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On the fate of the Anthropocene-geomorphological evolution of the Outer Dieng Highland (Indonesia) under massive anthropogenic acceleration

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Abstract

The Great Acceleration since the mid-20th century, resulting from the dominance of anthropogenic activities on Earth, has had a significant impact on the environment, including geomorphological evolution. This paper aims to investigate the Anthropocene-geomorphological evolution in the outer Dieng Highlands, shaped by massive anthropogenic acceleration. This study employs a geomorphological approach. Data were collected through observation, remote sensing image interpretation, literature, and documents. The data were analyzed using descriptive geomorphological analysis, supported by geographic information systems and remote sensing. There are two significant findings in this study. First, anthropogenic activities during the Anthropocene have been highly dominant, marked by extensive land use for agriculture and settlements over the past five decades. Second, the Outer Dieng Highland is a volcanic complex; however, its current geomorphological evolution is primarily driven by the acceleration of exogenic processes induced by anthropogenic activities. Erosion and mass movements occur on a large scale, increasing drainage density, particularly in older volcanic units and less-resistant materials. In sum, this study offers new insights into the impact of anthropogenic activities on the acceleration of exogenic destruction across various structures within the volcanic complex.

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Introduction

For thousands of years, geomorphology has focused on the shape of landforms on the Earth's surface. As a scientific discipline, geomorphology reached its modern stage of development in the fifth phase in the early 20th century, marked by various theories regarding the aspects of geomorphological study (Huggett, 2017; Oldroyd, 2013; Pramono & Ashari, 2014). In general, geomorphology concerns two main areas: long-term landform dynamics, studied through historical geomorphology, and short-term geomorphic processes, studied through process geomorphology, with detailed descriptions (Huggett, 2017; Urban, 2013). Today, as the impact of massive anthropogenic activities continues to grow, anthropogenic geomorphology is developing rapidly. Human influence on geomorphology has been recognized for thousands of years and has only recently been formally recognized as a distinct field within geomorphology (Goudie, 2020). James et al. (2022) explain that anthropogenic geomorphology is a current subdiscipline of science focused on human impacts on the landscape.

It is now widely believed that Earth has entered a new epoch in geological history: the Anthropocene (Hamilton, 2019; Zalasiewicz et al., 2020). Although it has not yet been formally accepted in the geologic time scale, the concept of the Anthropocene is based on the fact that human activity has become the primary force influencing the Earth system globally, on a scale unprecedented in geological history (Clark, 2019; Lewis & Maslin, 2015). The mid-20th century, or the 1950s, is often cited as the beginning of the Anthropocene, coinciding with the Great Acceleration, during which human population, energy consumption, pollution, and the environmental footprint experienced a dramatic surge (Ludwig & Steffen, 2018). With the emergence of the Anthropocene, interest in anthropogenic geomorphology has been growing. Tarolli & Sofia (2016) explain that Earth's surface morphology results from key driving factors, including tectonic uplift, erosion, sediment transport, and climate. However, in recent years, the geomorphology community has had to consider biota as geomorphological agents that shape the landscape, albeit on a different scale and at a different magnitude than geological processes.

The problem is that the impact of anthropogenic activities on geomorphology is so extensive that it has not yet been fully addressed in the studies conducted. In general, research on anthropogenic pressures on geomorphology is still in its early stages, even compared with the impact of vegetation on geomorphic processes, which has been extensively explored in modern literature (Tarolli & Sofia, 2016). Studies on Anthropocene geomorphology have been conducted in lowland or urban areas (Brandolini et al., 2020; Luengo et al., 2025). Meanwhile, the influence of anthropogenic activities on the acceleration of denudation by exogenic forces within volcanic complexes remains underexplored in the literature. This situation highlights a gap that poses a challenge for subsequent studies. Anthropocene geomorphological studies of volcanic complexes are crucial, not only to enrich geomorphological understanding but also to provide additional considerations for the acceptance of the Anthropocene itself within geology (Brown, 2014; Brown et al., 2013).

The Dieng Highlands in Central Java, Indonesia, are a volcanic complex. Harijoko et al. (2010, 2016) refer to the Dieng region as the Dieng Volcanic Complex (DVC), which comprises 12 stratovolcanoes. Data from the Global Volcanism Program indicate that the DVC comprises multiple stratovolcanoes and more than 20 small Pleistocene-to-Holocene craters and cones, spanning an area of 6 by 14 km (Smithsonian Institution, 2025). The DVC is situated adjacent to two large stratovolcanoes with elevations exceeding 3,000 meters: Sundoro and Sumbing, the twin stratovolcanoes as described by Lavigne et al. (2008). Interestingly, although the area contains numerous volcanic features, there have been no magmatic eruptions in this region for several centuries. As a result, geomorphological evolution has been driven primarily by exogenic climate-driven denudation rather than by volcanism (Ashari, 2019; Wardoyo et al., 2021). On the other hand, Dieng is a densely populated volcanic complex. By 2025, no fewer than 1 million people will live within a 10-kilometer radius of the Dieng Highlands' center(Smithsonian Institution, 2025). A large population exerts pressure on land and can accelerate denudation by exogenic forces. Therefore, the Dieng Highlands serve as a good example for understanding how anthropogenic activities impact geomorphological development within complex volcanic structures, particularly during the Anthropocene.

A study of geomorphological evolution in the Dieng Highlands during the Anthropocene, under the influence of climatic denudation accelerated by anthropogenic activities, will be crucial for at least two reasons. First, to examine how anthropogenic pressures have come to dominate geomorphological development in the volcanic complex following the era of magmatic eruptions that were constructive to the structure. Second, to contribute new insights to the study of anthropogenic geomorphology during the Anthropocene. In this paper, we investigate geomorphological development in the Dieng Highlands during the Anthropocene to address these two objectives. The study focuses on the eastern side of the outer Dieng Highlands due to the abundance of stratocone units in this area, coupled with the adjacent Sundoro Stratovolcano, thereby providing deeper insights and exploring potential spatial variations. This study provides alternative insights into the geomorphology of the Dieng Highlands. Additionally, it provides new insights into the influence of anthropogenic activities on the acceleration of exogenic destruction of various structures within the volcanic complex.

Method

Data Collection and Analysis

This study employs a geomorphological approach, specifically the process geomorphology approach. This approach is one of the two main approaches in geography, aimed at studying short-term geomorphological dynamics (Huggett, 2017; Urban, 2013). This study also employs geomorphological variables to identify geomorphological dynamics. The geomorphological aspects used in this study include morphology, materials, processes, structure, stage, landforms, genesis, environment, and climate. These various aspects constitute a combination of those proposed by Davis, King, Penck, and Verstappen (Oldroyd, 2013; Pramono & Ashari, 2014). This study employs the spatial and temporal scales used in geomorphology, namely absolute space and absolute time (Millar, 2013; Summerfield, 1991).

Data for this study were collected using various methods, including field observations, remote sensing image interpretation, literature reviews, and document analysis. Field observations were conducted to obtain quantitative data through on-site measurements of, among others, (1) terrain morphology and morphometry, (2) materials, (3) geomorphic processes, (4) natural land cover, and (5) land use. Remote sensing image interpretation was used to identify (1) natural land cover and its temporal changes, (2) vegetation density, (3) slope gradient, (4) drainage density, and (5) settlements. Natural land cover was identified using Worldview imagery zoomed in 21 times, recorded in 2025. This imagery has a spatial resolution of 1 meter and consists of three bands: red, green, and blue. In addition to the current natural land cover, this study also analyzes changes in land cover over time. Land cover dynamics are demonstrated by the conversion of forest to non-forest areas, identified through Landsat image classification from 1995 to 2025. Land cover classification was performed for four time periods: 1995, 2005, 2015, and 2025, based on image availability.

Vegetation density, which also indicates anthropogenic pressure on the land, was determined using the Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2A imagery. Slope gradient is identified using the National Digital Elevation Model (DEMNas) data with a spatial resolution of 8 meters. Drainage density, which forms radial valleys and indicates the level of denudation, is identified using a medium-resolution DEM (30 meters) to extract river networks and determine flow order using the Strahler method.

Literature and documents were used to obtain secondary data on eruption history and eruption products. Information from the literature was essential for identifying and describing the geological and geochronological conditions of the DVC and Sundoro Volcano. Literature was obtained from previously published studies, while documents were obtained from various institutions, including the Indonesian Topographical Map, the Landslide Map, reports on mass movement disasters, and descriptions of the physical, social, cultural, and economic environments from the Statistical Agencies of Wonosobo Regency and Banjarnegara Regency. Settlement development, indicated by the expansion of settlement areas and increased density between settlement units, was identified through multitemporal built-up area analysis, using data from documents published by the Global Human Settlement Layer (GHSL). The relationship between the types of data collected, data collection methods, and data instruments or sources is presented in Table 1.

Table 1. Type of data, data collection methods, and data instruments/sources

No	Data	Data collection	Instrument/data sources
1	Morphography and Morphometry	Observation	Observation sheet, GPS, geological compass, clinometer, roll meter, digital camera
		Remote sensing image interpretation	National Digital Elevation Model (DEMNas)
2	Materials	Observation	Observation sheet, GPS, geological hammer, trowel, digital camera
		Document	Indonesian Geological Maps of Banjarnegara and Pekalongan Quadrangle (Condon et al., 1996), Geological Maps of Dieng Volcano (Luthfian, 2014; Sukhyar et al., 1986), Geological Map of Sundoro Volcano (Sukhyar et al., 1992).
		Literature	Harijoko et al. (2010, 2016); Wibowo et al. (2022)
3	Geomorphic processes	Observation	Observation sheet, GPS, geological compass, roll meter, digital camera,
		Document	Regional Disaster Management Agency
4	Drainage density	Remote sensing image interpretation	National Digital Elevation Model (DEMNas)
5	Land cover	Remote sensing image interpretation	Worldview Imagery, Landsat Imagery
6	Vegetation density	Remote sensing image interpretation	Sentinel 2A imagery
7	Settlement	Document	Global Human Settlement Layer (GHSL)
8	Geochronology	Literature	Harijoko et al. (2010, 2016); Prambada et al. (2016)

The data obtained were then analyzed using descriptive geomorphological analysis, supported by remote sensing and geographic information systems (GIS). A descriptive geomorphological analysis was conducted to interpret geomorphological dynamics using cause-and-effect reasoning. According to Sunarto (2004), this analytical method comprises four explanatory stages, namely: (1) the descriptive level, (2) the comparative level, (3) the associative level, and (4) the causal level. Geomorphological-descriptive analysis is conducted both qualitatively and quantitatively. Qualitatively, the analysis emphasizes geomorphological aspects. Meanwhile, quantitatively, the analysis is combined with GIS to determine the density of river valley orders as an indicator of geomorphological development, namely the width-to-depth ratio as used by O'Hara et al. (2024, 2025).

