



Observing River Morphology Dynamics in the Upper Senowo River (Merapi Volcano) to Promote Environmental Awareness of Lahar Hazards

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ABSTRACT

Merapi Volcano experienced a significant eruption in 2010, which deposited large amounts of pyroclastic material along its slopes and valleys. The Senowo River, located on the western flank of this volcano, has been a significant lahar flow channel since 2010. This study aims to investigate the morphodynamics of the upper Senowo River between 2012 and 2014. Two datasets from LiDAR dan UAV data acquisition were used to assess these changes: Orthophotos and Digital Elevation Models (DEMs) from 2012 and 2014. Orthophotos were used to identify changes in channel shape and width, while the DEM of Difference (DoD) method was applied to measure vertical changes in the riverbed. LiDAR dan UAV method are highly favorable for detailed morphological analysis. Currently, the UAV method is the handiest and most cost-effective to conduct. Field surveys were conducted to observe geomorphic features directly. Results showed significant valley widening (~98,845 m²) and riverbed aggradation (~9.4 m) caused by continued sediment transport since the 2010 eruption. Natural geomorphic features such as meandering rivers, deep U-shaped channels, and unstable slopes control these dynamics. Although this area is far from residents, it remains highly susceptible to secondary volcanic hazards, especially during the rainy season. This study highlights the importance of risk mitigation strategies, particularly the use of LiDAR and UAV for monitoring river dynamics to improve disaster awareness and preparedness.

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1. INTRODUCTION

Merapi Volcano is one of the most active volcanoes in Indonesia, among more than 100 other volcanoes across the archipelago. It is located on the border between the Special Region of Yogyakarta and Central Java Province. This volcano has a long history of eruptions. Tephrostratigraphic records dating back approximately 4,500 years indicate alternating occurrences of large and small eruptions, with varying eruption intervals (Andreastuti et al., 2006). The most recent significant eruption occurred in 2010, classified as a Volcanic Explosivity Index (VEI) 4 event (Subandriyo et al., 2023). The 2010 eruption started in October with an initial explosion followed by pyroclastic density currents (PDCs) directed to the southern flank of Merapi, the Gendol Valley (Subandriyo et al., 2023). This eruption caused the loss of ~380 lives and displaced nearly 400,000 people (Mei et al., 2013; Subandriyo et al., 2023).

Following the primary hazards (e.g., ash, PDC), the secondary hazard from Merapi is lahar (De Bélizal et al., 2013; Hadmoko et al., 2018). Lahars are affected almost everywhere in the main valleys around Merapi, with a distance exceeding 15 km in some cases. More than 200 lahar events were reported from October 2010 to March 2012, predominantly occurring on the western flank of Merapi. The Senowo River is one of the rivers located on the western flank of Merapi Volcano and serves as one of the primary channels for lahar flows (De Bélizal, dkk., 2013). Lahar is a volcanic mass flow consisting of a mixture of water and volcanic debris (e.g., pyroclastics, rock fragments, and sediment) (Vallance and Iverson, 2015). The Lahar movement is strongly influenced by the type of material, rainfall, and gravity (Ferruci, et al., 2005).

The transport of lahars along river channels results in significant erosion of both the riverbed and riverbanks (Lavigne et al., 2007). Persistent erosion can lead to riverbank failure and slumping (Aubaud et al., 2013; Legono and Rahardjo, 2017). These processes can dramatically alter the morphology of the river valley and channel (Gob et al., 2016; Mock et al., 2023). In addition, human activities such as material extraction contribute to increased dynamics within the river valley (Malawani et al., 2020). These processes are evident in the Senowo River, influenced both by natural lahar flows and subsequent anthropogenic activities. The primary objective of this research is to analyze the morphodynamics of the upper Senowo River using remote sensing data, i.e., LiDAR (Light Detection and Rangin) and UAV (Unmanned Airborne Vehicle). Previous studies on morphological changes on the western slope of Merapi Volcano relied on direct measurement data, without incorporating LiDAR or UAV data (Dipayana et al., 2013; Hadmoko et al., 2018). Some researchers have frequently used the combination of LiDAR and UAV datasets to monitor morphological changes on Merapi Volcano. However, most of these applications have focused on the crater and lava dome areas (Darmawan et al. 2018; Gomez et al., 2021; Darmawan et al., 2023) rather than on the broader slope or riverine regions, except for studies conducted in the Gendol River (Ville et al., 2015; Mayaudy et al., 2021). This research may provide critical insights into how lahar events alter the surrounding river environment. Understanding these dynamic processes can enhance environmental awareness, inform sustainable river management, and support preparedness measures for lahar-related hazards. (Pierson et al., 2014).

