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Integrating X-MP radar data to estimate rainfall induced debris flow in the Merapi volcanic area

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ABSTRACT

After the 2010 eruption, more than 50 volcanic debris flow (lahar) events occurred during the rainy season of 2010–2011 at Mount Merapi, Indonesia. The lahars occurred following rainfall of severe intensity in the upstream area, where remaining volcanic material was deposited. Estimation of rainfall-induced lahars at Mt. Merapi is difficult and uncertain because the upstream area is dangerous and inaccessible. On 17 February 2016, a lahar occurred in the upstream region of the Gendol River on the southeastern flank of Mt. Merapi after a maximum rainfall intensity of 69 mm/h was monitored on the peak of Mt. Merapi by X-band multi-parameter (X-MP) radar. In this study, rainfall intensity estimates from X-MP radar were applied to generate boundary discharge of a numerical model of debris flow at the catchment scale. The numerical simulation was able to estimate volcanic debris flow occurrence and magnitude. The reliability of radar-rainfall data and the effects of the sabo dam on reducing the impacts of lahar disaster were also examined. The numerical lahar simulation showed relevant results that were comparable to the real condition. The closed type sabo dam caused more than 50% lahar sediment decrement and a flow delay time of 40 min. However, the sediment accumulation has caused increasing flow velocity and higher erosion rate in the 2D area. This study demonstrated the effectiveness of remote monitoring of rainfall combined with numerical debris flow modeling for applied practical use in disaster management.

1. Introduction

Mt. Merapi (7.40° S, 110.4° E) in Indonesia is one of the most active and dangerous volcanoes in the world. The 2010 eruption was the largest since the beginning of the 20th century, and the following secondary lahar disaster resulted in the deaths of almost 400 people (Pallister et al., 2012; Surono et al., 2012).

The word “lahar” is a Javanese term, which is defined as a rapidly flowing, high-concentration, poorly sorted sediment-laden mixture of rock debris and water from a volcano that is usually triggered by rainfall. It is a continuum flow type that includes debris flows, hyperconcentrated streamflows, and mudflows (Lavigne et al., 2007; Neall, 1976). Typically, lahar flows enter a river valley at a velocity of 2.5–11 m/s (Lavigne et al., 2007).

Studying lahar behavior is important because of the complex mechanisms and disastrous impacts of lahar events. Some numerical models have been developed to estimate rainfall-induced lahar flows and their destructive impacts (Castruccio and Clavero, 2015; Jones et al., 2017; Lee et al., 2015; Procter et al., 2010). However, field application of these models has two main problems. The first is that lahars usually occur at elevations higher than 1200 m amsl (Legowo, 1981), whereas most rainfall monitoring instruments are available at lower elevations. The second problem is that lahars following an eruption are usually initiated in an area that is relatively inaccessible and dangerous, making direct verification difficult. These problems cause uncertainty of debris flow and lahar analysis based on measured rainfall data (Nikolopoulus et al., 2014; Staley et al., 2013).

Recent studies have shown the effectiveness of remote monitoring, such as by weather radar, for debris-flow estimation and risk management. Weather radar provides finer spatial and higher temporal resolution, which is desirable for debris-flow and lahar studies. It offers the advantage of being able to monitor rainfall in the area where lahars initiate (Chiang and Chang, 2009; David-Novak et al., 2004). Marra et al. (2014) confirmed that the scarcity of rain gauges has

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resulted in underestimation of the rainfall threshold for debris flow occurrence, but weather radar performs well for monitoring debris flow occurrence during short-duration convective storms.

Currently, two X-band multi-parameter (X-MP) radars monitor the rainfall condition in the Merapi volcanic area (MVA). However, their application for lahar estimation has not been well established because previous systems relied on rain gauge data (Lavigne et al., 2007; Lavigne et al., 2000a). Studies on utilizing weather radar data are also few and have focused mostly on determining the rainfall threshold for debris flow occurrence (Chen et al., 2007; David-Novak et al., 2004; Marra et al., 2014).

This study examined the effectiveness of remote monitoring by X-MP radar with a numerical model for measuring debris flow in the field. The rainfall intensity estimated from X-MP radar was used as the triggering forcing in the boundary condition of the numerical model (HyperKANAKO) for debris flow simulation in the MVA. HyperKANAKO is a graphical user interface (GUI) debris flow model developed by Nakatani et al. (2012). The model based on hydrologic and hydraulic processes following Takahashi model for debris flow. In this paper we simulate a lahar event on 17 February 2017 in Gendol River by first, discusses the reliability of radar-rainfall data and second examines the performance of the numerical model for lahar countermeasure management.

