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Driver-Pressure-State-Impact-Response (DPSIR) Analysis of Landslide Potential in Punten and Gunungsari Villages, Bumiaji District, Batu City, East Java, Indonesia

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ABSTRACT

Landslides are a recurring hazard in the highland villages of Punten and Gunungsari, Batu City, where natural fragility intersects with human-induced landscape change. This study applied the Driver–Pressure–State–Impact–Response (DPSIR) framework to analyse the socio-ecological dynamics of landslide risk and inform context-appropriate mitigation. A qualitative descriptive approach was employed from May to July 2025, combining field observations, Focus Group Discussions, and in-depth interviews with 100 residents and village authorities. The DPSIR analysis shows that the main Drivers include steep volcanic slopes, high rainfall, agricultural expansion into former forest areas, tourism-driven land conversion, and weak spatial-planning enforcement. These create Pressures such as deforestation, continuous cultivation of shallow-rooted vegetables, soil degradation, inadequate drainage management, and limited financial capacity for soil conservation. The State of the system is characterised by declining slope stability, reduced vegetation cover, increased runoff and sedimentation, and high dependence on climate-sensitive agriculture. Impacts observed include damage to farmland, houses, and infrastructure, livelihood losses, psychological distress during the rainy season, and unequal recovery among households. Existing Responses comprise early warning systems, vetiver and bamboo planting supported by Perhutani and the Indonesian National Armed Forces, disaster awareness activities, and community mutual aid, yet these remain intermittent, weakly maintained, and lacking long-term coordination. The study highlights the need for more preventive, participatory, and integrated land-use governance, supported by sustained community capacity-building and improved seedling access to strengthen slope rehabilitation efforts.

INTRODUCTION

Landslides are natural hazards that adversely impact people and the economy, triggered by both natural processes and human actions (Guzzetti, 2016; Zamroni et al., 2020; Li et al., 2022; Capobianco et al., 2025; Van Wyk de Vries, 2025; Nguyen et al., 2025). Landslides are responsible for significant social and economic losses, particularly in upland and hilly regions (Perera et al., 2018; Nseka et al., 2021; Sim et al., 2022; Fidan et al., 2024; Tran et al., 2024; Alcántara-Ayala, 2025). Lanslide occurrences have shown an increasing trend in Indonesia over the years due to climate change, reflecting the country's growing vulnerability to hydro-meteorological hazards (Putra et al., 2021).

Batu City, situated in East Java Province, represents one of the regions that consistently experiences recurrent landslide events (Lutfi et al., 2024). The city lies within a highland area surrounded by three major volcanic mountains, i.e., Mount Welirang (3,156 m), Mount Panderman (2,010 m), and Mount Arjuno (3,339 m). The East Java Regional Disaster Management Agency

(BNPB) has designated Batu City as a hilly region highly prone to landslides. Based on susceptibility modelling, landslide-prone areas in Batu City are classified into three categories, i.e., low, moderate, and high, with spatial coverage of approximately 15,448.32 ha (77.75%) falling under the low-susceptibility zone, while the remaining areas exhibit moderate to high vulnerability (Riestu & Hidayat, 2022). This distribution indicates that although a large portion of Batu City is categorised as low susceptibility, localised zones, particularly in steep agricultural and settlement areas, still pose significant landslide hazards due to slope instability and intense rainfall. There are ten sub-districts in Batu City, with most high-risk areas concentrated within Batu District.

The mountainous topography of Batu City, coupled with intense rainfall and extensive land-use changes resulting from agricultural expansion and settlement development, creates conditions highly conducive to landslides. The city's steep slopes and high precipitation rates accelerate soil saturation and reduce slope stability, leading to frequent mass movements. Most of the soils in Batu City are classified as Andosols (Batu City Government, 2011), which are volcanic in origin and typically have low bulk density, high porosity, and a loose structure. While these characteristics promote good water retention and fertility, they also reduce soil cohesion and shear strength, making Andosols particularly vulnerable to erosion and slope failure during prolonged or intense rainfall events.