2. METHOD

2.1 Study Area

This study was conducted in the upper reaches of the Senowo River. The Senowo River is located on the western slope of Mount Merapi, administratively within Magelang Regency, as shown in Figure 1. It is a tributary of the Pabelan River. This river system frequently experiences lahar flows during the rainy season (November to March), particularly couple years after the 2010 eruption (Legono and Rahardjo, 2017; Ikhsan et al., 2023). The research focuses on the upper section of the river, as this area exhibits more dynamic fluvial processes, including erosion, sedimentation, and riverbank failure. Due to these significant dynamics, this section is particularly interesting for observing morphological changes. It is also the initial segment through which the lahar flows during rainfall events. The downstream propagation of lahar flows is heavily influenced by the dynamics in this area, as well as by the presence of sabo dams in the upper segments (Aprilian et al., 2023).

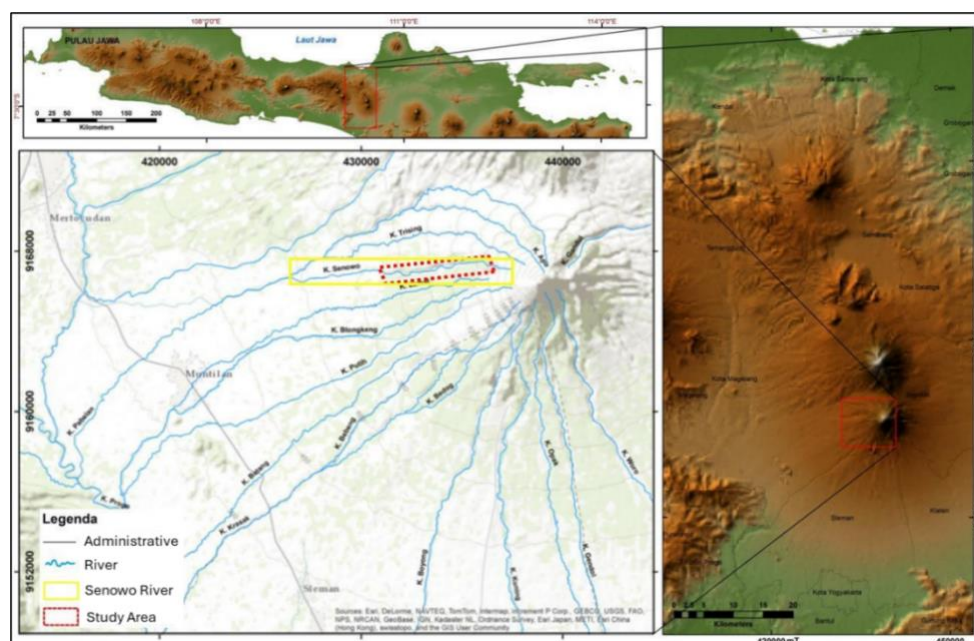


Figure 1. Study area: the upper Senowo River in the western flank of Merapi Volcano

2.2 Data Analysis

The primary data used in this study consists of two types: orthophoto and Digital Elevation Model (DEM). These datasets were obtained from two different sources and periods, i.e., Light Detection and Ranging (LiDAR) data from 2012 and Unmanned Airborne Vehicle (UAV) imagery from 2014. Several studies have also used these two types of data for observing and monitoring changes in river morphology (Borrelli et al., 2019; Beckes et al., 2020). From 2010 to 2012, the frequency of lahar occurrence in Merapi Volcano was the highest after the eruption; then, from 2012 to 2014, there was a decrease in frequency, gradually leading to a stable channel (De Bélizal et al., 2013; Hadmoko et al., 2018). In the following years, many morphological changes were caused by anthropogenic processes (Malawani et al., 2020). Gomez et al., (2022) also investigated a similar period (2012-2014) to observe morphological changes in the summit area of Merapi.