Remote sensing analysis to identify natural land cover was conducted using supervised methods, specifically maximum likelihood. The analysis results were then classified into three land cover classes: built-up land, agricultural land, and vegetation. To analyze forest-non-forest land-cover change, image classification was performed using the Gradient Tree Boost algorithm. Meanwhile, in the analysis of crop area land cover change, image classification was conducted using a supervised Random Forest classifier. To analyze settlement distribution patterns, GIS analysis was employed using the Average Nearest Neighbor (ANN) technique. To perform the ANN analysis, GHSL data in 100×100-meter pixel format was converted to point features using the pixel-to-point method, with each point representing one pixel. Meanwhile, settlement density was analyzed using Kernel Density Estimation (KDE), a GIS analysis technique. The research workflow is shown in detail in Fig 1.

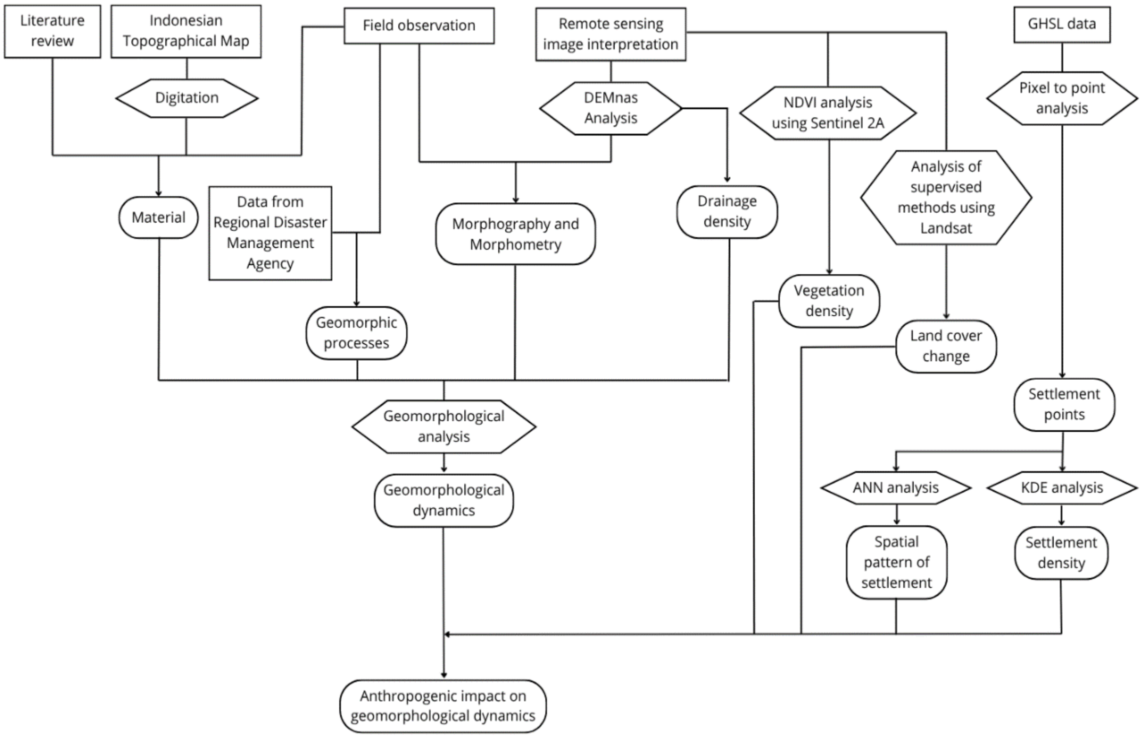

Fig 1. Research procedure

The Study Area

This study was conducted on the eastern flank of the Dieng Highlands. This area marks the transition between the DVC and the Sundoro Volcano to its southeast. Purwantara et al. (2025) note that DVC and Sundoro are part of the Wonosobo Volcanic Area, characterized by a SE-NW alignment of stratovolcanoes and volcanic complexes. This study area consists of a cluster of volcanoes. In this area, there are 10 volcanic units ranging in size from small to large, including Prau, Bucu, Kendil, Pakuwaja, Prambanan, Sikunir, Seroja, Bisma, Telerejo, and Sundoro (Fig. 2). The last-mentioned volcano is a non-DVC stratovolcano. At the same time, the rest are members of the DVC complex. All the volcanoes in the study area are Quaternary in age, with some formed during the Pleistocene and others during the Holocene. The total area is 384.99 km^2.

The study area is located in a tropical monsoon climate zone characterized by two seasons: the dry and rainy seasons. One of the most distinctive climatic phenomena in this area is frost, which forms at the peak of the dry season. Frost is rare in tropical regions with high temperatures. The geomorphological conditions, featuring numerous stratocones, are a key factor, as frost forms in the basins between them. Ashari et al. (2024) discovered a unique relationship between the local geomorphology and climate that triggers the formation of this frost.

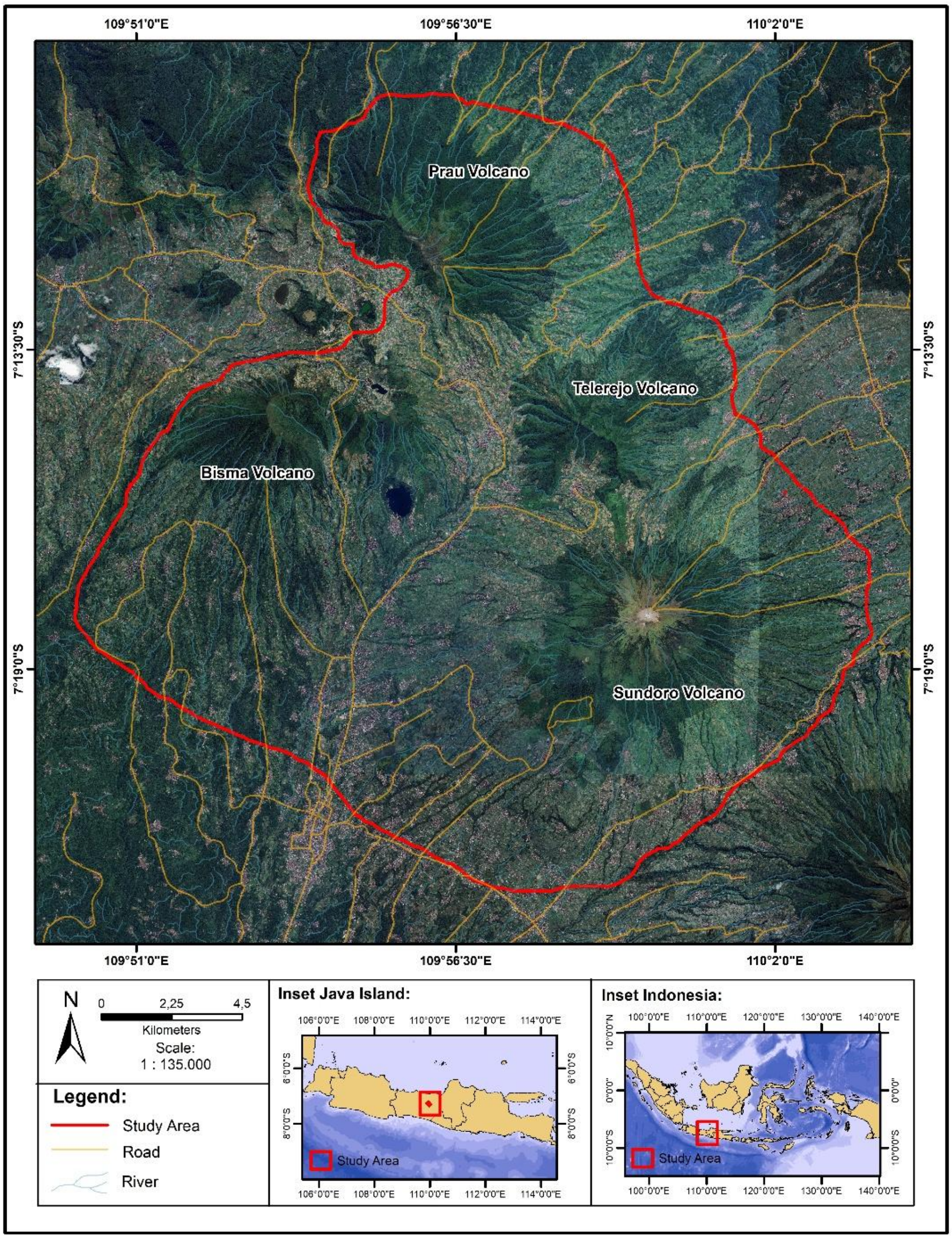

Fig 2. The Study Area

The study area plays a crucial role in the hydrological system, as the upper reaches of the Serayu River one of the largest watersheds in Java are located within this region. As in most volcanic regions, the study area's hydrological characteristics are characterized by a high density of springs. The distribution of springs on Mount Sundoro follows a clustered pattern, as is typical of stratovolcanoes (Ashari, 2014; Ervin et al., 2022; Purwantara et al., 2026). Meanwhile, the distribution pattern in the DVC is random; in addition to the large number of volcanic units, the occurrence of springs in the DVC itself does not always correspond to specific morphological features, such as the break of slope that is present in stratovolcanoes (Purwantara et al., 2026). Administratively, the study area is located in Central Java Province, Indonesia. Wonosobo Regency comprises the largest administrative unit within the study area, while the remainder is located in Temanggung, Banjarnegara, Kendal, and Batang Regencies. See Fig. 2.

