THE POTENTIAL OF LAHARIC FLOWS DISASTER ALONG GENDOL AND OPAK RIVERS, YOGYAKARTA, INDONESIA

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Abstract

Gendol River flows from the south slope of Merapi Volcano meets Opak River to form a wider river, namely Opak River. In the upper stream of Opak and Gendol Rivers area, volcanic material accumulated from the 2010 Merapi Volcano eruption that ready to flow downstream through both rivers. The total amount of volcanic material in the Merapi's peak area is predicted as much as 140 million cubic meters, part of it is distributed in the upper stream of both rivers. In the downstream area, the Opak River flows nearby the great Prambanan Temple and across the main road of Yogyakarta-Surakarta capital cities.

To know the laharic flow disaster potential of both rivers, collecting of primary data along the river flows is needed in order to understand the characteristic and mechanism of *laharic flows*. DEM analysis combined with ArcGIS 9.3 tools are applied to know the additional volume of volcanic material after 2010 Merapi Volcano eruption. The triggering factor of *laharic flows* in the study area including the *runoff*, soil water saturation rate, rainfall and soil water saturation time are mathematically calculated based on data analysis on soil mechanics.

Based on the calculation of thickness and distribution in the Merapi Peak area, the mass volcanic material that is ready to be transported as the *laharic flows* through Gendol and Opak Rivers is around 14,745,496 m^3. The volcanic material can transform into *laharic flows* by initial runoff if the soil water saturation column reach at least 5.96 m. With the rainfall average in the southern part of Merapi Volcano is 17.32 mm/day, that saturation value can be reached by 21.8 hours in the upper stream area and 17.67 hours in the lower part area. If the *laharic flows* occurred, the damage would happen in villages along the rivers, Prambanan Temple, and Opak River's Bridge connecting Yogyakarta-Surakarta main road.

Keywords: Gendol-Opak Rivers, Laharic Flows, Water Saturation Column, Rainfall

Introduction

Gendol and Opak Rivers flow on the southern flank, with upper reaches on the peak of Merapi Volcano. Both rivers flow southward and meet at the Ringinsari Village, become a bigger stream known as the Opak River, flows and passes the Prambanan Temple Area and the main road connecting Yogyakarta-Surakarta (Figure 1, insert Figure). The Merapi Volcano (2,965 m) is well known as one of the most active volcano in the world, situated at the border line between Central Java and Yogyakarta Special Provinces, Indonesia, with a bell shape topography and the volcano's peak coordinate of 7.542°S / 110.442°E [1]. Yogyakarta, the capital city of Yogyakarta Special Region, is located 30 km to the south of Merapi Volcano, with dense population and settlements spread up to the Merapi slope at the elevation of around 1,700 m high and just about 4 km to the mountain peak.

