Dynamics of lahar-affected river tributaries of the Progo river after the 2010 Mt. Merapi eruption

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Abstract. Riverbeds in the Mt. Merapi area are dominated by gravel originating from Mt. Merapi. The 2010 Mt. Merapi eruption has formed a riverbed consisting of sediments of various size. Since then, the morphology of the rivers has changed dynamically, depending upon the natural and anthropogenic factors. Most of the rivers drain into the Progo River, whereas the main river system of the Progo River drains into the Indian Ocean. The dynamics of the tributaries of volcanic rivers along the Progo River are the major concern to identify the capacity of the tributaries against potential lahar flow disasters that may occur. This paper presents the results of a series of observations of several tributaries of the volcanic rivers, taking into account the natural flow phenomena as well as the sediment mining activity along the river under investigation. The investigation included the hydraulic simulation, which employed a numerical model. The results of the simulation showed that the downstream part of the Progo River is influenced by sediment from Mt. Merapi through its tributaries. These also suggest cost-effective river tributary maintenance to mitigate the risks of lahar flow disasters.

Keywords: River tributaries, lahar flow disaster, risk mitigation, cost-effective maintenance

1. Introduction
Mount Merapi is one of the most active volcanoes in Indonesia as well as in the world. It is located on the island of Java at 7°32′26.99″ S 110°26′41.34″ E, on the border of the Provinces of Central Java and the Yogyakarta Special Region. It generally erupts every 3 years with a major eruption every 9 years. It has erupted 42 times in the last 200 years, including 16 major eruptions. Its eruptions have produced large amounts of volcanic material such as ash falls, lava, and pyroclastic flows. The most recent eruption occurred in October 2010, on the south-eastern and the western slopes. Based on the 2011 data from the BNPB (National Disaster Management Agency) [1], sixty percent of the 140 million cubic meters of eruption material released by the 2010 eruption was deposited on the western slope and the remaining was deposited on the south-eastern slope. When high-intensity rainfall occurred, the material
would flow down by debris flows. The debris flows took place frequently in almost every river that originate from the volcano, and as the material flowed down to the sea through the main rivers, this results in river morphology changes. Therefore, it is important to investigate the river morphology changes after the Merapi eruption in 2010. The aim of this research is to investigate the river morphology changes and sand mining activities, as well as to simulate the condition of the downstream part of the Progo River using a numerical model.

1.1. Tributary System of the Merapi Area
In the area of Mt. Merapi, there are three tributaries: Progo Tributary, Opak Tributary, and Dengkeng Tributary. The Progo Tributary consists of Pabelan River, Trising River, Senowo River, Blongkeng River, Lamat River, Putih River, Batang River, Krasak River, and Bebeng River. The Opak Tributary consists of Boyong River, Kuning River, Opak River, and Gendol River. The Dengkeng Tributary consists of the Woro River.

1.2. Sediment Disasters and Resources in Merapi Area
In the Mount Merapi area, debris flows start on the upper slope at elevations of 1,000 to 2,000 m. The total number of the recorded debris flows from 1931 to 1996 is more than 500 times [2]. 212 debris flow events occurred in almost all the rivers, especially Batang River, during the 17 months after the eruption in November 1930. 247 debris flow events occurred in many rivers during the 10 years after the eruption of 1969. 103 debris flow events occurred during the 12 years after the eruption of 1984, mainly in the Putih, Bebeng, and Boyong Rivers. A number of debris flow events continued to occur in the tributaries in the Mount Merapi area until 1997. After the eruption in 2010, several debris flows took place in the tributaries in the Mount Merapi area, as shown in Figure 1. The debris flows have the impact of morphological changes of the river in the downstream part.

Due to the deposited sediment being of good quality for construction material, people use the material for resources. Local people conduct sand mining activities using traditional equipment, and mining companies use heavy industrial machines. Quarry sites of sand mining in Mt. Merapi Area are extended to not only the riverbed but also private lands and riverbanks.