Result

Anthropogenic activity in the outer Dieng Highland in the second half of the last century

In the second half of the last century, during the Anthropocene, significant anthropogenic activity occurred in the Outer Dieng Highlands. There are two indicators of anthropogenic activity: increased land use for agriculture, marked by a shift in land cover from forest to non-forest, and an increase in built-up areas and settlement density. This rise in anthropogenic activity has occurred in tandem with population growth. In 2024, the population of Garung Subdistrict was 61,249, while that of Kejajar Subdistrict was 49,203 (BPS-Statistics Wonosobo Regency, 2025a, 2025b). Both subdistricts are located in Wonosobo Regency and constitute the core area of this study. Thus, the total population in the core area is 110,452 people. In 2024, population density was 1,137 people/km² in Garung and 753 people/km² in Kejajar. Population growth over the past ten years was 1.68% in Garung and 1.18% in Kejajar.

Human settlement in this area has existed for a very long time. In fact, the study area is part of a region known as the cradle of Javanese civilization (Degroot, 2009). During the Middle Ages, both DVC and Sundoro were part of an advanced civilization, as evidenced by the scattered archaeological sites throughout this area (Degroot, 2009, 2017; Sukronedi et al., 2018). Evidence of human life in the DVC dates back 17 centuries. During that period, residents cleared forests and utilized the land for agriculture (Harriyadi, 2019; Pudjoarinto & Cushing, 2001). This pattern has persisted for thousands of years up to the present. In Sundoro, particularly on the eastern flank, archaeological sites are distributed in clustered patterns and follow the distribution of springs (Ashari, 2014). This indicates that settlements initially formed in groups around specific resources, particularly springs. The lives of ancient inhabitants were also impacted by volcanic eruptions, as evidenced at the Liyangan site (Riyanto, 2014, 2017). The situation is similar to that at Merapi Volcano; the difference is that at Merapi, such threats remain a reality to this day (Ashari, 2013; Kapisan, 2025).

During the Anthropocene, over the past few decades, the population has grown rapidly and spread more widely across the study area. This is evident from the growth of settlements and the distribution patterns of built-up areas. Over the past half-century, from 1975 to 2025, the area of built-up has increased. In 1975, the built-up area in the study area was only 8.67%, then increased to 12.04% in 1985, 14.79% in 1995, 16.07% in 2005, 17.53% in 2015, and 19.21% in 2025. The area in 2025 reached 73.97 km², more than double that of the previous five decades, which covered only 33.00 km². The source of this data is image analysis spanning five decades. Over the past half-century, the trend of built-up land in the study area has continued to increase, with sharp growth occurring during the 1975–1995 period (Fig. 3).

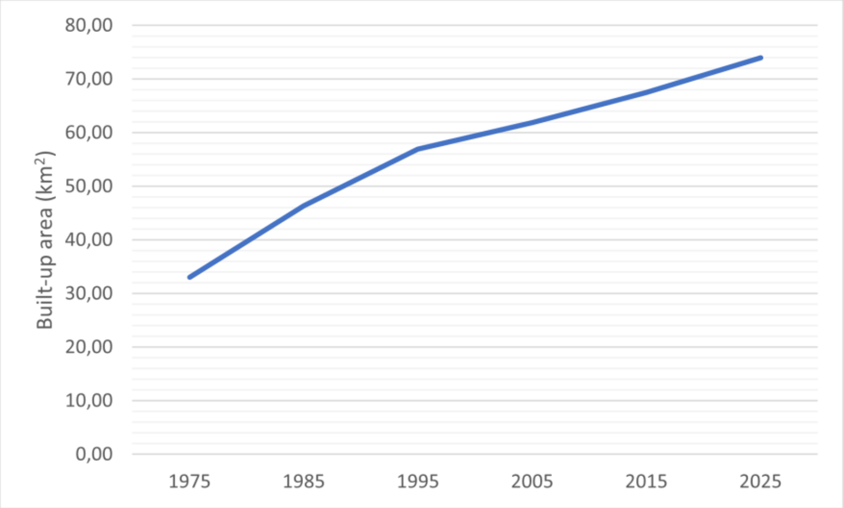

Fig 3. Growth of built-up areas over the past half-century

The increase in built-up area has primarily occurred in the valleys between stratocones, extending to the foothills of stratocones and stratovolcanoes. By 2025, built-up area will cover nearly one-fifth of the study area. This figure is relatively high because not all of this land is suitable for residential development. Landforms such as stratocone peaks, cones, and the slopes of the Sundoro stratovolcano are not suitable for habitation, both geomorphologically and climatically. The southern part of the study area, encompassing both the DVC and Sundoro sides, has experienced the most significant growth in built-up area over the past half-century. It can be concluded that settlement development tends to occur on relatively flat to gently sloping land with low elevations. The northern side, with its mountainous relief and high elevations, is an agricultural area that has experienced relatively slow settlement growth. On the Sundoro stratovolcano, settlement development follows the contour lines along the base of the volcano. See Fig. 4.

The Garung-Kejajar Valley, located between DVC and Sundoro, is the main corridor for settlement development. This area has indeed been inhabited since the earliest days of human settlement. Over the past five decades, settlement development has primarily occurred in this area. In recent decades, expansion has occurred at the foot of the Bisma Stratocone (Fig. 5). Settlement density has also increased, starting in this Garung-Kejajar corridor. In 1975, a high settlement density was observed at the foot of Sundoro Volcano due to its proximity to the city of Parakan. However, after 1985, a high-density population area began to form in the Garung-Kejajar region. This area has continued to grow into a high-density center over the last couple of decades due to population growth, agricultural production, and the advancement of tourism in the Dieng region. See Fig. 6.