The LiDAR data was obtained from the *Balai Penyelidikan dan Pengembangan Teknologi Kebencanaan Geologi* (BPPTKG) in Yogyakarta, while the UAV imagery was captured by the team from the Faculty of Geography, Universitas Gadjah Mada (UGM). Their spatial resolutions are ~25 cm and ~20 cm, respectively. The use of data from two different years

allows for the analysis of morphological changes in the river landscape over time (Hammelder et al., 2018). Orthophotos were used for visually assessing the condition of the Senowo River valley. Visual observation through orthophotos is useful for identifying and delineating the dynamic of river channel's morphology, particularly channel width and shape. The DEM data from the two different periods enables a differencing analysis, known as the DEM of Difference (DoD) analysis, which is used to detect changes in the riverbed surface (Williams, 2012; Mock et al., 2023). The results of the DoD analysis enable the identification of areas within the valley that have experienced either degradation or aggradation. Field survey was also conducted to confirm the dynamic channel morphology and to collect the field photos. The LiDAR and UAV data used have already been verified for accuracy by the provider; therefore, the field survey and ground check are conducted only to confirm the delineation results of the morphological changes. The workflow diagram of the research is presented in Figure 2.

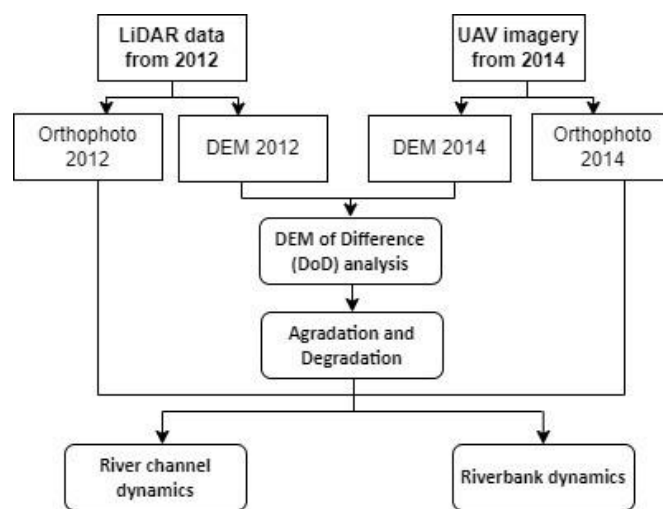


Figure 2. Workflow diagram of the research

3. RESULTS AND DISCUSSION

3.1 Unstable Riverbank Slope

The 2010 eruption of Merapi volcano produced a large volume of pyroclastic material. This material was widely distributed across the upper slopes and has since become the source of dynamic geomorphological processes in the post eruption period. These processes, including lahar flows, gully erosion, and sedimentation in river systems. These processes have significantly affected the environmental conditions of the rivers. The abundance of pyroclastic deposits after the 2010 eruption is not limited to the summit area near the crater. These deposits, which serve as a major source of lahar material, are also found in valleys and along riverbanks. Even without rainfall, those unconsolidated materials can be detached by wind and gravity (Figure 3A). During rainfall events, this material that lies on slopes is easily eroded and mobilized into lahars that flow through river channels. Figure 3 illustrates the initial sources of lahar deposits from the unstable riverbank slopes of the Senowo River valley.