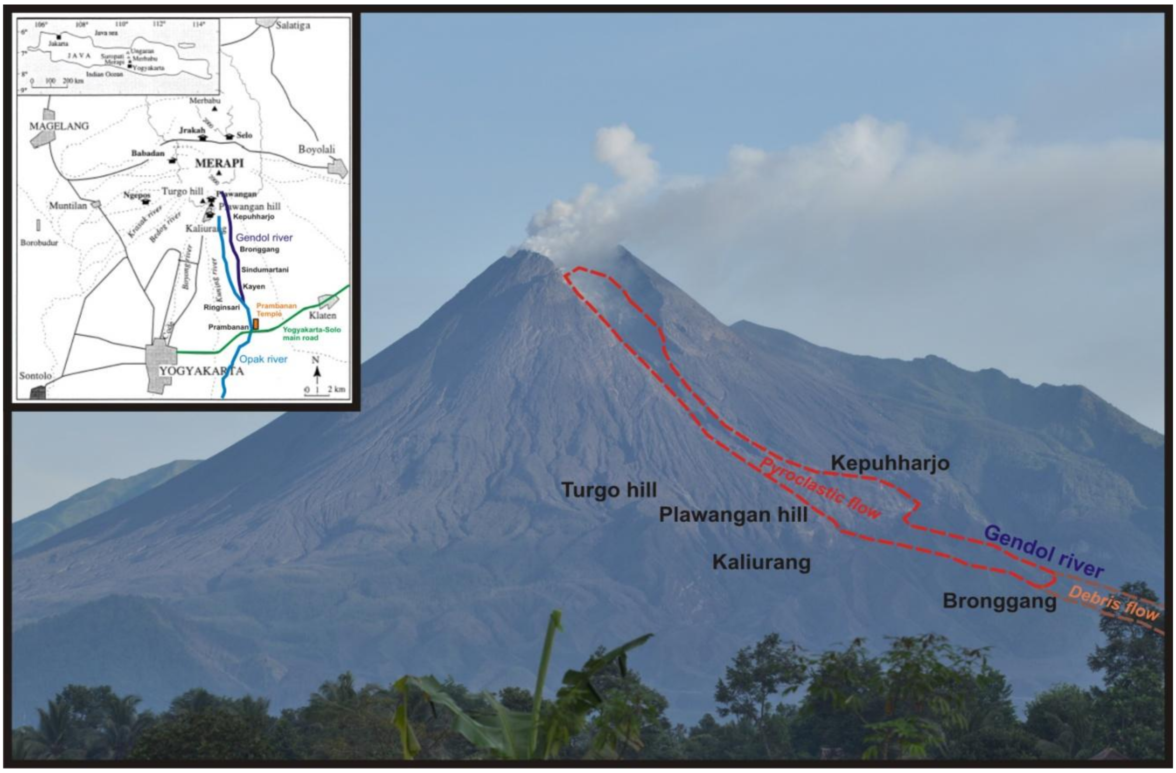

Figure 1. Phanoramic of Merapi Volcano after 2010 eruption. Pyroclastic flow was blew to the south through Gendol River reached up to Bronggang Village, around 14 km distance from the crater. Insert figure is location of Merapi Volcano in Yogyakarta Region Photograph was taken from northern Yogyakarta

Merapi Volcano eruption on October 26th – November 7th, 2010 expelled a total volume of pyroclastic materials around 140 million m^3 and placed mostly on the peak area [2]. A huge explosion on 5th November caused the collapse on the southern part of border crater. As the result, a vast amount of pyroclastic materials were deposited on the southern and south western slope of Merapi Volcano. Today, the accumulation of volcaniclastic deposit is a potential source of *laharic flows* disaster to the southern slope of Merapi. Such disaster has already occurred on rivers flowing to southwest – west directions; among them are Pabelan and Putih Rivers, which causes many losses and damages [3,4]. The similar disaster may also happen to Opak River, which is at the proximal zone on the southern part of Merapi's peak. A potential *laharic flows* through Opak River is considered threatening Prambanan Temple, which is located in the lower part of Opak River near Yogyakarta, including settlements and the main road access in Central Java. Prambanan temple is the biggest Hindu temple in Indonesia built in the 9th century and was pointed as UNESCO World Heritage Site.

Considering to the high potential damaging due to laharic flows, disaster mitigation need to be done in order to avoid victim and fatal destruction. Objectives of this paper are to know the factors of *laharic flows* in Opak and Gendol Rivers, including material and processes. Runoff mechanism as the initial process of laharic flow and the time need for happening runoff become main focus of discussing. By understanding the mechanism and characteristic of *laharic flows* that may happen along Opak and Gendol rivers area, mitigation and aid in hazard preparedness can be done effectively and accurately.

Methods and Data

Focusing on the stream of Gendol and Opak Rivers, this research took place from the upper stream to lower part, in Prambanan Temple area, near Yogyakarta-Surakarta main road. This research initiated by collecting secondary data and theory on characteristics of Merapi deposit, mechanism of *laharic flows,* and factors controlling the *laharic flows* disaster on the Merapi's flanks. Remote sensing interpretation was done utilizing satellite image, DEM, and topographic map scale 1:10,000. DEM image analysis is used to know the elevation changing in the research surrounding area. It was obtained from the previous research conducted in proximal area of Merapi Volcano [5,6]. Data on rainfall and hazard zone map of Merapi Volcano was obtained from BPPTK (Volcanological Technology Research and Development Agency) Yogyakarta [2].