2. Lahar early warning system in the Merapi volcanic area

Lahar events are one of the major disasters in the MVA; therefore, the government of Indonesia developed an early warning system (EWS) for lahar disaster preparedness prior to 1970 (Hardjosuwarno et al., 2013; Lavigne et al., 2000b). The system consisted of wire sensors that crossed the perimeter of the river at the height of 1 m from the river bed that could calculate the velocity of any lahar. Radio communication was used to send pertinent information to residents. During the continuation of the system, it was equipped with a movie camera for recording lahar events. A lahar warning was issued if the flow was large enough to break the wire(s). However, some large lahar events did not break the wire because of their diluted concentration (Lavigne et al., 2000b).

In 1980, remote monitoring was begun by introducing a radar rain gauge (RRG) system. This system covered an area of 60 × 80 km and had three observational modes (maximum, normal, and enlarged image). The best data were obtained by the enlarged mode, which defined a minimum observation area of 20 km W–E × 15 km N–S that was divided into a 4000 mesh grid (250 m × 300 m). However, the radar could not consistently provide continuous rainfall data compared to the performance of the rain gauge (Shuin et al., 1996) and was reported to have functioned for only one week because of a data storage problem (Lavigne et al., 2000b).

A telemetry system consisting of an automatic rainfall recorder (ARR), automatic water level recording (AWLR) devise, and seismometer was installed during 1980–2000. The seismometer detects ground vibrations from lahar events and is connected by the US Geological Survey Volcano Crisis Center (USGS VCAT) for data processing instrumentation.

In 2010, the centennial eruption of Merapi destroyed most of the lahar monitoring instruments. During the recovery, the Sabo Works Agency (Balai Sabo) installed the new generation of X-MP radar to replace the RRG. The radar measures Doppler velocity and transmits an electromagnetic signal at a frequency of 9.345 GHz. It covers a radius range of 90 km, and its X-band radar specifications are a 3 cm wavelength and short-range distance (Hardjosuwarno et al., 2013).

In 2015, the Science and Technology Research Partnership Sustainable Development Program (SATREPS) project installed another X-MP radar that uses a wavelength of 3.3 cm closer to the summit of Mt. Merapi (8.7 km). The radar has a 150 m mesh spatial and 2 min temporal resolution. It is designed to monitor not only the rainfall condition but also some of the volcanic material ejected from the volcano during an eruption. Table 1 provides the specifications of this radar.

Table 1
X-MP radar installed in the MVA by the SATREPS project.
Source: Furuno, Compact X-band dual polarimetric doppler, WR-2100 information brochure

Parameter	Description
Transmitter	Solid state 200 W per channel (H,V)
Polarity	Dual polarimetric horizontal (H) and vertical (V)
Pulses	PRF 600–2500 Hz, Width 0.1–5.0 μs
Antenna	1086 mm Φ, 2.7° beam width
Antenna gain	33.0 dBi
Operating frequency	9.47 GHz
Wavelength	3.3 cm
Scan mode	PPI, CAPPI, RHI
Resolution of distance	Maximum of 50 km
Maximum range fixed observation level	30 km
Data output	Reflectivity intensity – Z_h [dBz], Differential reflectivity – Z_{dr} [dB], Doppler velocity – V_D [m/s], Doppler velocity spectrum width – σ_{VD} [m/s], Specific differential phase shift – K_{DP} [°km^{-1}) Correlation coefficient between two polarizations – ρ_{HV}, Rainfall intensity – R [mm/h], Cross polarization difference phase – Φ_{DP}

3. Study area

The study area was the Gendol catchment and Gendol River, which are located on the southern flank of the MVA. The Gendol catchment suffered the effects of the 2010 eruption as most of the volcanic material from the pyroclastic flow was deposited in this area (Wardoyo et al., 2013). The Gendol catchment has an area of 58.07 km^2, and the length of the main river is 21.73 km. Before the 2010 eruption, the average riverbed slope of the Gendol River was about 0.12°, but the slope was increased just after the eruption. The riverbed slope deformation also changed the sediment transport process, such that high-concentration flows can extend as far as 12 km from the summit of Mt. Merapi (Wardoyo et al., 2013). To year 2016, according to our interviews and direct visit in February 2016, volcanic materials remain at elevations higher than 1200 m amsl and the temperature is still warm.

The monitoring system in this catchment includes 10 tipping bucket automatic rainfall recorder (ARR) telemetry systems, separated by an average distance of 5 km, and two automatic water level recorders (AWLRs) equipped with a CCTV camera to record flood and lahar occurrences in the downstream area ($<$350 m amsl). The ARR distribution and a map of the study area are presented in Fig. 1. The rainfall in the upstream region of the Gendol catchment should be represented by ARR-Kaliadem (Baru) station. However, during the lahar event on 17 February 2016, the ARR did not report any rainfall due to technical problems. These technical problems have occurred frequently and have constrained the use of ARR data in lahar estimation requiring continuous rainfall data. Table 2 shows a summary of the data availability at the 10 ARRs in the Gendol catchment.

4. Materials and method

4.1. Materials

This study combined a semi-distributed model of rainfall runoff with a numerical model of debris flow to estimate lahar occurrence