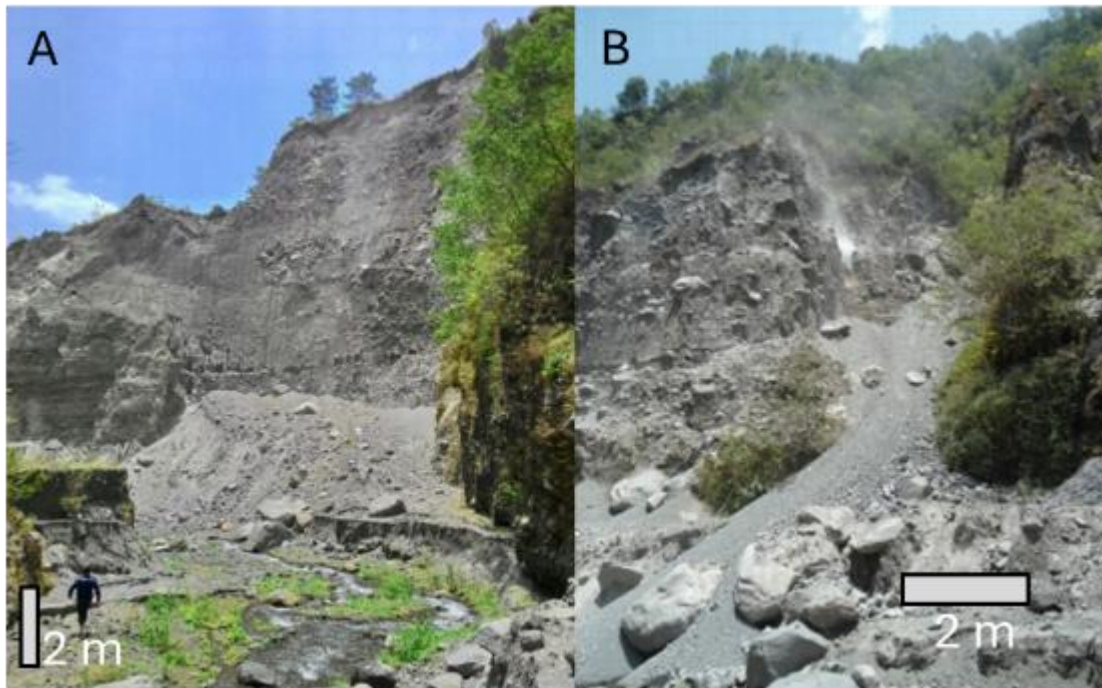


Figure 3. (A, B) Sliding of unconsolidated material on the slopes of the Senowo River (Photo: Handayani, 2014)

3.2 Dynamic of river channels

The morphological dynamics of the upper channel of the Senowo River can be observed across three segments: A, B, and C (Figure 4). These segments were delineated to identify variations in river dynamics based on different channel forms. Segment A represents a straight river channel, segment B represents a meandering channel, and Segment C marks the confluence of two river channels. Segment A exhibits a relatively stable morphology, with no significant changes in channel form. A maximum narrowing is measured up to 20 m. In this segment, erosion and sedimentation processes are minimal. Segment B shows more dynamic changes. The meandering flow pattern causes irregular distribution of flow energy, resulting in lateral erosion on the outer bank and sedimentation on the inner bank. As a result, the northern part of segment B experienced channel narrowing, while several of the southern part showed channel widening. Segment C, located at the confluence of two channels, demonstrates the most significant and extensive morphological changes. The convergence of two channels carries a higher volume of water during rainy conditions and a higher sediment load, leading to more extreme channel dynamics. In this segment, channel displacement may reach ~35 m, while channel narrowing may occur up to ~60 m.