Primary field data was collected along Opak dan Gendol Streams, started from Prambanan area (distal zone) up to Kepuhharjo Village (proximal zone). Data analysis was performed both qualitatively and quantitatively. Result of those two analyses were combined with secondary data in order to synthesize conclusion which is then used as a basis of mitigation of *laharic flows* disaster. During data retrieval, checking of engineering construction along the stream, such as sabo dam, artificial bank, bridges, and disaster area were also carried out. Interview with local peoples around the streams was also conducted.
Laboratory analysis was conducted to obtain physical properties of volcaniclastic sediment deposited by *laharic flows*. Samples were then grouped based on sampling locations. Qualitative analysis was carried out by predicting *laharic flows* mechanism based on sediment characteristic, river morphology, slope, and laharic deposit succession. Quantitative analysis was performed by calculating volume of volcanic material which is possibly become laharic source. Deposit thickness is known by comparing DEM before and after the 2010 eruption, while coverage area of deposit is obtained from ArcGIS 9.3 calculation on upstream of Gendol River. Number of run-off needed to generate movement volcanic material (Ro), saturation rate (V), total rainfall rate (T), Rainfall intensity (R,I) and time required by deposit to saturated (t), were calculated based on soil mechanics data of Merapi deposit in the proximal area. Those numbers can be formulated as follow:

$$R = \sqrt{\frac{Ro \times T}{0{,}954\left(\frac{D}{\sqrt{A}}\right)^{0{,}55}}} \;;\; R = I \;;\; V = 90\% \times K \times I \;;\; t = \frac{sedimentary\ thickness}{V}$$

with: Ro = runoff ; R, I = rain intensity minimum ; T = total rainfall rate ; V= saturation rate ; D = elevation difference ; K = infiltration coefficient ; A = laharic spread area ; t = time required deposit to be saturated

Process and Product of Merapi Volcaniclastic Deposits

In 2010, Merapi Volcano has a great series of eruption, starting on October 26th, followed by several eruptions that gradually decrease in intensity and totally stop on December 3rd. The biggest eruption happened on November 5th, which generated column eruption type. Center of Volcanology and Geological Hazard Mitigation (PVMBG) estimates that the material removed from the Merapi 2010 eruption is approximately 140 million m^3 accumulated at the top and mostly distributed to the south and west of Merapi's peak.

The characteristic of Merapi eruption is explosive, producing pyroclastic deposits at the peak following with generating dome on top, flank collapse, and sometimes generates pyroclastic flow and hot avalanche (*nuee ardente*). Huge eruption occurred at least once in every 1000 years. The last major eruption before 2010 occurred in 1872 which was the Vulcanian-subplinian eruptions type with VEI: 4 [7]. The authors referred the terminology of volcaniclastic deposit to all volcaniclastic products, formed during and after the volcanic activity, which are: pyroclastic, resedimented volcaniclastic deposit (syn-eruptive product), and volcanogenic sedimentary deposit (post eruptive product after weathering, erosion, reworking and re-sedimentation) [8]

Volcaniclastic deposit on the upper stream of Gendol River, the main channel of volcanic material during eruption in 2010, consists of sand- to boulder-size material. At the most upper stream area, volcaniclastic deposit was resulted by the pyroclastic flows, where the maximum distance can reach Bronggang Village, about 14 km from the crater (Figure 1). In Kepuhharjo area, about 6 km from the peak, pyroclastic flow deposits were dominant (Figure 3A), determined by large boulders, floating within sand- to gravel-size matrix, intercalated by volcanic ash or sometimes occur boulder of charcoal. Towards downstream area, deposits gradually change from debris flow to normal flow. Debris flow deposits are well-identified also in Kepuhharjo area, characterized by the large abundance of boulders, poorly sorted, and less amount of matrix (Figure 3B). While at Bronggang and Sindumartani area, these deposits were composed by boulder-size materials (in diameter >64 mm) found in large dimension. Compare to pyroclastic flow deposit, Bronggang and Sindumartani area have greater amount of sand-size material, with subrounded to rounded clast texture, than in Kepuhharjo. Laharic flows extend to the east and had destroyed several houses in Bronggang area, about 11 km from Prambanan Temple. This situation happened because the sabo dam could no longer hold volcanic materials carried by the *laharic* flows.

