yogyakarta City is implemented. This monitoring system is easy to replicate for rivers threatened by debris flow disaster at the surrounding of Mt. Merapi area.

5 Conclusions

The monitoring on hydrology and hydraulic parameters (including debris flow and rainfall characteristic) should be carried out with consideration to the physical phenomenon laws of the parameters. Information from the monitoring results should be quantitative and complimentary to the existing system. Both the historical logger type and the real-time monitoring system are necessary for further study in determining rainfall and debris flow characteristic for warning criteria. Collaborative-based debris flow early warning system is considered more sustainable as community understands the value of the information they receive. However, support from the local government is still required. More integrated and effective application in the future is still vastly needed, including completion of monitoring system along Boyong/Code River and also the integration of this system to the others debris flow monitoring at Mt. Merapi area. Further establishment of Standard Operating Procedure utilizing the established early warning system in collaboration with the local community is considered important. By this mechanism, such effort in maintaining its sustainability will be gained.

References

Legono D, Rahardjo AP, Fathani TF, Prabowo IE (2008) Development of community-based early warning system against debris flow at Mt. Merapi Indonesia. In: Proceeding of the first world landslide forum, 18–21 Nov 2008, Tokyo, Japan, pp 404–406

Legono D, Prabowo IE, Karnawati D, Fathani TF, Rahardjo AP (2011a) Lahar flow disaster monitoring and mitigation based on community collaboration. In: Proceeding of symposium Merapi, 21 Feb 2011, Yogyakarta, Indonesia pp 11–16

Legono D, Prabowo IE, Fathani TF, Karnawati D, Rahardjo AP (2011b) Development of collaborative-based lahar flow early warning system for Code River at Yogyakarta City. In: Proceeding of international seminar on water related risk management, 15–17 July 2011, Jakarta, Indonesia

Ministry of Land, Infrastructure and Transport—MLIT (2004) Development of warning andevacuation system against sediment disasters in developing countries, Guidelines for constructiontechnology transfer, Infrastructure Development Institute, Japan

Takahashi T (1991) Lahar flow—monograph. IAHR, AA Balkema, Rotterdam, The Netherlands

Wardoyo W, Legono D, Fathani TF, Jayadi R (2010) Pyroclastic deposit characteristics of volcanic rivers and its affect to the transport mechanism. In: Proceeding of IAHR-APD international seminar, 21–24 Feb 2010, Auckland, New Zealand

Wisner B (2006) Self-assessment of coping capacity: Participatory, proactive and qualitative engagement of communities in their own risk management. Measuring vulnerability to natural hazard. United Nations University Press, Tokyo, pp 316–328