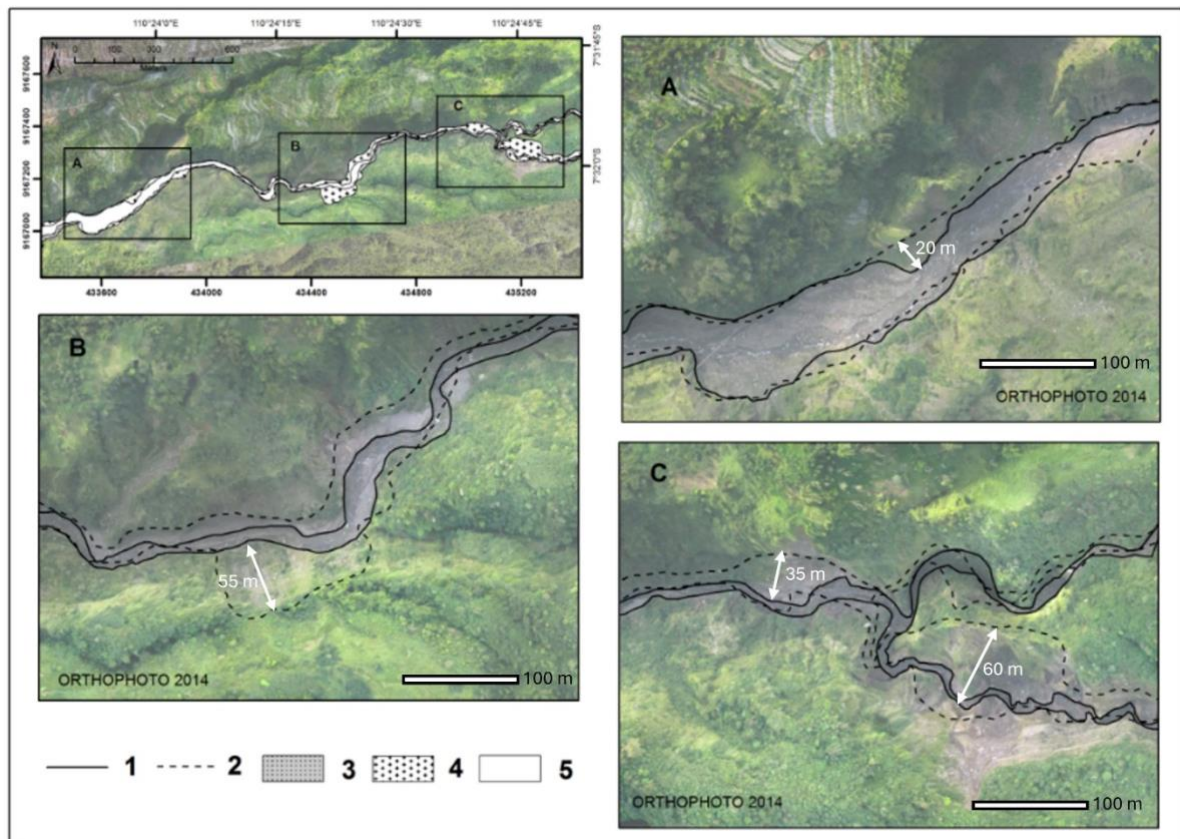


Figure 4. Dynamics of the river channels in the upper Senowo River (1: channel 2014; 2: channel 2012; 3: widening; 4: narrowing; 5: stable)

As shown in Figure 3, channel narrowing and shifting are predominantly in all segments of the study area, influenced by the meandering and confluence of two channels (Segment C). In addition, this condition is influenced by the prevalence of deep U-shaped channels (Segment B) and relatively wide and flatbeds (Segment A), making them more susceptible to sediment accumulation and shifts in flow direction.

3.3 Dynamics of riverbank boundaries

Figure 5 illustrates the morphological changes along the riverbanks in the upper Senowo River. Lateral changes are primarily characterized by valley widening. Over the two-year observation period, approximately 98,845 m² of the riverbank area experienced widening, while narrowing occurred over 19,355 m². These shifts were predominantly concentrated on the northern side of the river. The riverbank boundary has shifted approximately by 45 to 90 m. This pattern is influenced by both the direction of river flow and the slope orientation, which are aligned toward the west-northwest, leading to deformation along the northern riverbank. The irregular, non-parallel alignment of the northern bank relative to the southern bank may also suggest the presence of an ancient landslide (Segment B), which likely contributed to the formation of an asymmetrical riverbank profile.