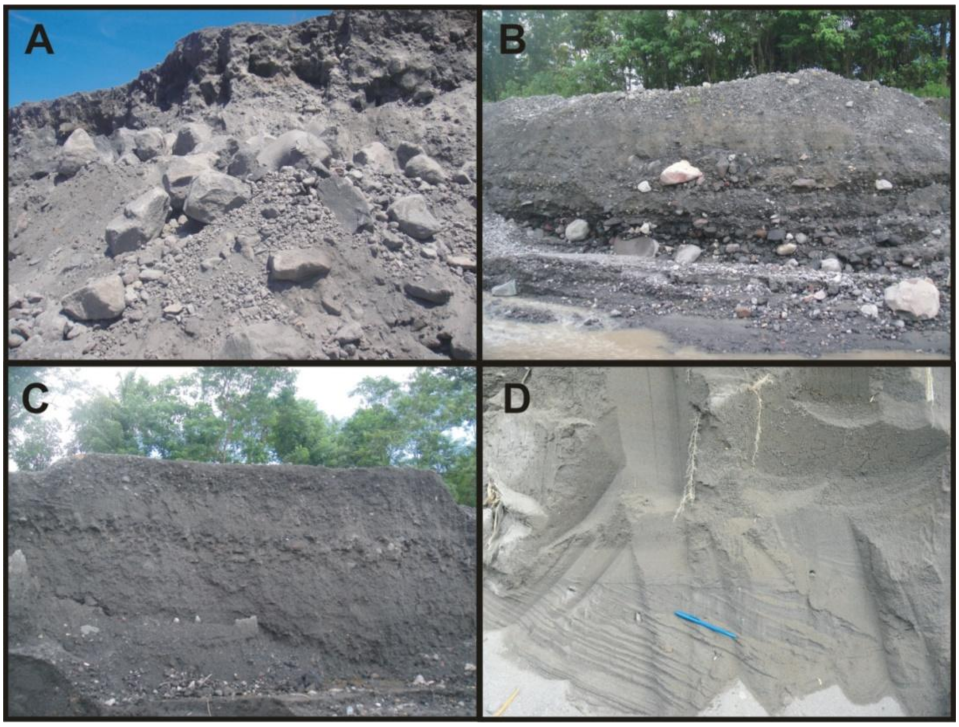

Figure 3. Characteristics laharic deposit along Gendol and Opak Rivers

A. Boulder-size pyroclastic deposit in Kepuhharjo, upper part of Gendol River
B. Debris flow deposit in Bronggang area, the farthest area reached by pyroclastic flows of 2010 eruption
C. *Hyperconcentrated* flow deposit in Kayen area, Gendol River
D. Normal stream flow deposit in Ringinsari, Opak River, showing *trough cross-stratification* sedimentary structure

Further to the south, the *laharic flow* was dominated by *hyperconcentrated flow*, indicated by floating boulder within fine-size matrix (Figure 3C). The granulometry analysis for this samples mentioned that the grain size distribution is ranging from fine grains (clay to coarse sand: 50%) to very coarse grain (granule to pebble: 50%), mixed together and has very poorly sorted texture (Figure 2). Dilution process has higher mobility to transport sediment resulting *hyperconcentrated flow* deposit further to distal area [9]. Towards downstream area, the angle of slope is lower and river valley become wider.

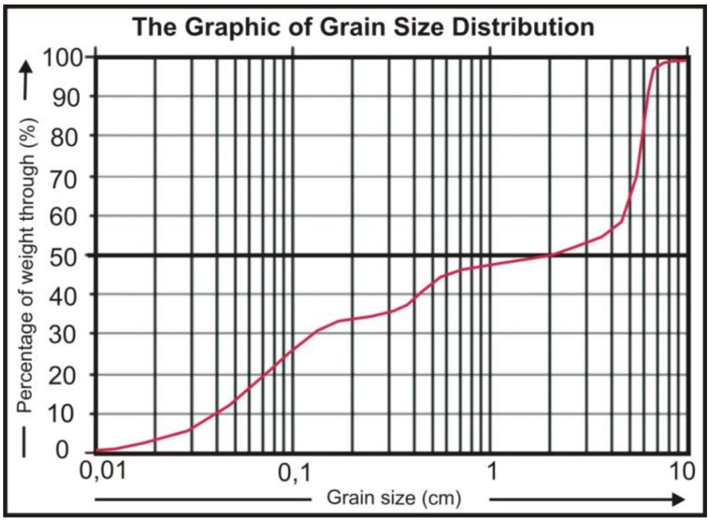

Figure 2. Grain-size distribution of Merapi deposit in the upper part of Gendol River, indicate mixture of clay to gravel-size sediments

Gendol River flows to south direction and merged with Opak River in Ringinsari area, 5 km north of Prambanan Temple. Opak River is a typical parenial river with upper stream at Krajan, Cangkringan, which is the proximal zone of Merapi. Characteristic of deposit in the lower stream shows less *laharic flows* deposit, generally finer grain size, even at the spill out flood area. In some higher elevation on the river bank, fluvial deposits indicated normal flow with typical of *trough cross-stratification* (Figure 3D).