Within Batu City, Punten and Gunungsari Villages in Bumiaji District have been identified as among the most landslide-prone areas. In 2023, both villages experienced a significant landslide event that resulted in considerable physical damage and disruption to local livelihoods. The recurrence of a similar incident in 2025 in Gunungsari Village, where landslide material temporarily obstructed the main road, further underscores the persistence of geomorphological instability and the pressing need for effective land management and disaster mitigation measures in the region. Bumiaji District itself, situated at an average altitude of around 1,500 metres above sea level and dominated by slopes exceeding 15 percent, has recorded 31 landslide incidents between 2016 and 2021 that affected houses, farmlands, and key tourism infrastructures, highlighting how the combination of steep terrain, land-use conversion, and intensive tourism and agricultural activities amplifies the district's vulnerability to recurrent landslides (Prasetya et al., 2021),

From a physical perspective, Gunungsari Village is considered highly vulnerable to landslides, a condition exacerbated by human activities, such as land conversion, agricultural expansion, and eco-tourism development that often overlook environmental sustainability. Similarly, Punten Village is also prone to landslides due to its climatic and topographic characteristics. In fact, there has been a significant increase in residential development in landslide-prone zones within Bumiaji District, Batu City, driven by the growing demand for housing.

Given the aforementioned issues, it is essential to establish comprehensive policies for the sustainable protection and management of mangrove ecosystems. One of the conceptual approaches that can be employed in formulating such policies is the Driver, Pressure, State, Impact, and Response (DPSIR) framework. This framework serves as an analytical tool to identify and interpret the causal relationships between environmental systems and human activities (Kristensen, 2004). By applying this model, policymakers and local communities can enhance their understanding and awareness of effective strategies aimed at promoting sustainable disaster mitigation and adaptation, particularly in areas prone to environmental degradation and natural hazards such as landslides. Moreover, the DPSIR framework provides a structured basis for integrating scientific knowledge with participatory decision-making, ensuring that both ecological and socio-economic dimensions are considered in the management process.

The DPSIR framework is extensively recognised for its usefulness in describing the cause-effect relationships between anthropogenic activities and environmental components. It enables researchers and decision-makers to identify key driving forces, pressures, and impacts that influence ecosystem conditions, thereby supporting evidence-based policy development. However, the practical implementation of the DPSIR approach in problem-solving remains suboptimal in many developing countries, often due to limited data availability, insufficient institutional capacity, and weak cross-

sectoral coordination (Sekar et al., 2020). Existing literature reveals that DPSIR-based research has been predominantly conducted in the context of environmental issues in Europe, whereas relatively few studies have applied this analytical framework to examine environmental cases in Asia, Africa, the Americas, and Oceania (Troian et al., 2021). This imbalance highlights the need to strengthen the application of DPSIR in diverse geographical contexts to better capture regional socio-environmental dynamics and support more context-sensitive policy responses (Ehara et al., 2018).

The present study aims to comprehensively analyse landslide occurrences in Punten and Gunungsari Villages, Bumiaji District, Batu City, using the DPSIR framework, from identifying the underlying causes to formulating recommendations to prevent future events. Landslides in these areas are not solely triggered by natural factors such as topography and climate, but are also influenced by human activities, highlighting the need for appropriate land-use policies and management strategies. These two villages were selected as study sites because they are frequently affected by landslides during the rainy season. Furthermore, this research seeks to provide practical and evidence-based recommendations for sustainable area management, serving as a valuable reference for relevant policymakers and stakeholders.

MATERIALS AND METHODS

This study was carried out in Punten and Gunungsari Villages, located in Bumiaji District, Batu City, East Java, Indonesia. Both villages lie on the foothills of Mount Arjuno, at elevations of approximately 800 metres (Punten) and 1,000 metres above sea level (Gunungsari). The total area of Punten Village covers 281.935 hectares (Media Gema Desa, 2012), while Gunungsari Village spans 318.833 hectares or 4.106 km² (Gunungsari Village, 2022). This research adopted a qualitative descriptive approach and was conducted between May and July 2025. The study sites were selected due to their recurrent landslide occurrences and high environmental vulnerability.

The materials used in this study included interview forms, stationery and field notebooks, and a digital camera equipped with a GPS Camera Map for spatial documentation. Before conducting interviews, all potential participants were asked for their informed consent, ensuring that they fully understood the purpose of the research and voluntarily agreed to participate. Ethical considerations were maintained throughout the data collection process to respect the privacy and autonomy of all respondents.

A literature review was first undertaken to gather secondary data and historical information on landslide events in both villages. Sources were drawn from peer-reviewed journal articles, government documents, books, and reputable online news and reports. This preliminary review provided a contextual understanding of the geomorphological, climatic, and anthropogenic factors influencing landslides in Batu City and served as the theoretical foundation for the subsequent analysis.