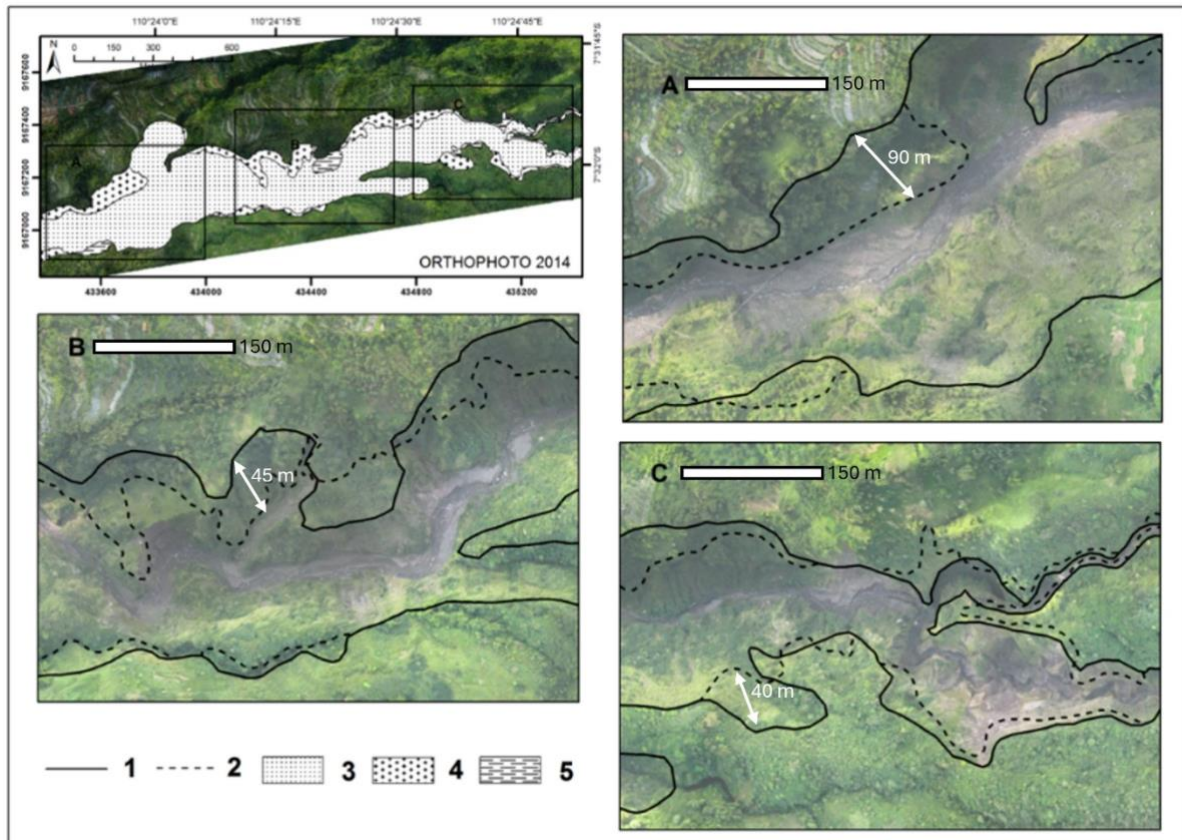


Figure 5. Dynamics of the riverbanks in the upper Senowo River (note: 1: riverbank boundary 2014; 2: riverbank boundary 2012; 3: stable; 4: widening, 5: narrowing)

The presence of lahar deposits also influences the dynamics of the riverbank. Many of the lahar deposits are found on either side of the riverbank, as shown in Figure 6. A large number of lahar deposits may form river terraces. This terrace influences riverbank dynamics by acting as a barrier to lateral erosion, helping to keep the riverbank relatively stable. Erosion subsequently occurs vertically, causing changes to the riverbed. These stable slopes are then covered with small-medium to large vegetation, strengthening the riverbank structure and making it more stable.



Figure 6. Lahar deposits along the base of riverbanks (Photo: Handayani, 2014)

3.4 Dynamics of riverbeds

Lahar transport is a powerful agent in reshaping the riverbed. Since the upper Senowo River dried during the observation periods (2012 and 2014), a Digital Elevation Model (DEM) of the riverbed could be generated to calculate changes in sediment thickness. The DoD calculation focuses on an unvegetated river channel, both types of data used are sufficient. However, if the area were vegetated, LiDAR data would be more appropriate. The analysis resulted in two classifications: positive values indicate aggradation or the accumulation of riverbed sediment, while negative values indicate degradation or the removal of riverbed material (Figure 7). The DoD analysis revealed a maximum degradation of 2.1 m and a maximum aggradation of 9.4 m. These results indicate that sedimentation is more dominant than riverbed erosion.