Terminology of *lahar* originally comes from Javanese language that was introduced into scientific term by van Bemmelen in 1949 [10], referring to debris flow sedimentation mechanism composed of volcanic material as well as deposits from that kind of flows. The *laharic flows* is destructive if the flow contains huge volume of volcanic material. Along the volcanic slope is where most intensive erosion and anything that blocks the flow will be easily broke down [9]. In the case of *laharic flows* along rivers on the slopes of Merapi, the vertical erosion rate can reach over 10 meters [4].

For the Merapi Volcano case, *laharic flows* are derived from different flank of volcanoes, usually caused by long term heavy rainfall, mainly as pyroclastic deposits [9]. Three main factors that trigger *laharic flow* at Merapi are 1. millions cubic of pyroclastic deposits resulted during 2-4 years interval, 2. high intensity of rainfall (average rate 40 mm during 2 hours) during the rainy season from November to April, and 3. very dense drainage pattern [9]. Empirical events of *laharic flows* generally occur a few minutes after heavy rainfall.

The critical time of laharic flow initiation is when the runoff begins, in other word, when the soil is water saturated and rain can no longer infiltrate into the soil. Toth [11] mentioned that when rainfall (P) reach lithosphere, it will be transformed into evapotranspiration (ET), runoff (R) and infiltration (I), which is formulated into P = ET + R + I. This empirical formula also proved that runoff may occur if there is no infiltration (I=0) due to water saturated soil. Based on the laboratory soil mechanical analysis for Merapi volcaniclastic deposit in study area, the runoff will happen if saturated water zone thickness of deposit reach around 234.65 inch (5.96 m).

Time required for deposit to be saturated, both in upper stream and lower part, is obtained by applying the equation mentioned in Methods and Data. Parameters of this equation are: slope, rainfall rate, and area coverage. Slope itself is D/√A, where D is elevation difference and A represents area. In this study, the slope is calculated from topographic map of study area, with average value 38.75% on the upper stream and 19.9% on the lower part. Infiltration Coefficient (K) equals 1 – C, where C represents runoff coefficient, which is the sum of coefficient of several surface conditions C = Ct+Cs+Cv [12]. Each several surface condition has its own value referring to the assessment in Table 1. The upper stream has empiric slope >20% categorized as mountainous and Ct = 0.26, while slope on the lower part is <20% categorized as hilly and Ct = 0.16. As for soil consists of sand and gravel with no vegetation covering on both area, value of Cs and Cv are also same, 0.04 and 0.28, respectively. By substituting those numbers into the equation, the value of K on the upper stream is 0.42 [1-(0.26+0.04+0.28) = 1 - 0.58] and 0.52 on the lower part. Saturation rate (V) is formulated as V = 90% x K x I, where I is rain intensity minimum. Based on the rainfall data in the Merapi area and surroundings [2], it is known that average rainfall rate in the rainy season (October – April) is 17.32 mm/day, with maximum rainfall can reach around 160 mm/day (Figure 4), therefor saturation rate on the upper part is 6.55 (V = 90% x 0.42 x 17.32) and 8.10 on lower part.

Time required for deposit to be saturated (t) is water saturated soil (5,96 mm) divided by its saturation rate (V). On the upper stream, (t) is reached in 0.91 day or 21.8 hours and on the lower part needs only 0.73 day or 17.65 hours. A shorter to reach the time required for deposit or soil to be saturated on the lower area is due to higher percentage of water that infiltrates than run off.