Field observations were then conducted to qualitatively examine and document the physical landscape and environmental conditions of Punten and Gunungsari Villages. The observations encompassed all hamlets within each village, i.e., Krajan, Gempol, Kungkuk, and Payan Hamlets in Punten Village, and Pagergunung, Kapru, Brumbung, Jantur, and Brau Hamlets in Gunungsari Village, ensuring spatial representativeness across the study area. During these observations, attention was given to slope morphology, land-use patterns, vegetation cover, drainage conditions, and visible indicators of soil instability.

To complement field observations, separate Focus Group Discussions (FGDs) were conducted in each village, involving 20 participants from Punten Village and 20 from Gunungsari Village. Each FGD was held on a different day and in a different venue to maintain contextual relevance and avoid cross-community influence. Participants comprised local residents and village government representatives, purposefully selected to ensure that all hamlets were represented and diverse local perspectives were captured. The FGDs served as a platform for community members to share their experiences, perceptions, and collective knowledge relating to landslides. Discussions centred on the historical occurrence of landslide events, their socio-economic impacts on livelihoods, and both existing and proposed mitigation and adaptation strategies.

In addition to FGD, in-depth interviews were carried out with 50 residents from Punten Village

and 50 residents from Gunungsari Village, selected through purposive sampling based on their proximity to landslide-prone areas and direct experience with such events. Interviews were also held with village government officials to gain insight into institutional responses and local policy frameworks. The interviews used open-ended questions, allowing respondents to narrate their experiences freely. Questions focused on historical landslide occurrences, land use changes, perceived impacts, mitigation measures, and the role of government and community initiatives in tackling landslide risks.

The following questions were addressed to local community members to explore their perceptions of landslide risk:

1. What is the historical condition of landslide events around your area?
2. What is the historical condition of land cover around your area (for example, forests being converted into residential areas)?
3. What are the impacts of landslides that you have experienced (both direct and indirect impacts)?
4. Have you ever experienced material and/or non-material losses due to landslides?
5. What mitigation and/or adaptation efforts have you or the government undertaken to address landslides?
6. What policies should the government implement to prevent landslides from recurring?

Meanwhile, the following questions were addressed for the village government officials, i.e., Village and Hamlet Heads:

1. What are the historical occurrences of landslides, and what are their impacts?
2. What mitigation and/or adaptation efforts have been or will be carried out by the village government to address landslides?
3. Has the village government conducted or will it conduct mentoring or training to strengthen residents' awareness and knowledge about landslides?
4. Has the village government collaborated or will it collaborate with other parties in mitigation and/or adaptation efforts related to landslides?

All collected data were subsequently analysed using the DPSIR framework, which offers a systematic and integrative lens for examining the causal relationships between human activities and environmental change. Within this framework, Drivers refer to underlying forces such as population growth, land conversion, or economic development; Pressures denote the direct stresses exerted on the environment; State represents the existing environmental and socio-economic conditions; Impacts encompass the tangible effects of environmental degradation, including physical damage and livelihood disruption; and Responses reflect the actions taken by individuals, communities, or institutions to mitigate or adapt to these impacts (Kristensen, 2004).

Through the integration of field data, community narratives, and DPSIR-based analysis, this study offers a comprehensive understanding of landslide dynamics in Punten and Gunungsari Villages. Triangulating multiple data sources ensured the inclusion of both scientific and local knowledge were incorporated, thereby further enhancing the validity and interpretive depth. Local knowledge can assist in recognising the factors that contribute to landslide risk (MacAfee et al., 2024). This study captures not only the biophysical aspects of landslides but also the socio-economic and behavioural drivers that exacerbate their impacts.