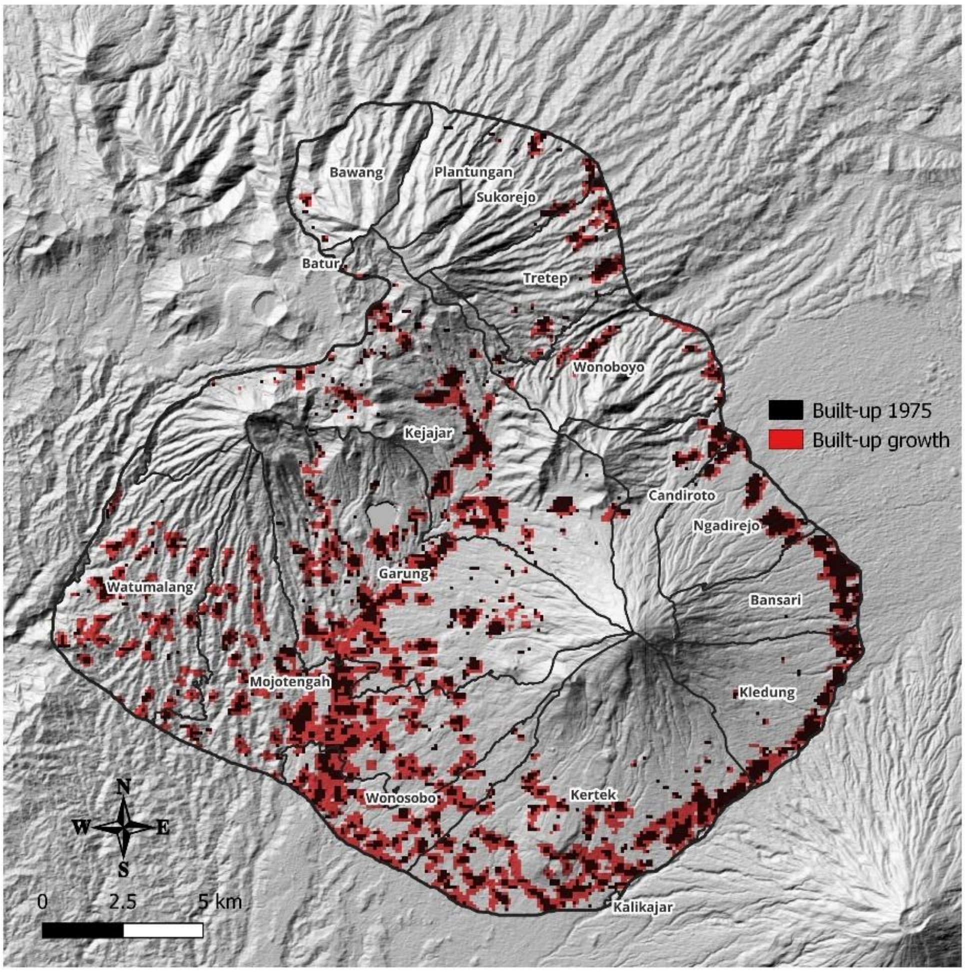

Fig 4. Settlement development since 1975 in the study area

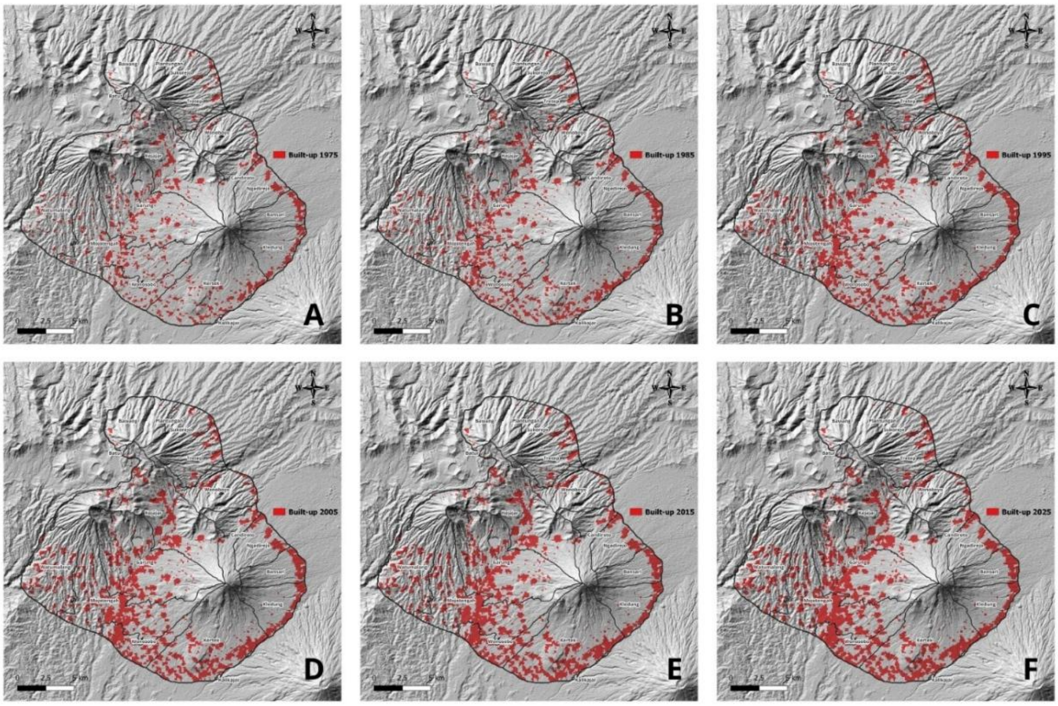

Fig 5. Settlement development since 1975 in the study area.
(A) 1975, (B) 1985, (C) 1995, (D) 2005, (E) 2015, (F) 2025.

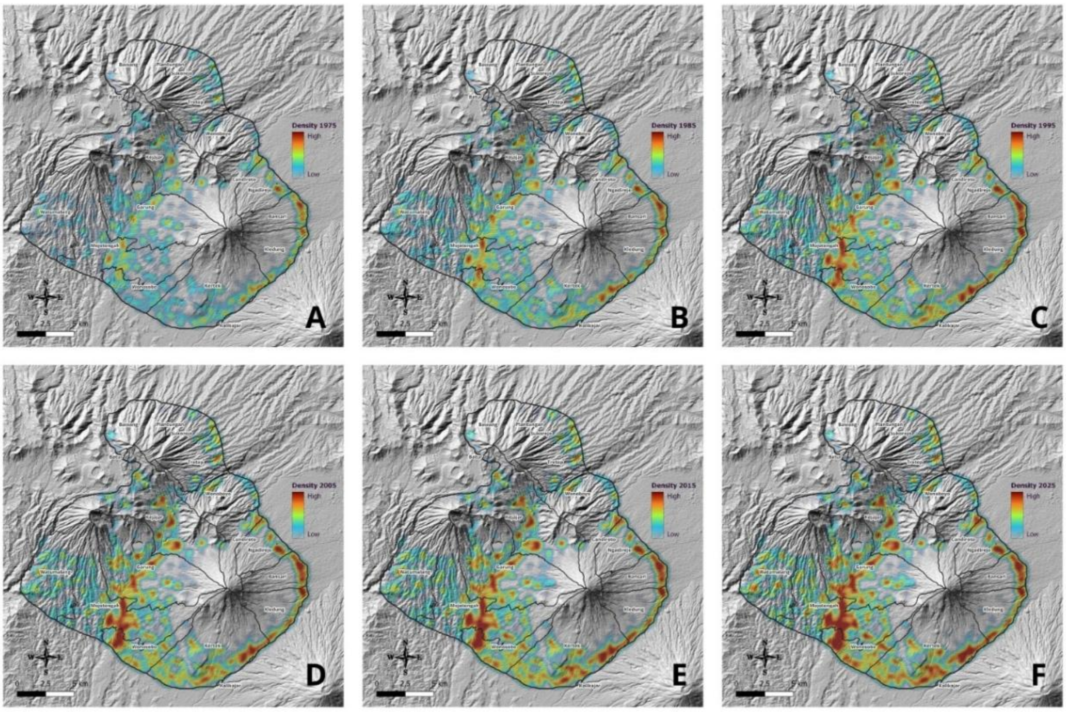

Fig 6. The growth in the density of settlement over the past five decades in the study area.
(A) 1975, (B) 1985, (C) 1995, (D) 2005, (E) 2015, (F) 2025.

The development of settlements in the study area is also indicated by a pattern of increasingly random settlement distribution from 1975 to 2025. The nearest-neighbor ratio has continued to increase toward 1 since 1975, reaching 0.53, 0.60, 0.64, 0.67, 0.69, and 0.71, respectively. The nearest-neighbor ratio, which continues to increase toward 1, indicates that settlements initially tended to be clustered in specific areas. However, as development progressed, settlement areas expanded. Many new settlement units were formed, leading to a more random distribution of settlements. The tendency for clustering in specific areas continued to decrease, giving way to a random pattern indicative of an increasingly widespread distribution. Significant developments in this random distribution pattern occurred in 1985 and 1995, coinciding with a significant increase in the number of settlement units and their density during that period.

Population growth is driving anthropogenic pressure on land. As a result of the population's need for food, land is converted from forest to non-forest use. Changes in land cover from forest to non-forest, particularly for agriculture, are actually fluctuating in tandem with ongoing deforestation and reforestation efforts. Areas experiencing significant forest loss include the foothills of stratovolcanoes such as Bisma and Prahu on the DVC side, as well as certain sections of volcanic slopes and volcanic foothills in Sundoro (Fig 7). Areas with flat and slightly sloping terrain have experienced changes in land cover because they have long been used for settlements and agriculture. As forest area decreases, agricultural land area increases, and vice versa. Land-use conversion, in turn, significantly accelerates denudation processes driven by exogenic factors.

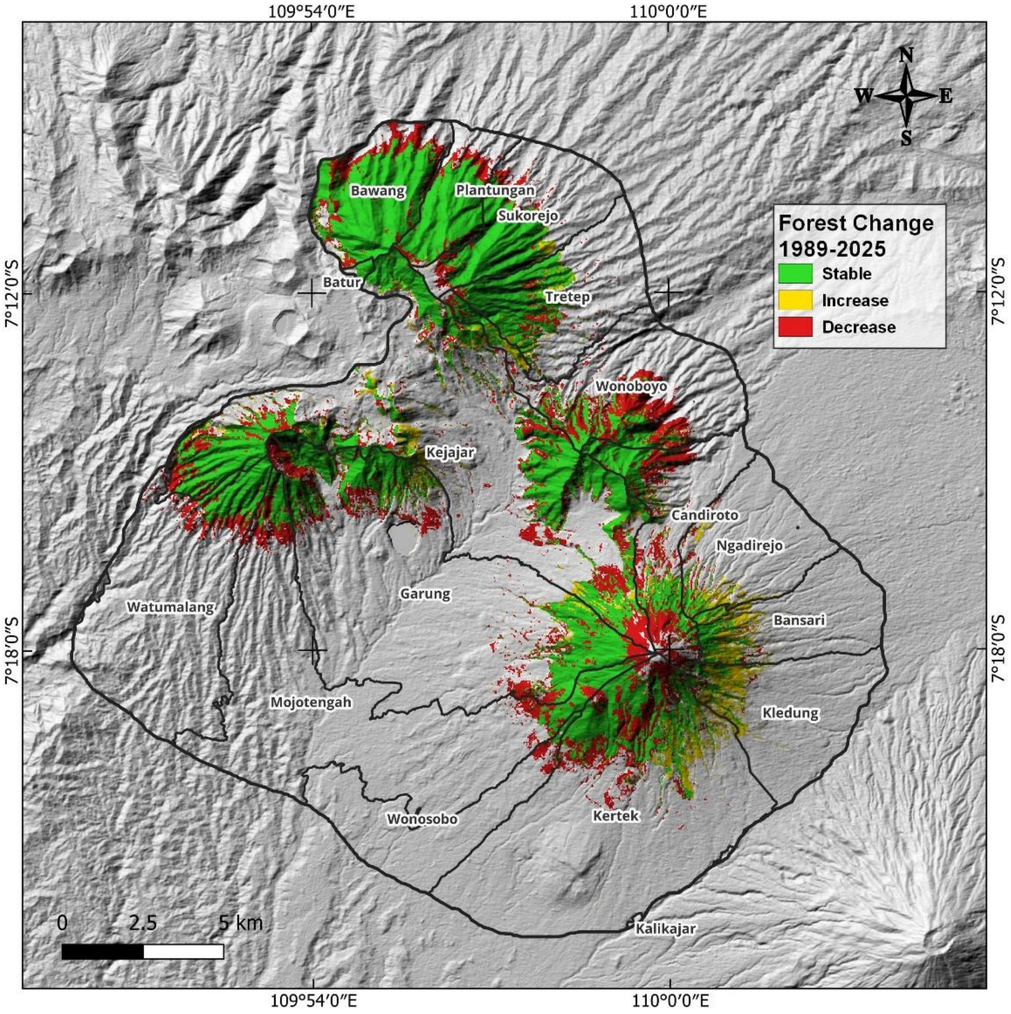

Fig 7. Forest change since 1989 in the study area

Geomorphological dynamics in the outer Dieng Highland in recent decades

In this section, we discuss the geomorphological dynamics of the outer Dieng Highland. This study addresses three geomorphological aspects: morphology, materials, and processes. Volcanic landforms characterize the outer Dieng Highland. The various landforms in this region are, by genesis, volcanic, ranging from small to medium-sized stratocones to large stratovolcanoes. Small stratocones have diameters <1 km and relief heights <300 meters, including Sikunir, Sidede, Bucu, Prambanan, and Pakuwaja. Medium-sized stratocones have diameters of 1–5 km and relief elevations of 500–1,000 meters, such as Bisma, Seroja (crater diameter 0.7 km), Kendil, Telerejo, and Prau.