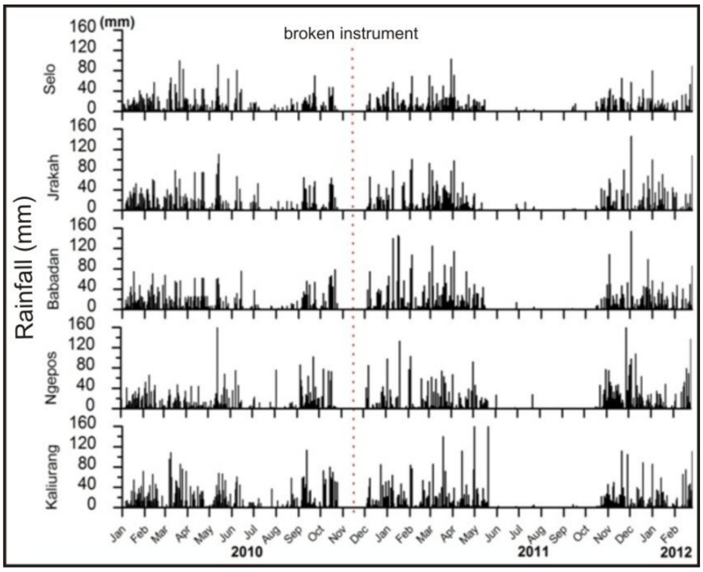

Figure 4. Rainfall in several places flank of Merapi Volcano [2]

Laharic flows is the movement of mixtured rainfall and volcanic material which cause erosion along the river. In this case, the erosion produces small channels that *laharic flows* are accumulated into the Gendol River. Proximal area with steeper slope is relatively less stable and susceptible to landslides that could increase the amount of volcanic material into the *laharic flows*. Lahar that initially was derived by the *debris avalanche* can be undergone dilution by rain water, transformed into *debris flow* or *hyperconcentrated flow* that has a higher level of mobilization, and therefore can be transported to further distance [13]. The typical deep valley of Gendol River cause *laharic flows* become confined and have further extension.

Table 1. Runoff Coefficient in Several Surface Conditions (Hassing, 1995 with Modification)

Runoff coefficient C = Ct+Cs+Cv					
Topography (Ct)		**Soil (Cs)**		**Land cover (Cv)**	
Flat (1%)	0.03	Sand & gravel	0.04	Forest	0.04
Undulating (1-10%)	0.08	Sandy clays	0.08	Farmland	0.11
Hilly (10-20%)	0.16	Clay and Loam	0.16	Grassland	0.21
Mountainous (>20%)	0.26	Stratified rocks	0.26	No Vegetation	0.28

In the valley, dilution is happened due to addition of water, resulting *dilute streamflow* [14]. This dilution is reducing the ability of *laharic flows* to transport volcanic materials and caused boulder-size material no longer can be transported [15]. Based on information from local residents, the *laharic flows* in Ringinsari area could spill over into residential areas because of its proximity (about 20 m) and the low elevation difference (about 1.5 m above the river). Towards south, flows of mixture material were dominated by *normal streamflow*, moving along Opak River through the Prambanan Temple. In general, fine-size sediments transported by floating or suspension mechanism, while the coarse-size material moves at the bottom of the river in *traction*, *rolling* and *saltation* mechanism [16]. This typical stream flow is less erosive, therefore the impact to Prambanan area is minor. However, theoretically for the *density flow*, where it is possible to happen along Opak River up to Prambanan area, sometimes large clast can also be transported floating within matrix [17].

Threats of Laharic Flows

Laharic flow in Merapi Volcano flank is generated by rainfall (*rain triggered lahar*) [18]. Apart from rainfall, morphology, slope, rivers morphology and characteristics of volcanicalstic deposits are also need to be considered as factors that controls *laharic flows* in Gendol – Opak Rivers.

Morphology of Merapi Volcano is divided into 3 zones: the center of eruption, proximal and distal zone. Study area only include proximal and distal zones of Merapi where *laharic flows* able to generate. Based on the slope analysis, average of slope for proximal zone is 38.75% and distal zone is 19.9%. In general, rivers morphology on the proximal area are steeper as the result of dominant vertical erosion that the deposit is prone to move and surface water runs faster, therefore *laharic flow* in this area is easy to be generated. Volcanic material resulted by 2010 Merapi eruption itself is mostly loose to semi consolidated, makes it easy to be eroded. Field investigation and DEM analysis on the proximal area of Merapi, mentioned the volcaniclastic deposit that is potential as the *laharic flows* source and transported into Gendol dan Opak Rivers is 1..799.971 m^2 and the volume is 14,745,496 m^3 (Figure 5). The average thickness of deposit is 8.19 m, calculated on the basis of elevation changes before and after 2010 Merapi eruptions (Figure 5) in the summit area and along Gendol and Opak Rivers.