![Figure 1. Number of debris flows between October 2010 and March 2012 [3]](image)

2. Materials and Methods
The research methods for this research consist of a survey and a simulation. The activities in the survey involve a morphological survey and a sand mining survey. The morphological survey was conducted on the tributaries of Progo River and along the Progo River. The sand mining survey was performed along the Progo River. One-dimensional simulation was performed downstream of Progo River. In this study, the HEC-RAS v.4.1.0 software was used to perform one-dimensional hydraulic calculations for
morphology analysis in the longitudinal section. The scope and delimitation of study in this research are cross-section simplification in numerical modelling as a rectangle, because the width of the channel of the Progo River is ten times larger than the height of water flow, which is classified as a wide channel and has bed gradation homogenization along the modelling section. The research location is in the Progo watershed area. The section of the river that was used as the object of research is a section of the Progo River ± 57 km from the downstream part to the middle section located at Duwet Hydrological Station. The data used in this research consist of secondary data such as hydrograph data, topography, and coordinates of infrastructure of the Progo River. Hydrograph data, from October 2010 to October 2015, were used as boundary conditions for the upstream part of the modelling section.

3. Results and Discussion

3.1. Morphological Survey of the Tributaries of the Progo River

Figure 2 shows the longitudinal riverbed profile of the Putih River. Morphological changes on the upstream, midstream, and downstream parts of Putih River that were obtained from PPK PL of Mt. Merapi [4] are shown in Figure 3, Figure 4 and Figure 5. From these figures, it can be seen that the red line shows the cross-section of the Putih River taken in 2012, while the green line shows the cross-section of the Putih River in 2015. From the figures, it can be seen that there were some changes on the morphology of the Putih River, especially on the riverbed, which experienced a sedimentation process. According to Figure 1, the sedimentation phenomena generally occurred along the Putih River. Based on Figure 3, Figure 4 and Figure 5, the average width of the Putih River is about 110 meters. The previous data is quite different compared to the data taken in 2019. The river width from the data taken in 2019 is 60 meters. This is due to the river alignment made from point 15 + 0 to point 10 + 0 and the construction of a dike on the riverbank dominated by concrete embankments.

![Figure 2. The longitudinal trace of the Putih River](image)

![Figure 3. Cross-section of the Putih River on the upstream part at point 44 + 0 [4]](image)
Figure 4. Cross-section of the Putih River on the midstream part at point 20 + 0 [4]

Figure 5. Cross-section of the Putih River on the downstream part at point 2 + 0 [4]

Figure 6, Figure 7, and Figure 8 show the cross-section of the Pabelan River on the upstream, midstream, and downstream parts.

Figure 6. Cross-section of the Pabelan River on the upstream part at point 69 + 0 [4]
Figure 7. Cross-section of the Pabelan River on the midstream part at point 34 + 0 [4]

Figure 8. Cross-section of the Pabelan River on the downstream part at point 0+100 [4]

Figure 6 shows that between 2012 and 2015, on the upstream part of the Pabelan River, a riverbed erosion phenomenon occurred. The depth of the riverbed erosion is approximately 45 m. In contrast to Figure 6, Figure 7 shows that in the midstream part of the Pabelan River there is a riverbed deposition of approximately 30 m. As Figure 8 indicates, degradation had occurred on the downstream part of the Pabelan River, which is approximately 5 m long.

3.2. Morphological Survey of the Downstream Part of the Progo River
Based on the survey in 2009, 2012, and 2013, on the downstream part of Progo River, due to the material supply from the Mt. Merapi eruption in 2010, the type of riverbed material tended to become fine sand. This is indicated by changes in riverbed material diameter in the Kebon Agung II Bridge and Progo-Putih confluence, from 10 mm to less than 0.5 mm. Then, due to the decrease of fine material from Mt. Merapi, riverbed material diameter became a sandy type with a diameter of about 2 mm in 2013. The mean diameter of riverbed material at Sapon and the Kebon Agung I Bridge in 2013 was still fine sand type, because in both locations, a new ground sill was built, causing local sedimentation in both areas. The physical conditions of the river flow in the selected locations are shown in Figure 9 and Figure 10. From Figure 9 and Figure 10, it is shown that in 2006 there was no supply of material through the tributaries of Progo River that originated from Mt. Merapi. This situation caused the river flow to be relatively stable at the Progo-Putih confluence and Srandakan Bridge locations. The river flow conditions of the Progo River tributaries were very narrow, with a width of less than 10 meters,
especially at the downstream part of the Putih River as well as downstream of the Pabelan River. In the period from 2000 to 2010, the riverbed elevation of Progo River tended to be decreased by the natural transport of sediment and sand mining activities in the channel of the Progo River.