Unlike stratocone units, Sundoro is the only morphology that exhibits the characteristic features of a stratovolcano, namely a conical structure with concave slopes from the summit to the valley, divided into three sectors, each separated by a break of slope. As a stratovolcano, Sundoro not only has a composite cone morphology but also features several parasitic cones, including Mount Kembang, Mount Watu, and Mount Kekep. This morphology indicates complex geomorphological development at Sundoro, where the volcanic cone structure developed atop the older Dieng rocks (Purwantara et al., 2025).

Geochronologically, the volcanic units in this region were formed partly during the Pleistocene and partly during the Holocene. Of the 11 volcanic units in this region, Prahu is the oldest, dating back 3.6 Ma; other sources indicate an age of.09 ± 0.92 Ma (Harijoko et al., 2016). The oldest volcanic units are found in the DVC, and the youngest is Sundoro. Generally, there are three volcanic groups in the DVC based on their age. Harijoko et al. (2016) refer to these three groups as the Pre-Collapse, Second Episode, and Youngest Episode; Harijoko et al. (2010) use the terms Pre-Caldera, Post-Caldera I, and Post-Caldera 2; While Sukhyar et al. (1986) refer to them as Old Dieng, Mature Dieng, and Young Dieng.

The first group, the Pre-Collapse group, consists of volcanoes that formed before the Prau volcano collapsed onto its southern flank, forming a plateau structure. This group includes Prau, Bisma, and Sidede. The second group, the Second Episode group, consists of volcanoes in the center of the DVC that erupted explosively, forming wide craters. This group is not found in the study area. The final group, or Youngest Episode, consists of effusive volcanoes on the southeastern edge of the DVC. Included in this group are Bucu, Prambanan, Sikunir, Kendil, Telerejo, and Seroja. See Table 2.

Table 2. Geochronology of the volcanoes in the DVC area

No	Group			Volcanoes	Age (Ma)
	Sukhyar et al. (1986)	Harijoko et al. (2010)	Haijoko et al. (2016)		
1	Old Dieng	Pre-Caldera	Pre-Collapse	Prau Bisma Sidede	1,09 ± 0,92 2,53 n.a.
2	Mature Dieng	Post-Caldera I	Second Episode	n.a.	n.a.
3	Young Dieng	Post-Caldera II	Youngest Episode	Bucu Prambanan Sikunir Kendil Telerejo Pakuwaja Seroja	n.a. n.a. n.a. 0,27 ± 0,12 0,13 ± 0,03 0,13 ± 0,03 0,07

Source: Sukhyar (1986), Harijoko et al. (2010), Harijoko et al. (2016).

The rock types in the study area are highly diverse, including basaltic and basaltic-andesitic lava, andesitic, dacitic, and latitic lava; complex volcanic rock groups, tuff, and lake deposits. Basaltic and basaltic-andesitic lava is found in the Bisma and Sidede stratocones. Andesitic lava is widely distributed, including at the Prambanan, Sikunir, Kendil, and Pakuwaja stratocones. Dacitic lava is found at the Seroja stratocone. Latitic lava is found at Pakuwaja. In addition to these lava types, a volcanic rock group is also found in the Prau and Bucu stratocones. A volcanic rock group is a combination of various types of eruption products, namely tuff, breccia, and lahar.

Observations of outcrops at Prau Volcano reveal layering of pyroclastic density currents (PDC) and pyroclastic fall (Fig. 8A). This material has weathered to such an extent that the fragments and matrix constituting the PDC are no longer clearly visible. However, they remain identifiable by their poor sorting. Layering of PDC with pyroclastic fall is also observed at Pakuwaja, where the material is less weathered due to its much younger age than at Prau (Fig. 8B).

Dieng Tuff extensively fills the basins between stratocones, particularly on the Dieng Plateau. This material is part of the Dieng Tephra, produced by volcanoes that erupted explosively during the second episode, namely Pangonan-Merdada and Pagerkandang. The volcanic edifices of these volcanoes lie outside the study area, but their products fill this region. Lake deposits are found in the Dieng Basin and Telaga Cebong, which are surrounded by stratocones. Core samples taken in the Dieng Basin indicate that lake deposits have accumulated to a thickness of 3 meters, and beneath them lies Dieng Tephra, a pyroclastic fall material from the second episode.

The diversity of materials in the various stratocones within the DVC is closely linked to the characteristics of the magma in the DVC itself. Harijoko et al. (2016) explain that the magma at DVC has evolved. The pre-caldera episode featured more mafic magma with low SiO_2 content, the second episode involved intermediate magma, while the youngest episode was more felsic with high SiO_2 content. These conditions indicate a trend of magma evolution becoming increasingly silica-rich over time. The DVC has multiple shallow magma chambers. The pre-caldera group, with its primitive, more mafic magma, produced basaltic lava, as found at Bisma and Sidede. Meanwhile, the youngest episode group, with its evolved, more felsic magma, tends to produce andesitic to dacitic lava, as observed at Prambanan, Sikunir, Kendil, Pakuwaja, and Seroja. The increasingly viscous magma from the youngest episode even led to the formation of lava domes, as observed at the Stratocone at Kendil, Sikunir, and Prambanan.

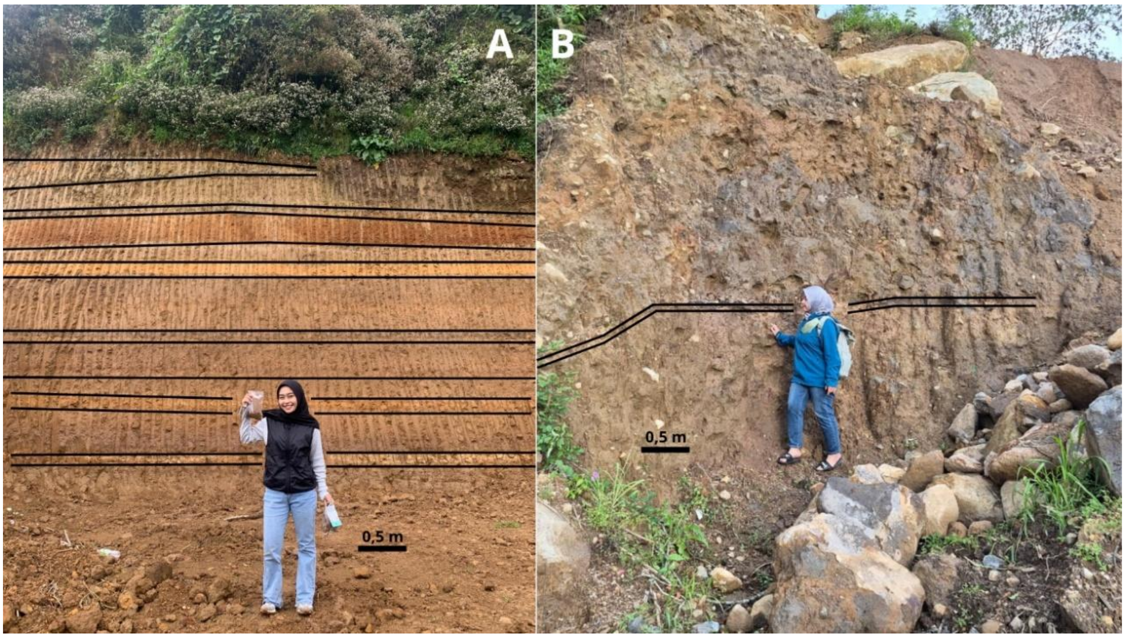

Fig 8. Materials from explosive volcanic activity at DVC. (A) Pyroclastic fall layers interbedded with PDC from an outcrop at the base of Prau Volcano; the material is highly weathered, making visual identification difficult. Located on $7^0$12'25.09"S and $109^0$55'07.96"E. (B) PDC layers interbedded with pyroclastic fall from an outcrop at the base of Pakuwaja Volcano; the PDC material is relatively fresh. Located on $7^0$15'41.09" S and $109^0$57'03.48" E (Source: Fieldwork on September 30, 2025, for Fig. A, and February 7, 2026, for Fig. B).

The rock material at Sundoro Volcano consists of several lava and pyroclastic series, as is commonly found in composite volcanoes. In addition, there are also lahars and phreatic or phreatomagmatic deposits. Referring to Sukhyar et al. (1992), at Sundoro Volcano, there are 11 lava flow deposits, six pyroclastic deposit units, and two pyroclastic fall deposits. In addition, there is one lahar deposit and three flank eruption units. Prambada et al. (2016) explain that the lava flow is distributed across the entire slope and consists of basaltic andesite to andesite. The pyroclastic deposit (PDC) also consists of basaltic andesite to andesite with very poor sorting; it extends up to 13 km from the crater and reaches a thickness of 10 meters (Fig. 9A). The pyroclastic fall consists of pumice, scoria, and ash. This material is widely distributed, with 75% of the volcanic edifice covered by pyroclastic fall. Pyroclastic fall alternates with PDC, as observed in outcrops found on the northern flank (Fig. 9B and 9C). Phreatomagmatic material is found around the modern crater. At the same time, lahars which are reworked deposits are distributed on the volcanic flank.

Geomorphic processes in the study area, both on the DVC and Sundoro sides, were initiated by volcanic activity. On the DVC side, the various stratocones in this study area were largely formed by effusive eruptions interspersed with several explosive eruptions. Each stratocone unit was formed by the accumulation of lava flows, interspersed with pyroclastic deposits both PDC and fall deposits and occasionally the formation of lava domes. These recurring cycles subsequently formed layered stratocones; structurally, the layered materials resemble those of a stratovolcano but on a smaller scale. It can be concluded that the stratocones in Dieng were formed by a multi-center volcanic system with separate shallow magma chambers. Each eruption center forms a stratocone by accumulating lava and pyroclastic deposits during repeated eruptions. Various eruptions on the DVC side occurred in the very distant past, as evidenced by the landform's great age (see Table 3). The only historically recorded eruption on the DVC side of this study area occurred at Pakuwaja, which was large enough to reach VEI-3.