The extensive riverbed degradation (0.7 to 2.1 m) was observed in the central segment, particularly in Segment B, as shown in Figure 7. In Segment A, aggradation is more dominant and occurs widely along the river channel (2.2 to 5 m), reflecting the deposition of lahar material that covers the previous riverbed. A highly concentrated aggradation pattern is evident in Segment C, indicated by darker colors on the DoD map, with changes reaching up to 9.4 m. This highlights the main deposition zone of lahar material, especially at the

confluence of the two river channels. Such conditions have led to the formation of new lahar terraces and indicate that this segment serves as a major area of sediment accumulation.

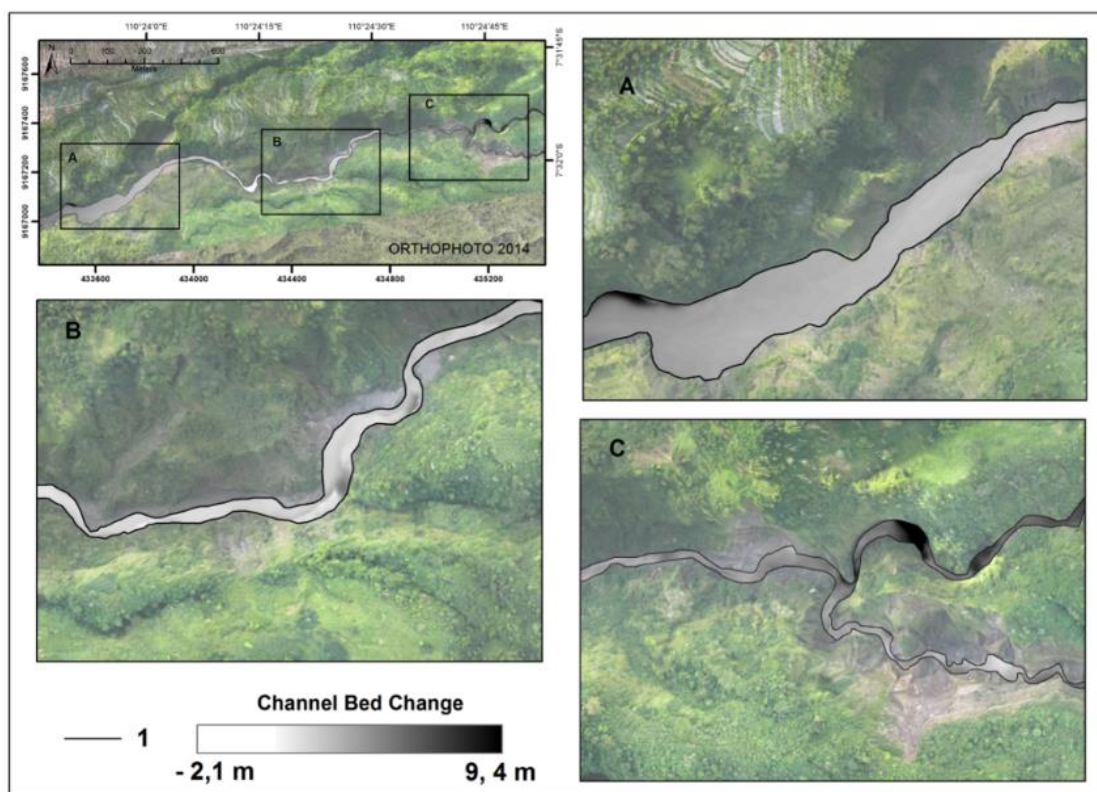


Figure 7. Dynamics of the riverbed in the upper Senowo River (1: channel 2014)