RESULTS AND DISCUSSION

Table 1. DPSIR Framework of Landslide Dynamics in Punten and Gunungsari Villages

Component	Empirical Findings (based on FGDs and Interviews)
Drivers (D)	1. Steep volcanic slopes (800–1,000 metres above sea level) with fragile Andosol soils and > 2,500 mm annual rainfall. 2. Agricultural expansion since the 1990s has converted forest to horticultural land in Brau, Pagergunung, Jantur, Kungkuk, and Gempol. 3. Population pressure and dependence on short-cycle vegetables (cabbage, leek, potato, etc.) ⟶ continuous cultivation > 40 % slopes. 4. Tourism-driven land conversion (villas, homestays) without geotechnical assessment. 5. Weak BPBD–village coordination, limited spatial-planning enforcement.
Pressures (P)	1. Soil disturbance and loss of organic matter from frequent tillage and chemical input. 2. Deforestation and replacement of deep-rooted vegetation by annual crops. 3. Hydrological stress: blocked drains (Brau, Jantur), waterlogging (Payan, Gempol). 4. Economic constraints limit the adoption of terracing/vegetative barriers. 5. Tenure insecurity near the Perhutani forest discourages investment in slope protection. 6. Institutional fragmentation, inconsistent maintenance of Early-Warning Systems (EWS). 7. Behavioural normalisation of small slides
State (S)	1. Visible erosion scars, cracked terraces, and exposed subsoils in Kapru, Jantur, Gempol. 2. Low vegetation-cover persistence; poor survival of vetiver/bamboo replanting. 3. Increased runoff ⟶ siltation of drainage & temporary flooding. 4. High agricultural dependence; recurrent financial stress after crop loss. 5. Limited institutional readiness; committees function only in emergencies. 6. A fragile socio-ecological equilibrium combining biophysical fragility and institutional inertia.
Impacts (I)	1. Damage to terraces, houses, and roads (Brau 2023 slide; Gempol 2025 event). 2. Reduced yields and abandonment of eroded plots; uneven recovery between wealth groups. 3. Psychological anxiety during rainy seasons and temporary displacement. 4. Downstream sedimentation and water-quality decline from agrochemical runoff. 5. Fiscal burden on village budgets ⟶ “disaster-induced stagnation”.
Responses (R)	1. Five EWS units were installed across both villages (three in Gunungsari Village, two in Punten Village), but maintenance remains irregular and technically reactive. 2. Annual drills and strengthen and regularise disaster education with broader community participation. 3. Promote and maintain terraced farming in high-risk areas to reduce runoff and soil erosion. 4. Intermittent slope rehabilitation through vetiver and bamboo planting carried out by Perhutani and the Indonesian National Armed Forces (TNI), with limited long-term mentoring or monitoring. 5. An active cooperation culture in post-disaster clean-ups and communal repair efforts. 6. Emerging community initiatives to integrate slope conservation into tourism activities (e.g., eco-trails and reforestation volunteer programmes).

7.	Absence of risk-informed development planning within RPJMDes and RKPDes; need for formalised multi-stakeholder governance, sustained funding, and participatory mitigation mechanisms.

Drivers (D)

The underlying drivers of landslides in Punten and Gunungsari Villages arise from a complex interplay between natural topography, climatic conditions, and human-induced landscape modification. Both villages are situated on the steep foothills of Mount Arjuno, within an elevation range of approximately 800-1,000 metres above sea level. The region's high annual rainfall, exceeding 2,500 mm, coupled with its rugged terrain and deeply weathered Andosol soils, creates an inherently unstable geomorphic setting. However, the intensity and frequency of landslides in recent decades have been exacerbated by accelerated land conversion. According to testimonies from residents in Gunungsari Village, agricultural expansion has encroached upon forested zones since the 1990s, particularly in Brau, Jantur, and Pagergunung hamlets, where steep slopes once stabilised by forest roots are now used for horticultural crops. Similarly, in Punten Village, hamlets such as Kungkuk and Gempol have seen widespread transformation of mixed gardens into vegetable plots and residential clusters, motivated by population growth and the economic attraction of highland farming.

A second critical driver lies in population pressure and socio-economic dependency on agriculture. Both villages exhibit livelihoods dominated by smallholder farmers who cultivate short-term crops such as cabbage, potato, and leek. These crops require frequent soil tillage, pesticide use, and often continuous cultivation across slope gradients exceeding 40% (Figure 1). Similar observations in Buhinyuza, Burundi revealed that plots located on slopes above 40% exhibited higher levels of surface roughness and erosion indicators due to water leakage and soil instability, indicating that steep slopes are inherently more vulnerable to degradation when intensively cultivated (Nsabiyumva et al., 2025). Community interviews reveal that many residents persist with these practices due to economic necessity and limited access to alternative livelihoods. The dependence on sloping agricultural land, combined with fragmented land ownership, has forced cultivation into marginal and highly erosive areas. Population growth has further amplified the demand for housing, resulting in new settlements being constructed along unstable hill slopes and riverbanks, particularly in Punten's Gempol Hamlet and Gunungsari's Kapru Hamlet. Consequently, demographic and economic pressures continue to reshape the highland environment in ways that reduce ecological stability.