Fig 9. Eruptive products from Sundoro Volcano. (A) PDC from the Kembang Group on the southern flank of Sundoro, located at 7°19'00.53 "S and 109°56'45.26" E. (B) A pyroclastic fall deposit at the northern flank of Sundoro with soil at the topmost layer, located at 7°16'17.29" S and 109°59'09.31" E. (C) The PDC is at the very bottom, overlain by the pyroclastic fall deposit above it. Figure C is a continuation of the right side of Figure B. (Source: Fieldwork on February 7, 2026).

Table 3. Recorded-Eruption on the DVC Side of the Study Area

No	Year	Location	Eruption type	Description
1	1375 ± 75 years	Pakuwaja	Explosive eruption	A VEI-3 eruption spewed ash and sand that covered all the temples in Dieng.
2	1825	Pakuwaja	Explosive eruption	A VEI-3, ejected ash and sand.

3	1826	Pakuwaja	Explosive eruption	A VEI-2, ejected ash and sand. The eruption on October 9, 1826, was heard as far away as Yogyakarta (~100 km). The eruption on October 11, 1826, caused tremors lasting 2 hours that were felt as far away as Pekalongan (~50 km). The eruption ended on October 15, 1826.
4	1847	Pakuwaja	Explosive & Phreatic eruption	A VEI-2 on December 4, 1847, produced ash.

Source: Central of Volcanology and Geological Hazard Mitigation (2025).

Interestingly, tectonism also played a role in the geomorphological processes during the early development of the DVC. Tectonism caused the collapse of the southern flank of Prau Volcano, forming an ancient caldera. Harijoko et al. (2016) noted that the arcuate structure of Prau Volcano had previously been interpreted as a caldera that had survived only in its northern portion. However, since the DVC is located above a fault intersection, it can alternatively be interpreted that the arcuate structure of Prau Volcano formed as a result of a volcano-tectonic collapse rather than solely a caldera-forming eruption. The Bisma stratocone shows signs of flank collapse on its southeastern side, where debris is heavily accumulated in front of the collapsed flank area. Verstappen (2013) has identified this phenomenon, which is comparable to that observed in large stratovolcanoes such as Merbabu and Merapi (Bronto et al., 2014; Suhendro et al., 2025).

At Sundoro Volcano, geomorphological development began with the formation of volcanic structures through a series of explosive and effusive eruptions. Eruptions at Sundoro Volcano are driven by basaltic-andesite to andesite magma with high viscosity and high gas content. 12 major eruption groups have occurred since approximately 34 ka, namely the Ngadirejo, Bansari, Arum, Kembang, Kekep, Garung, Kertek, Watu, Liyangan, Kledung, Summit, and Sibajak groups (Prambada et al., 2016). These eruptions produced PDCs, pyroclastic flows, and lava flows that covered a wide area and shaped the Sundoro edifice over time. Eruptions during the early period played a significant role in shaping morphology, whereas those during the later period did not. In the early stages, eruptions produced large amounts of material that contributed to the formation of the Sundoro edifice. Meanwhile, more recent eruptions have tended to be concentrated around the crater, resulting in minimal geomorphological impact. See Table 4.

Following the volcanic era that formed the volcanic structures, geomorphic processes on both the DVC and Sundoro sides were dominated by exogenic processes of denudation. Denudation driven by rainfall and surface runoff over a long period of time led to the formation of radial valleys on the slopes of the volcanic structures. The older DVC side has more developed valleys compared to the Sundoro side. Analysis results show that valleys on the DVC reach order 5, the highest order in this area, whereas on the Sundoro side, they reach only order 4. Additionally, the DVC has a total river valley length greater than that of the Sundoro side. Meanwhile, in terms of valley orders, the Sundoro side is longer only at order 3 compared to the DVC; for the remaining orders, the river valleys on the DVC are consistently longer. On both the DVC and Sundoro sides, order 1 is the longest due to the greater number of streams. Furthermore, higher orders have shorter valley lengths because they are formed as junctions of two lower orders at the same level (See Table 5 and Fig 10).

Table 4. Chronology of the Eruptions of Sundoro Volcano

No	Unit	Age (Ka)	Eruption characteristics	Morphological implication
1	Ngadirejo	~34	The oldest eruption group represents the early stage of Sundoro's formation. Its activity was dominated by explosive eruptions that produced	Plays a key role in shaping the mountain's early morphology and contributes significantly to its total volume.

			pyroclastic fall deposits and PDCs over a wide area.	
2	Bansari	~20	Characterized by widespread pyroclastic flows and pyroclastic deposits filling the valleys, this indicates a phase of fairly intense explosive activity following the volcano's initial formation.	Expanding the volcanic edifice and increasing the stratigraphic complexity of Sundoro.
3	Arum	~17–19	Characterized by repeated explosive eruptions similar to those of Bansari.	Reinforcing the structure and filling in the existing topography.
4	Kembang	~13–17	Characterized by thick tephra fall and widespread PDC.	Increasing the volume of the mountain and reinforcing the conical shape of the stratovolcano.
5	Kekep	~13–17	The eruption pattern is the same as Kembang's	Reflecting a period of intense activity marked by repeated eruptions that significantly shaped the morphology of Sundoro.
6	Garung	~11–13	Dominated by the PDC deposit	Forming a large volcanic fan around the volcano
7	Kertek	~9	A combination of explosive and effusive	Forming slopes through lava flows and adding to the complexity of the morphology
8	Watu	Unknown	Early Holocene activity was characterized by smaller eruptions than in the previous phase.	Produces thin pyroclastic deposits (ash, lapilli, and andesite fragments) that are spatially limited.
9	Liyangan	~1	An important eruption from the early Holocene, particularly due to its connection to the Liyangan archaeological site.	The deposits consist of pyroclastic fall and possible small-scale PDC, indicating a local explosive eruption.
10	Kledung	~1	It is of a similar age to Liyangan and shows evidence of recent, limited-scale eruptions.	Produces ash and lapilli deposits with a local distribution.
11	Summit	Unknown	Eruptive activity is concentrated in the main crater.	Produces ash and fine material associated with small to moderate eruptions.
12	Sibajak	Unknown	The most recent eruption phase reflects the current activity of Sundoro Volcano.	Producing ash, fine lapilli, and light pyroclastic material scattered around the crater.

Source: Prambada et al. (2016)

Table 5. Stream morphometry as an indicator of long-term denudation processes in volcanic structures

No	Category	Stream Length (km)	
		DVC	Sundoro
1	Orde 1	555,97	463,89
2	Orde 2	285,90	249,73
3	Orde 3	122,11	126,06
4	Orde 4	50,80	30,61
5	Orde 5	8,42	n.a.
6	Total	1023,20	870,30

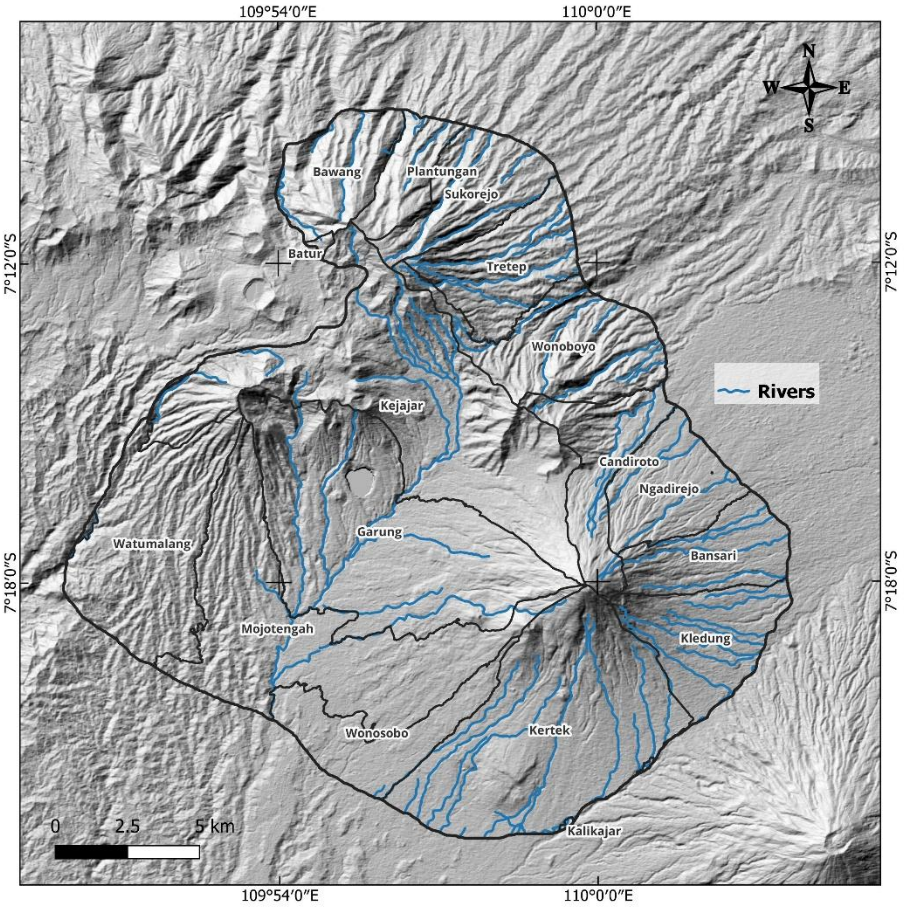

Fig 10. River system in the study area

During the Anthropocene, denudation processes have become increasingly widespread on both the DVC and Sundoro sides. In the DVC, erosion occurs across all stratocones and intensifies during the rainy season. High erosion rates occur primarily on land where natural vegetation cover has been significantly reduced for agricultural purposes. Erosion types vary, including splash, sheet, and rill erosion. Areas with high-density forest cover exhibit very low erosion rates. On lands with limited large vegetation cover, sheet erosion occurs. Splash erosion followed by rill erosion occurs on agricultural lands with little large vegetation to act as a barrier against rain-induced erosion. Erosion leads to soil loss, resulting in very thin soil layers. Stratocones such as Pakuwaja, Kendil, and Prambanan, which contain abundant lava, have resistant rocks that weather slowly; many outcrops are found there, with thin soil layers overlying them. Similar to the DVC, land in Sundoro generally also experiences erosion with the same patterns. The reduction in natural land cover triggers more extensive soil erosion. Erosion occurs during the rainy season, when rain and runoff are important geomorphic agents, since Sundoro is located in a wet tropical region.