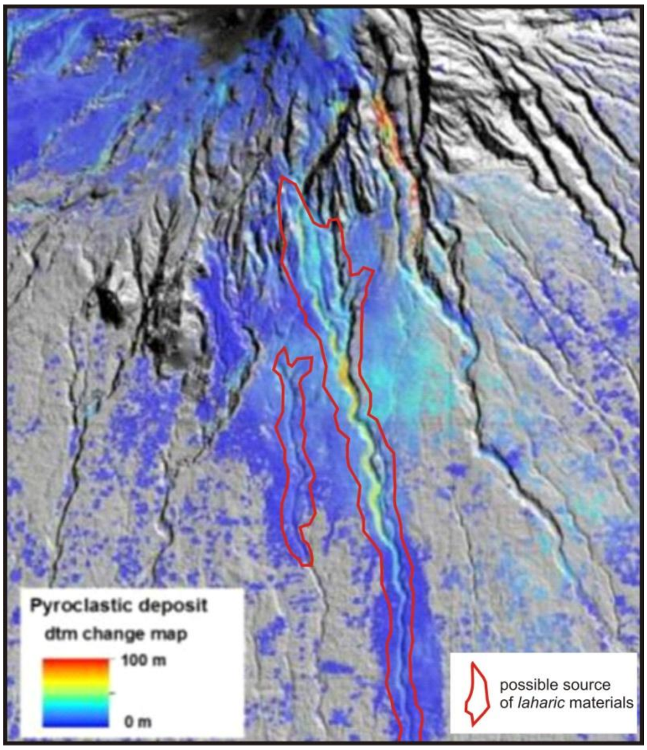

Figure 5. Elevation changing map of Merapi before and after 2010 eruption [19]. Deep blue to red on the color bar shows increasing elevation

Based on the discussion above, theoretically, the possibility of *laharic flows* in Gendol and Opak Rivers can be predicted. Time required for soil to be water saturated, which is obtained from the empirical formula, is basically the constant accumulative time, and begins when the soil is in total dry condition. In a matter of fact, rainfall rate during rainy season may experience fluctuation which required shorter time to reach water saturated condition, also means that time to begin runoff is faster. Empirically, laharic flow might be generated around 1-2 hours after the heavy rain started [2].

So far, the *laharic flows* from both rivers are still hold by the main channel, no report has mentioned any *laharic flows* spilled out into the Prambanan area. Volcaniclastic deposits in this area mainly resulted by *debris sheet flow* to *normal flow* that still held within river valley. However, several circumstances must be considered concerning *laharic flows* threat along Gendol-Opak River such as:

- Reducing sediments or deposit filling trapped by sabo dam, which recently has almost reached its maximum capacity. In several sections along the river, the volume is significantly reduced as the river valley gradually become shallower. This circumstance may cause laharic flows spilled out.
- The collapse of Geger Boyo Peak on the south side due to November 5th, 2010 eruption has caused an increasing volcaniclastic material, deposited to the southern slope.
- Periodically Merapi eruption in every 2-5 years contributes in the increase amount of volcaniclastic material.
- Sand mining activities [20] along Gendol and Opak Rivers caused looser deposit along the river to be easily remobilize. It might generate debris flow or *hyperconcentrated flow* in the lower zones and able to reach Prambanan Temple area

- Turning points of Opak River near Prambanan Temple might be the potential point where spill out of *laharic flows* occur. There are two river turning in this area; if the spill out occur in the first turning point, the lahar can spill out to the southeast direction toward the main Prambanan Temple area. If the spill out occur in the second turning point, the lahar will spill out to the south through the main road of Yogyakarta-Surakarta (Figure 6). Spill out may occur in this area due to the capacity of the river channel is low and small in dimension. Moreover, the distance between Opak River and Prambanan Temple is approximately only 85 meters with elevation difference between river base and the temple is around 8.5 meters, and vertical acreage is 72 square meter.
- Bridge construction, that connects Yogyakarta-Surakarta main road, rest on the middle of river valley, this condition gives a high risk of failure to the construction when *laharic flows* reached and pass through under this bridge. The threat to the bridge is due to erosion of bridge foundation or direct impact from boulder size material strike.