Figure 1. A documentation of common sloping land use without terracing in Punten and Gunungsari Villages (source: personal documentation)

A third driver is the rapid development of tourism-related infrastructure in both villages. Punten and Gunungsari Villages, being part of Batu City's tourism corridor, have witnessed a surge in the construction of villas, homestays, and agricultural-based attractions. Interviews with local officials reveal that the proliferation of tourism facilities often occurs without comprehensive geotechnical assessment or environmental feasibility studies. Land clearing for access roads and parking areas frequently removes vegetative cover, destabilising slopes and increasing surface runoff. Tourism development, while economically beneficial, has inadvertently increased environmental vulnerability, as construction practices seldom include proper slope reinforcement or vegetative restoration. This unregulated expansion reflects the lack of integrated spatial planning and weak enforcement of building regulations in landslide-prone zones.

Institutional and governance-related drivers also play a crucial role. Both village governments acknowledge that coordination between the municipal Disaster Management Agency (BPBD) and local authorities remains limited to emergency responses rather than preventive land-use regulation. Regulatory mechanisms, such as slope utilisation restrictions and zoning policies, are poorly implemented due to bureaucratic fragmentation and limited technical capacity at the village level. As a result, risk reduction responsibilities are often devolved to individuals or community groups without structural support. The absence of consistent policy enforcement has permitted risky land-use practices to continue, thereby sustaining the underlying drivers of vulnerability.

Pressures (P)

The pressures emerging from these drivers manifest as a series of environmental, hydrological, and anthropogenic stresses acting upon the highland terrain. Continuous cultivation of shallow-rooted crops, combined with repeated ploughing on steep slopes, has led to the disintegration of soil aggregates and the depletion of organic matter, thereby diminishing the cohesive strength of Andosol soils. FGD participants in Gunungsari Village mentioned that the use of herbicides and synthetic fertilisers has reduced groundcover vegetation, leaving the soil surface more exposed to raindrop impact and surface erosion. Similarly, in Punten Village, farmers acknowledged that limited access to organic fertilisers and the pursuit of higher yields have promoted unsustainable cultivation practices. The replacement of deep-rooted species such as pine, bamboo, coffee, and banana with vegetables has eliminated the natural reinforcement of slopes, turning agricultural lands into erosion-prone patches that respond rapidly to heavy rainfall.

Replacing deep-rooted plants with shallow-rooted plants weakens soil stability, making it more prone to erosion, especially during heavy rainfall. In general, plant roots help prevent erosion by strengthening the soil and improving its stability (Rossi et al., 2022; Cao et al., 2023; Mairaing et al., 2024), and deeper roots provide stronger anchorage and retain soil moisture more effectively, while shallower roots offer less mechanical strength, which leaves the soil more susceptible to being washed away by water runoff (Li et al., 2016).

Nevertheless, awareness efforts have been initiated by Perhutani and the Forest Village Community Institution (LMDH) to discourage farmers from cutting down pine and bamboo trees within agricultural areas. Farmers are encouraged to cultivate crops beneath the canopy of these trees and to maintain them as part of slope protection measures. This approach gradually promotes an agroforestry system that balances agricultural productivity with ecological stability, integrating economic and conservation functions to reduce landslide risk. However, these measures remain largely advisory rather than mandatory, and monitoring mechanisms are still limited, meaning that tree cutting can still occur in some areas despite the existing guidance.

Hydrological pressures constitute another critical element. Both villages experience intense seasonal rainfall, particularly between November and March, which leads to high infiltration and saturation of the friable volcanic soils. In Gunungsari Village, villagers observed that drainage channels often overflow during storms due to sediment accumulation and inadequate maintenance, redirecting water flow towards residential areas. In Punten Village, steep road cuts and unlined irrigation canals accelerate runoff, producing gully erosion and slope undercutting. These hydrological pressures are compounded by deforestation in upper catchments and poorly designed water diversion systems, resulting in uneven water distribution and heightened pore-water pressure. Such conditions drastically reduce the shear strength of the soil, triggering shallow and deep-seated landslides during prolonged rainfall events.

Socio-economic pressures exacerbate the situation further. Farmers in both Punten and Gunungsari Villages frequently expressed financial constraints that prevent them from adopting soil conservation techniques such as bench terracing or vegetative barriers. The high cost of materials and labour discourages maintenance of slope protection structures. Moreover, the seasonal nature of income from horticulture forces many households into short-term decision-making, prioritising immediate production over long-term sustainability. Land tenure insecurity, particularly in areas overlapping with Perhutani forest zones, creates additional tension; residents are often hesitant to invest in

permanent soil conservation structures for fear of eviction or land disputes. This combination of economic limitation and insecure tenure maintains persistent pressure on the landscape, locking communities into unsustainable practices.