The most common type of landslide is a slide. Slides are associated not only with changes in land cover toward open terrain but also with slope conditions. Slides are more likely to occur on steep slopes. For example, a slide on the western flank of the Seroja Stratocone occurred in an area with natural shrubland vegetation. Events at the same location have been reported for five years and continue to occur to this day, although the landslide locations and intensities are not always the same (Wardoyo et al., 2021). A massive landslide occurred in mid-February 2026, triggered by heavy rainfall, along the arcuate arc structure of Prau Volcano. The landslide path was extremely long, extending hundreds of meters from the summit to the base of the caldera rim due to the steep slope. Anthropogenic activities, such as infrastructure development particularly road construction are also linked to landslide occurrences. At the base of the Prau caldera rim, within the Dieng Plateau area, there are road sections prone to landslides during every rainy season.

Slope cutting for road construction increases the slope gradient, thereby heightening the potential for slope failure, especially when the slopes are saturated and lubricated by rainwater. See Fig 11.

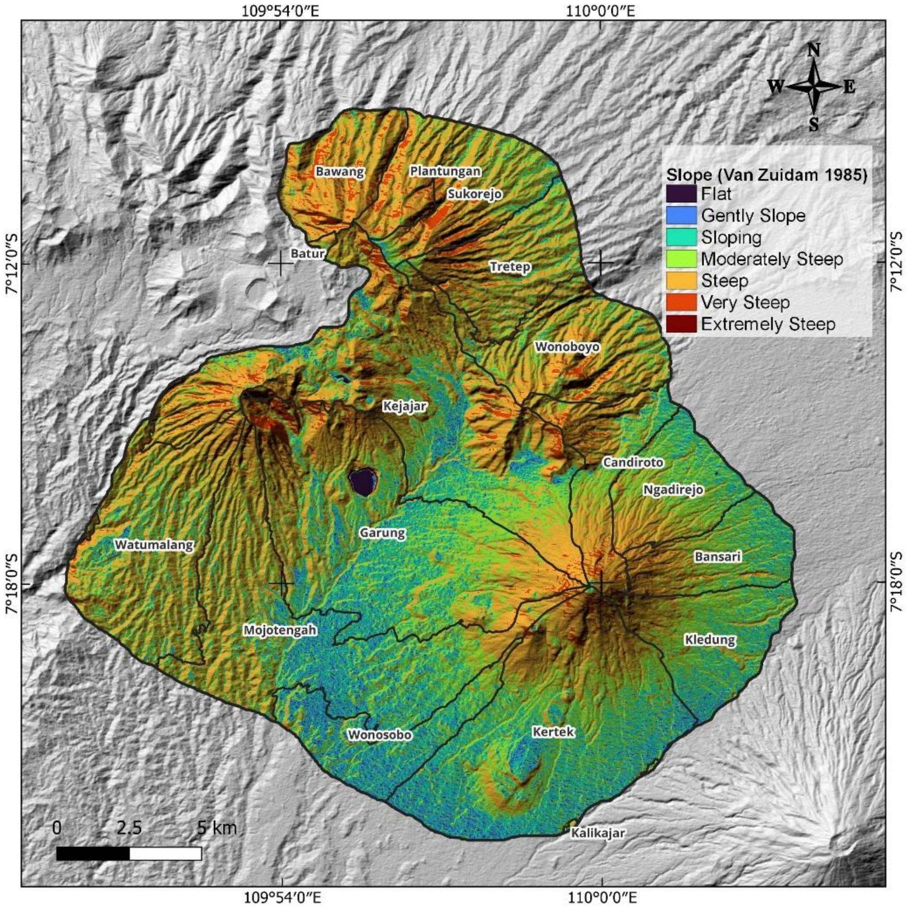

Fig 11. Slope in the study area. Steep slopes in the DVC sides tend to cause slope failure

In contrast to the DVC side, mass movements on the Sundoro side are very limited. The number of events, as well as their magnitude and impact, is smaller compared to those in the DVC. The older DVC has undergone advanced weathering. Given the rocks' already high degree of weathering, the potential for mass movements is greater in the DVC than in Sundoro. Meanwhile, in the Sundoro area, where the edifice's surface is largely filled with pyroclastic material, erosion tends to occur. Anthropogenic activities play a significant role in the various processes of denudation occurring in this region. Analysis results show that the average NDVI in DVC is 0.45, while in Sundoro it is 0.39. NDVI ranges from -1 to 1, where values from -1 to 0 indicate non-vegetation objects such as water, soil, or rock outcrops. However, values from 0 to 1 represent vegetation. The values obtained for both DVC and Sundoro are well below 0.5, indicating that the average vegetation density is low. In DVC, many forested areas remain, resulting in a high average, even though agricultural land use is extensive and extends to the peaks of various stratocones. Meanwhile, in Sundoro, the natural land cover at high elevations on the volcanic cone consists of relatively low-density shrubland.

Although there are differences between the DVC and Sundoro sides, it can be concluded that anthropogenic activities that alter land cover and modify slopes are accelerating denudation. In the future, as anthropogenic activities become increasingly dominant and volcanic edifice construction remains very limited, the landforms in the study area will continue to be denuded. As an indicator, the valleys on the volcano's slopes will continue to expand in length, width, depth, and density. Soil loss whether gradual through erosion or drastic through landslides can persist, leading to thin soil layers. Erosion and relief degradation may continue, resulting in increasingly rugged topography.

In this study, we analyzed land cover using a 19x-zoomed SASPlanet imagery captured in 2025. This image has a spatial resolution of 1 meter and consists of three bands red, green, and blue which were classified using the maximum likelihood supervised method. The maximum likelihood method classified the data into four land cover classes: built-up land, agricultural land, water bodies, and vegetation. Subsequently, landslide event data from the Regional Disaster Management Agency of Wonosobo Regency (locally known as BPBD) for 2021–2026 were overlaid onto these four land cover classes. Analysis results indicate that within the core area of the Outer Dieng Highland, 14 landslide events occurred during this period, with 64% occurring on agricultural land, 7% on built-up land, and 29% on land with natural vegetation cover. When areas surrounding the study area were included, 29 landslide events were recorded. Of these landslides, 55% occurred on agricultural land, 17% on developed land, and 28% on land with natural vegetation cover. These findings confirm that landslide occurrences are indeed associated with the impact of anthropogenic land-use activities. See Fig. 12.

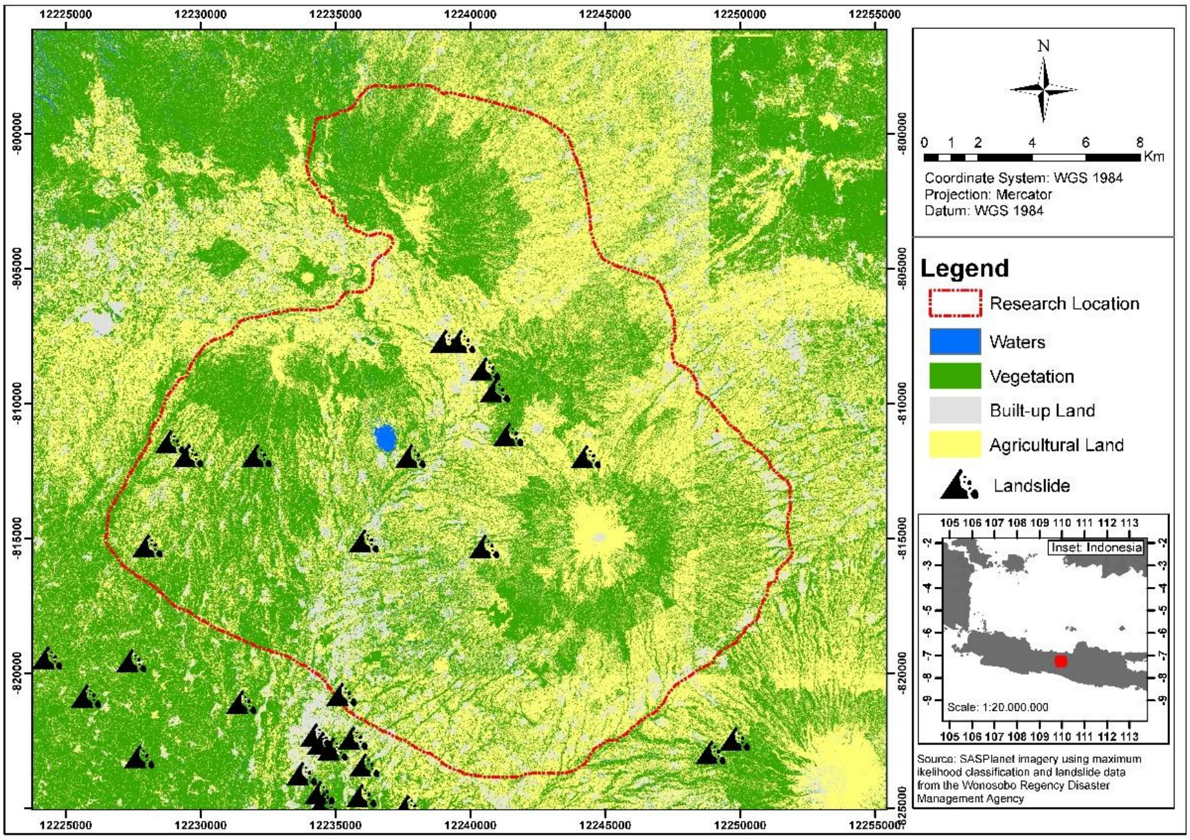

Fig. 12. Distribution of landslide occurrences across various land cover types in the study area and its surroundings (Source: Regional Disaster Management Agency of Wonosobo Regency, 2026).