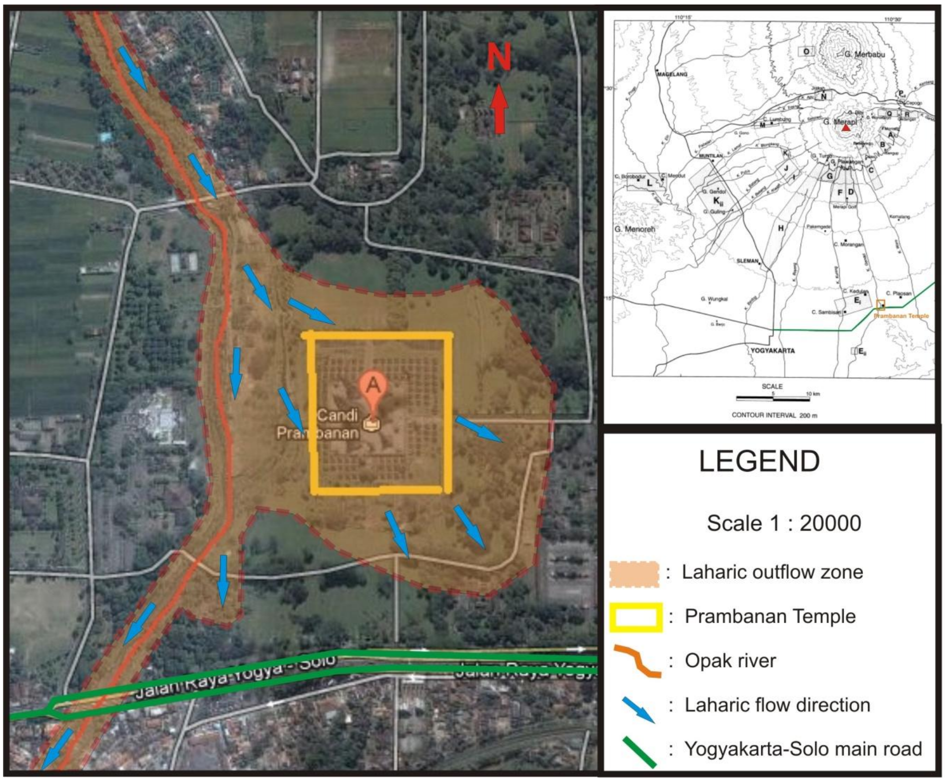

Figure 6. Laharic outflow zone in Prambanan Temple site and main road of Solo-Yogyakarta across Opak River

Prevention to Future Disaster

Several actions needed to be done for the geological disaster prevention along Opak and Gendol Rivers are:

- On the upper stream of Gendol River, reforestation can be carried out to lessen the occurrence of initial erosion / initial runoff. In term of Actual Conservation Index, forest has the highest value [21].
- The Gendol River flow needs to be divided into several other rivers to lessen the water debit. In case the *laharic flows* occurred, the volcaniclastic material

deposition has already breakdown into several channel before reaching Prambanan Temple.

- Build a dam on the riverside to prevent lateral erosion and landslides. The purpose of the dam is to keep the *laharic flows* still within the channel and prevent it flowing into the inhabitants' house.
- Build of laharic disaster map along the river up to Prambanan temple to inform the inhabitants about laharic flow range area.
- Build an early warning system and prepare the evacuation for the sand miner to facilitate the mobilization when the *laharic flows* occurred.
- Re-build or repair the damage of sabo dam due to volcaniclastic material accumulation.
- There are several steps to decrease the possibility of *laharic flows* in the Prambanan temple area. Firstly, strengthen and raise artificial bank in the eastern side Prambanan Temple. Secondly, making new channel, straight to the south from Jabang Bayi Dam to avoid turning point nearby Prambanan Temple and to add the distance of the temple from river valley.

Conclusions

- Laharic flow may occur when the effective runoff begins right after the water saturated soil. The time required to start the runoff becomes shorter in the peak of rainy season, where rain falls continuously.
- The potential of laharic flows will be higher equivalent to the increasing of rain intensity or volcaniclastic material due to periodically Merapi eruption.
- The mitigation on *laharic flows* is needed to minimize the damaged that could happen especially in the critical area such as on the Prambanan temple area and the main road of Yogyakarta-Surakarta.

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