Institutionally, the lack of coordinated governance adds another layer of pressure. Disaster management activities remain fragmented across agencies, with BPBD, Perhutani, and local governments operating with minimal information sharing. Village leaders in Gunungsari Village stated that although early warning systems have been installed, technical maintenance and calibration are inconsistent, often leaving devices inactive or prone to false alarms. Limited funding allocation from the city government further restricts preventive initiatives, leading to dependence on post-disaster assistance. The weak institutional response perpetuates a cycle where environmental degradation and community vulnerability reinforce one another (Cavalheiro et al., 2025).

Culturally and behaviourally, there are also subtle but persistent pressures. In several interviews, villagers described a tendency to ignore early warning signals or official advisories, viewing small landslides as routine seasonal occurrences. This normalisation of hazard events reflects both risk fatigue and limited understanding of cumulative impacts. Community members often prioritise daily agricultural routines even during high-risk weather conditions. Overall, pressures in Punten and Gunungsari Villages are multi-layered, spanning environmental degradation, socio-economic precarity, institutional weakness, and cultural adaptation that cumulatively intensify the system's exposure to landslides.

State (S)

The current state of the environment in Punten and Gunungsari Villages demonstrates a progressive decline in slope stability and ecological resilience. Field observations during FGDs indicated numerous small-scale landslide scars, exposed subsoils, and eroded terrace edges across agricultural slopes. In Gunungsari Village, particularly in Kapru and Jantur Hamlets, local residents described recurrent ground cracking and minor slope slips following heavy rainfall. These visible signs of degradation suggest that the soil structure has reached a critical threshold, unable to absorb and redistribute hydrological stress. Similarly, in Punten Village, areas such as Gempol Hamlet exhibit repeated shallow landslides near residential clusters, with sediment often blocking drainage ditches and irrigation canals (Figure 2). The overall physical state of both villages reflects a landscape undergoing continuous but uneven adjustment to anthropogenic modification.

Vegetation cover, which once played a key role in maintaining slope equilibrium (Comegna et al., 2013), has diminished significantly. Residents in both villages acknowledged that reforestation efforts had been carried out intermittently through government and community programmes, yet the survival rate of planted trees remains low due to poor maintenance and grazing pressure. The loss of perennial vegetation and its replacement by monocultural crops has reduced biodiversity and weakened the natural root network that binds the soil. In Gunungsari's upper slopes, abandoned fields and neglected terraces have become hotspots for erosion, as surface runoff forms rills and channels. This vegetative decline has not only affected slope stability but also disrupted the local microclimatic balance, increasing surface heat and evaporation rates, thereby further altering the soil moisture regime. Such ecological degradation illustrates the intricate link between vegetation dynamics, soil cohesion, and microclimatic regulation, proving that land-cover change accelerates geomorphic instability in tropical highland environments (Xue et al., 2025).

Hydrologically, both Punten and Gunungsari Villages face an altered water regime marked by declining infiltration capacity and increased surface runoff. The siltation of drainage and irrigation systems, frequently reported in FGDs, demonstrates how sediment yield from eroding slopes accumulates in low-lying channels. Waterlogging during storms has become a recurring issue in Punten's valley-bottom areas, indicating impaired subsurface drainage. In Gunungsari Village, the narrowing of river channels due to unregulated construction has intensified flooding episodes. Collectively, these phenomena highlight a deteriorating hydrological state that not only contributes to landslide occurrence but also affects agricultural productivity and water availability during the dry season.

Figure 2. Documentation of the landslide event in Gempol Hamlet, Punten Village, in February 2025 (source: personal documentation)

The socio-economic state mirrors this environmental deterioration. Communities remain highly dependent on agriculture for income, with limited diversification into non-farm sectors. In both villages, households affected by landslides report financial stress due to crop losses and repair costs. Despite increased awareness of environmental risks, access to credit or technical support for mitigation remains limited. The perceived responsibility for slope management is often individualised, leading to fragmented and inconsistent conservation efforts. Moreover, the rural youth's migration to urban centres has reduced the local labour force available for communal maintenance work, leaving critical infrastructure such as check dams and drainage systems in disrepair. These socio-economic vulnerabilities intersect with environmental fragility, forming a feedback loop that perpetuates risk.