Basically, this region experiences high rainfall. This is evident from rainfall totals in the Garung and Kejajar subdistricts of Wonosobo Regency, which constitute the core of this study area. The annual rainfall in the Dieng region is very high, over 3000 mm/year, which represents a primary trigger for landslides (Susena et al., 2025). Data from the Wonosobo Regency Central Statistics Agency indicates that rainfall in Garung Subdistrict in 2024 reached 4,579 mm with 208 rainy days; the heaviest rainfall occurred in February, totaling 685 mm over 26 rainy days. In Kejajar Subdistrict, rainfall in 2024 was slightly higher, reaching 4,708 mm with 241 rainy days. The highest rainfall occurred in December, totaling 1,025 mm. This high rainfall indicates that this region has strong geomorphic potential for denudation. Anthropogenic activities that have modified the natural environment during the Anthropocene have further accelerated the impact of climate change on denudation, characterized by high erosion rates and landslides on steep slopes.

Discussion

Anthropogenic geomorphology is an increasingly important topic as the impact of human activities on geomorphological processes has grown significantly during the Anthropocene. In this study, we found that anthropogenic activities accelerate climate-driven denudation, despite the absence of constructive volcanic processes in the formation of volcanic edifices for a very long time. The Outer Dieng Highland, the area studied in this research, represents a volcanic system formed through multiple episodes and characterized by complex geomorphological conditions. The diverse morphological variations, ranging from small stratocones to large stratovolcanoes, reflect strong control by magma dynamics. Tectonism also plays a significant role in geomorphological development, further demonstrating that volcanic morphology is often controlled by a combination of two processes: tectonic and volcanic processes (Widagdo et al., 2018). Also, the study area exhibits diverse lithologies, particularly on the DVC side, with varying volcanic facies resulting from the differences in each eruptive process (Yudiantoro et al., 2025). Due to high rainfall, climate exerts a strong influence on landscape denudation; however, in recent decades, anthropogenic factors have become increasingly significant in accelerating this process.

In the study area, morphological development driven by volcanic activity has indeed been absent for a long time. By comparison, at Merapi Volcano, for example, valley-shifting dynamics controlled by lahar deposition have persisted over the past century and even in recent decades (Ashari et al., 2021). Given the limited influence of magmatic volcanism, climate plays a significant role in geomorphological dynamics accelerated by anthropogenic activities. Land-use change drives erosion and mass movements. Several landslide events are associated with slope cutting for road construction and other infrastructure, as has occurred on Mount Merbabu over the past decade, providing a comparison (Nurhadi et al., 2015). On various stratocones on the DVC side, weathering has progressed significantly, resulting in low infiltration. Consequently, surface runoff causes erosion or landslides. Meanwhile, in Sundoro, where pyroclastic material is abundant and the strata are younger, infiltration still occurs, helping mitigate the impact of runoff. Sundoro, being relatively young, indeed has a high infiltration capacity and, consequently, serves as a potential water source, as is the case at Merapi Volcano for comparison (Ashari, 2017; Purwantara et al., 2020, 2026; Ratih et al., 2018, 2019; Setyawati & Ashari, 2017).

Indonesia is one of the countries with the highest levels of volcanism in the world (Ashari & Purwantara, 2022). Landform dynamics resulting from volcanic processes have, of course, been extensively studied. On the other hand, the influence of anthropogenic activities that accelerate the denudation of volcanic structures remains underexplored, as it has been relatively underrepresented in previous literature. Therefore, this study provides new insights into the anthropogenic influence on geomorphological evolution in volcanic landscapes. Our findings indicate that land-use changes can accelerate erosion, leading to a thinner soil profile on stratocones composed of weather-resistant rock. Erosion results in an increasing number of exposed outcrops. Meanwhile, landslides are strongly associated with steep slopes. Infrastructure development particularly roads that cut across slopes and increase slope steepness has also been shown to be associated with an increased risk of slope failure. As part of the Wonosobo Volcanic Area, the study area did indeed experience geomorphological dynamics controlled by volcanism during the early geological history (Purwantara et al., 2025). However, in the Anthropocene, the dominant influence has shifted from volcanism to climate, accelerated by anthropogenic factors.

The findings of our study reinforce those of previous studies, indicating that anthropogenic pressures can trigger denudation processes in volcanic landscapes. Purwaningsih et al. (2020) found that agroforestry, as the dominant land-use practice on the slopes of Java's volcanoes, increases vulnerability to landslides, soil creep, rill erosion, and gully erosion. Even semiconservative systems, such as agroforestry, still drive geomorphic processes on volcanic slopes. Pratiwi et al. (2024), in a study conducted at Sumbing Volcano adjacent to this research area found that landslides on volcanic slopes are not only triggered by natural factors but are also frequently triggered by human activities. This process primarily occurs in areas that have previously experienced landslides and have since been reused by humans. Thus, from a geomorphological perspective, relict landslides are reactivated by anthropogenic activities. As a preliminary study, our findings have not yet identified the details or established a typology of anthropogenic influences on geomorphological dynamics. Nevertheless, our study has confirmed that geomorphological dynamics in the outer Dieng Highlands since the Anthropocene have also unfolded under the influence of anthropogenic pressures.

As an evaluation, our study also has limitations, namely that it remains focused on identifying evidence that anthropogenic influences primarily drive current geomorphic processes. Consequently, we have not yet observed more in-depth findings, such as those reported by Abe et al. (2020) in West Sumatra, in our study area. In their study, Abe et al. (2020) found that intensive agriculture on volcanic soils specifically intensive vegetable cultivation can lead to soil degradation through acidification and loss of organic matter. Soil degradation weakens soil structure, thereby indirectly increasing vulnerability to erosion and landslides. The results of this study present intriguing findings for future research in the Outer Dieng Highlands regarding the impact of agricultural activities on soil degradation, within the framework of anthropogenic pressures on geomorphological dynamics in volcanic landscapes.

Finally, our study contributes to the understanding of the influence of anthropogenic activities on geomorphological dynamics in volcanic landscapes. This topic has received relatively little attention in the context of volcanic geomorphology in Southeast Asia. (Olivia et al., 2024) indicate that volcanic-geomorphology studies in Southeast Asia during the Anthropocene have primarily focused on: geology and volcanism, disasters, natural resources, typology of volcanoes, volcanic morphology, reconstructing paleomorphology and paleostructure, and geomorphic processes related to volcanism. Geomorphic processes influenced by anthropogenic activities that affect volcanic morphology have not been identified over the six decades from 1963 to 2024. Thus, this study initiates a discussion on the role of anthropogenic activities in volcanic geomorphological dynamics.

Conclusion

Anthropogenic activities have played an increasingly important role in geomorphological development, particularly in the Anthropocene. Here, we find that in complex volcanic and stratovolcanic environments where volcanism does not play a significant role in geomorphological construction, exogenic processes are becoming increasingly dominant and are accelerated by anthropogenic activities. The conversion of natural land cover to cultivated land can accelerate erosion beyond the rate of soil formation, leading to a thinner soil profile. Slope cutting for infrastructure development on stratovolcanoes also steepens slopes, thereby increasing the risk of slope failure. The climate in the study area is characterized by high rainfall, which strongly drives denudation processes. Under the influence of anthropogenic activities, these denudation processes become even more intense, as this study validates frequent reports of erosion and landslides in this region.

The findings of this study suggest that population pressure on land can accelerate denudation. This can occur across various landforms. In this study, we provide insights and alternative information regarding volcanic complexes. However, anthropogenic impacts are certainly not uniform across all regions. Other geomorphological aspects, such as structure, morphology, and materials, also determine the extent of the impact of denudation processes accelerated by anthropogenic activities. Finally, with additional information regarding the influence of anthropogenic activities on geomorphological processes, it is hoped that this will provide a basis for considering the Anthropocene as part of Earth's geological history.

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Author Contribution

Grace Helena A. Kapisan: Conceptualization, Methodology (Designing observation methods and instruments for geomorphological survey), Formal Analysis (Geomorphological analysis), Investigation (Field survey), Writing Original Draft, Project Administration. **Arif Ashari:** Conceptualization, Methodology (Designing observation methods and instruments for geomorphological survey), Formal Analysis (Geomorphological analysis), Investigation (Field survey), Writing Original Draft, Writing Review & Editing. **Xingzhou Jiang:** Conceptualization, Validation, Resources, Supervision. **Sumayyah Aimi Mohd Najib:** Conceptualization, Validation, Supervision. **Muhammad S. Roganda:** Methodology (Designing remote sensing methodology), Formal Analysis (Land cover and vegetation density analysis), Investigation (Field survey). **Yusuf Susena:** Methodology (Designing remote sensing and GIS methodology), Formal Analysis (Land cover change analysis, ANN analysis, and KDE analysis). **Afrinia L. Permatasari:** Methodology (Designing GIS methodology), Formal Analysis (drainage density analysis). **Anggoro Putranto:** Formal Analysis (Geomorphological analysis), Investigation (Field survey). **Edi Widodo:** Formal Analysis (Geomorphological analysis), Investigation (Field survey). **Bagus Tegar S. Prakosa:** Investigation (Field survey), Visualization (design map). **Raisya A. Olivia:** Investigation (Field survey). **Heng Zhang** Formal Analysis (Geomorphological analysis).

Data Availability Statement

All data generated or analyzed during this study are presented in the tables and figures within this article.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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