3.5 River Dynamics and Environmental Awareness

Lahars are among the most significant events that can drastically alter river morphology. Lahar flow acts as a dominant agent of erosion and sedimentation, causing frequent changes in the shape and size of river channels (Gob et al., 2016). Monitoring river changes due to lahar is essential for sustainable river management and is a valuable reference for lahar flood risk reduction strategies (Legono and Rahardjo, 2017). This study uses the river reach as the spatial unit. Appropriate monitoring at this scale (river reach) focuses on observing channel geometry, channel planform, and channel migration (Grabowski et al., 2014; Langat et al., 2019; Nones, 2021). This observation and monitoring can be conducted through direct field surveys or using remote sensing, including UAV and LiDAR (Grabowski et al., 2014; Abbass et al., 2023). This research aligns with these principles, both in terms of spatial scale and data sources. Therefore, the relevant findings can contribute to environmental management efforts and improve early warning and preparedness measures (Grabowski et al., 2014).

Figures 4 and 5 show that significant morphological changes occurred over just two years. Although the study area is far from residential zones, activities within this segment are highly restricted. The large volume of pyroclastic material and its potential to be used for mining may pose serious unpredictable hazards (Malawani et al., 2020). Several incidents have been reported, including heavy equipment and trucks being buried by pyroclastic material triggered by unstable slopes. Even in dry conditions, slides from the riverbank slope are likely to occur due to loose material (Figure 3B). Vibration from heavy equipment activity may also increase slope instability. During rainfall, aggradation processes will likely become more dominant (Figure 7), raising the potential for further hazard. We suggest the construction of

a new sabo dam in this river segment, particularly after the river confluence to serve as a sediment capture and help stabilize the surrounding slopes and the riverbanks (Istijono et al., 2025). Providing information on potential environmental changes, predicted periods of lahar occurrence, hazard zoning, and adaptive landuse planning will significantly help increase awareness and preparedness in dealing with lahar hazard (Peirson et al., 2014; Lavigne et al., 2018). With advancements in technology, LiDAR and UAVs can play a crucial role in providing such information. The usefulness of LiDAR and UAV technology has also been summarized within the disaster risk reduction (DRR) planning of the lahar hazard (Table 1).

Table 1. Advantages of LiDAR and UAV data for lahar hazard mitigation

DRR phase	Mitigation strategy	The usefulness of LiDAR and UAV
Pre-lahar event	Construction of sabo dams and lahar control dams	UAV and LiDAR can be used to determine the optimal location for the construction of dams
	Identification of lahar hazard zones	Imagery and DEM data generated can be use as primary data for lahar propagation modelling
	Evacuation routes and assembly points	UAV and LiDAR data are useful for determining safe evacuation routes and assembly points
Post-lahar event	Mapping of lahar impact	Useful for detecting areas affected by lahar
	Monitoring of erosion and sedimentation due to lahar	Monitoring and detecting river morphological conditions through aggradation and degradation calculations
	Evaluation of the infrastructure restoration	Monitoring the condition of post-eruption infrastructure and monitoring the infrastructure recovery efforts
	Updating hazard maps, element at risk, and capacity maps	As a basis for evaluating and updating the existing maps
Source: Mead et al., 2017; Rusnák et al., 2019; Jordan, 2019; James et al., 2020; Andaru et al., 2021; Andaru et al., 2022; Román et al., 2022; Munir et al., 2024		

4. CONCLUSION

The upper Senowo River is significantly influenced by subsequent geomorphological processes post-2010 Merapi eruption. The large volume of pyroclastic material deposited on the slopes and valleys has become a persistent source of lahar flows, as well as sedimentation and erosion processes. During the two-year observation (2012-2014), both the riverbed and the riverbanks experienced striking changes in the form of valley widening and aggradation. These processes were further exacerbated by geomorphic features of the river, such as deep U-shaped channels, meanders, and unstable slopes, especially near the confluence zone. Although located away from residential areas, the study area remains highly susceptible to secondary volcanic hazards, including sudden slope failures and lahar flows, especially during rainfall events. Therefore, proactive risk mitigation strategies such as the construction of sabo dams, refined land use planning, minimized on-site human activities (e.g., sand mining), and proper hazard communication are critical to ensure long-term environmental awareness and security.

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