At the institutional level, the state of preparedness and governance is uneven. While both Punten and Gunungsari Villages have disaster management committees and designated response teams, these structures function primarily during emergencies. Routine monitoring, data collection, and preventive planning remain sporadic. Coordination with BPBD tends to occur post-event, focusing on damage assessment and aid distribution rather than proactive risk mapping. The overall state, therefore, represents a fragile equilibrium, i.e., a landscape and society caught between awareness and inertia, where environmental degradation, socio-economic dependency, and institutional fragmentation sustain chronic vulnerability to landslides. This condition reflects the concept of adaptive governance theory, which emphasises that limited coordination, social learning, and institutional flexibility hinder societies from building long-term resilience to environmental risks, and vice versa (Azad et al., 2021).

Impacts (I)

The impacts of landslides in both study areas are diverse and interlinked across environmental, social, and economic dimensions. Physically, landslides have resulted in damage to agricultural terraces, housing, and public infrastructure. In Gunungsari's Brau Hamlet, a major landslide in 2023 disrupted access for several days, isolating households and halting the transport of agricultural produce. Such disruptions lead to significant short-term economic losses. Similarly, in Punten Village, road damage and debris flow have affected mobility to tourism sites, reducing visitor numbers and local income. These physical impacts have immediate economic repercussions that ripple across the community.

On the agricultural front, landslides contribute to declining crop productivity and soil fertility. Farmers report reduced yields following each landslide event, as nutrient-rich topsoil is washed away. Rehabilitating such land requires substantial effort and cost, often exceeding the capacity of smallholders. Some residents in Gunungsari Village have begun abandoning highly eroded plots, leading to fragmented land use and decreased overall

agricultural output. In Punten Village, however, wealthier landowners tend to replant quickly, creating uneven recovery between socio-economic groups. This differential resilience perpetuates inequality within the villages. Such disparities reflect the theory of social vulnerability, which posits that access to resources and adaptive capacity largely determine a community's ability to recover from environmental disturbances (Kumaresen et al., 2025).

Socially, the psychological toll of recurring landslides is substantial. Many residents express anxiety during the rainy season, fearing slope failure near their homes. FGD participants described disrupted schooling and temporary displacement as recurring experiences. In some cases, communities rely on informal early-warning mechanisms such as observing cracks or unusual sounds before a collapse. The persistent threat has created a sense of vulnerability that shapes local identity. Social cohesion, while strong, is periodically tested by the unequal distribution of post-disaster aid and the perception of favouritism by local authorities.

Environmentally, landslides have altered the hydrological and geomorphological character of the area. Sedimentation in downstream rivers increases flood risk and reduces irrigation efficiency. Water quality declines as runoff carries soil, fertilisers, and debris into waterways. Over time, these effects may disrupt aquatic habitats and affect water availability for domestic and agricultural uses. The cumulative environmental degradation thus extends beyond immediate slope failure, influencing the broader watershed system of Batu City.

Finally, the economic implications of repeated landslides constrain long-term development. Both villages must allocate substantial resources for rehabilitation, diverting funds from education and infrastructure improvement. This constant cycle of repair limits opportunities for innovation or sustainable investment. The indirect impact is a form of "disaster-induced stagnation," where environmental shocks continuously erode economic progress. Therefore, the landslide impacts cannot be viewed solely as physical phenomena but as structural constraints on rural transformation.

Responses (R)

Responses to landslides in Punten and Gunungsari Villages exhibit a combination of community-based resilience and institutional intervention, although their effectiveness remains uneven. Both villages have installed Early Warning Systems (EWS) through BPBD support (Figure 3). In Gunungsari Village, three units are operational in Brau, Jantur, and Brumbung Hamlets, while Punten Village hosts two in Payan and Kungkuk Hamlets. However, interviews reveal frequent technical malfunctions and unclear maintenance responsibilities. Some residents perceive the alarms as unreliable, highlighting the need for systematic maintenance and community ownership of the equipment. At times, the EWS units are triggered accidentally by minor vibrations, strong winds, or even children playing nearby, which further reduces trust in the system. Regular community simulations and drills are therefore essential to strengthen familiarity, response capacity, and collective trust in the early warning mechanism. Despite these challenges, the existence of EWS indicates growing institutional recognition of the need for anticipatory measures. This aligns with the concept of community-based disaster risk reduction (CBDRR) theory, which emphasises that disaster preparedness and response are most effective when technological systems are complemented by local participation, shared responsibility, and social learning within the community (Tumembow et al., 2025).