After the Mt. Merapi eruption in 2010, sediment flowed rapidly into Progo River through its tributaries that originated on Mt. Merapi. The reasons why material from Mt. Merapi quickly entered into the Progo River were that, first, the amount of sediment was abundant; second, changes in hydrological parameters caused the runoff to be greater; and third, there was a collapse of the sediment control structures in the Pabelan and Putih Rivers caused by debris flows in both rivers. At the beginning of 2011, sediment had reached the Progo-Pabelan and Progo-Putih confluences. In addition to the change in riverbed material diameter, due to the sediment supply from Mt. Merapi, the width of Progo River tributaries was also increasing significantly, as shown in Figure 10. As well, the sediment supply caused the increasing of the riverbed elevation. This condition occurred from 2011 to 2012. However, the sediment supply did not change the flow conditions of the Progo River significantly. Yet, sedimentation occurred in some locations. Due to the decreased amount of material from Mt. Merapi that flowed into Progo River, the tributaries of the Progo River became narrow once again as in the condition before the 2010 eruption. Since 2013, river flow conditions began to narrow, and the river flow conditions in 2015 were similar to conditions before the eruption. Likewise, the riverbed was degraded due to the limited supply of material from Mt. Merapi that flowed into the downstream part of the Progo River.

![Figure 9](image.png)

**Figure 9.** Physical condition of the Progo River flow at Srandakan Bridge: (a) November 2006, (b) July 2012, and (c) September 2015

3.3. **Sand Mining Activity in the Downstream Part of the Progo River**

In the downstream part of the Progo River, sand mining activities began from a long time ago. Sand mining locations are spread out from the Kebon Agung I Bridge to the river mouth, on both sides of the river bank, considering the ease of access for mining. Naturally, this kind of activity is greatly influenced by the availability of sediments in the river basin. When more sediment is available, this activity will also increase. The location of sand mining in the downstream part of the Progo River is shown in Figure 11 (a).
Sand mining activities are carried out by two methods – manually or by using pump machines – as shown in Figure 11 (b). These sand mining activities are also beneficial in providing employment opportunities for the people around the location. These activities have become one of the economic activities of the people. Based on the survey, the price of a sand truck route is approximately IDR 300,000 to IDR 750,000, depending on the volume of the truck. The marketing reach of sand mining from this location covers the area of Yogyakarta, cities in Central Java, and even some regions in East Java and West Java. The mining volume of each location varies, depending on the mining method and ease of access to the mining site. In the selected locations in this study, the total mining volume was 145 m$^3$/day or 73,080 tons/year.

3.4. Numerical Simulation
The results of numerical simulation for the downstream part of the Progo River [5] showed that the riverbed elevation downstream of the Kalibawang Intake had degraded by approximately 100 cm/year. On the other hand, an aggradation took place upstream of the Ngapak ground sill, by approximately 63.6 cm/year. Degradation that occurred downstream of the Ngapak ground sill was approximately 4.8 cm/year, and aggradation occurred by 38.2 cm/year upstream of the Bantar ground sill. Degradation downstream of the Bantar ground sill and aggradation upstream of the Sapon intake were 15.8 cm/year and 24.8 cm/year, respectively. 13 cm/year of degradation occurred approximately 125 m after the Sapon Intake to the downstream part, and 7.2 cm/year of aggradation occurred upstream of the Srandakan ground sill. The sediment supply from Mount Merapi impacted the riverbed condition in the downstream part of the Progo River.

4. Conclusion
The sediment from the Mount Merapi eruption in 2010 has changed the river morphology on the tributaries in the Mount Merapi area, as well as in the downstream part of the Progo River. The sediment is one of the key factors in the degradation and aggradation of the riverbed. In addition, the sediment
also increases sand mining activities if there is a greater availability of sediment. The people or inhabitants use the sediment as resources. Based on the numerical simulation, the sediment becomes an important factor in the degradation and aggradation process in the downstream part of the Progo River.

Figure 11. (a). Sand mining location in the downstream of Progo River, (b). Both methods of sand mining, manual method and pump method

Acknowledgements
The authors would like to thank the PPK PL of Mount Merapi for sharing data on the cross-sections of tributaries in the Mount Merapi area. Also, the authors would like to express gratitude to the Muhammadiyah University of Yogyakarta and the students for their support in this research.

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