Figure 3. Early Warning System (EWS) device installed in Payan Hamlet, Punten Village (source: personal documentation)

To mitigate landslide risk in Punten and Gunungsari Villages, promoting the adoption and maintenance of terraced farming systems on steep

agricultural slopes is essential. Global studies have consistently shown that terracing effectively reduces slope length, slows surface runoff, increases water infiltration, and consequently prevents landslides (Chalise et al., 2019; Deng et al., 2021; Rutebuka et al., 2021). Despite this, most agricultural land in the villages is still cultivated without terraces, leaving soils highly vulnerable to erosion during heavy rainfall. Farmers in both villages continue to rely on these sloping lands because they consider them their only available farmland, highlighting that technical measures alone are insufficient. Therefore, effective responses should combine terracing and vegetative barriers with social and institutional support, including community engagement, technical guidance, and awareness-building on long-term soil conservation. Integrating these initiatives into village development and agricultural extension programmes can enhance sustainability and reduce landslide vulnerability across Batu's highland agricultural landscapes.

Reforestation and slope protection projects have been carried out intermittently. In both villages, Perhutani and the Indonesian National Armed Forces (TNI) have collaborated to plant deep-rooted species such as vetiver (Chrysopogon zizanioides) and bamboo (Bambusoideae) on degraded slopes. Vetiver, in particular, is effective for erosion control due to its dense and deep root system that stabilises soil and reduces surface runoff (Asima et al., 2022; Aziz & Islam, 2023). Bamboo is also effective for erosion control due to its extensive fibrous roots (Tardio, 2018 et al.; Kaushal et al., 2020), but on excessively steep slopes, mature clumps with heavy canopies may become unstable and prone to toppling, especially in water-saturated soils. Compared to bamboo, vetiver grass technology offers a more practical, low-cost, and scalable solution for community-based slope protection. Yet, its long-term adoption by farmers remains limited, partly because the economic benefits are not yet evident at the household level (Oshunsanya et al., 2023). Community members also report limited follow-up, lack of maintenance, and unclear incentives for continued care. The focus tends to remain on government-led campaigns rather than sustained participatory conservation, resulting in varied plant survival rates across sites. Interviews and FGDs further reveal that vetiver planting is uneven, concentrated only in selected locations, and many residents do not know where to obtain seedlings. To strengthen adoption and long-term impact, seedling distribution should be expanded alongside more intensive outreach, training, and technical assistance on vetiver cultivation and maintenance.

Institutional responses are still predominantly reactive. For example, during the landslide incident in Gempol Hamlet, support and assistance were mobilised only after damage had occurred. There are no regular programmes integrating disaster mitigation into village development planning. Although institutions such as the Forest Village Community Institution (LMDH) and Perhutani have encouraged planting woody species on leased land, these recommendations have not been accompanied by sustained mentoring or structured community guidance. Village development documents, namely the Village Medium-Term Development Plan (RPJMDes) and Village Government Annual Work Plan (RKPDes), do not explicitly include landslide mitigation strategies, and not all village officials possess the capacity or training to undertake risk-informed development planning.

On the technical side, BPBD has provided early detection tools in Payan Hamlet, conducted periodic inspections, and distributed tarpaulin sheets (Figure 4) as well as small retaining structures (plengsengan) in several high-risk points to prevent further soil erosion during heavy rainfall. Plengsengan plays an essential role in stabilising slopes by reducing lateral soil movement and controlling surface runoff, thereby minimising the likelihood of slope failure. Tarpaulin sheets, meanwhile, help protect bare soil from direct raindrop impact and excessive water infiltration. While some households have voluntarily planted orange or pine trees on their land, these individual efforts remain too small in scale and insufficiently coordinated to achieve effective landscape-level protection.

Figure 4. Tarpaulin sheets provided by BPBD are used to prevent soil erosion caused by rainfall (source: personal documentation)

Disaster preparedness and education have improved but remain inconsistent. Awareness sessions at the hamlet level mainly target community leaders and teachers. In both villages, several outreach programmes have been conducted by the Batu City Government and the Regional Disaster Management Agency (BPBD), yet participation is still limited to selected residents who are expected to share the information with others. These messages are typically passed on informally through community gatherings such as religious study groups, tahlilan, or neighbourhood meetings, allowing wider public education even if indirectly. In fact, such informal settings have proven to be effective in mobilising attendance and fostering open discussion, as they make it easier to reach a broad audience within familiar social contexts. In Gunungsari Village, school-based initiatives have introduced early knowledge of landslide indicators, while Punten Village has begun integrating disaster themes into routine village meetings. Although these efforts have been ongoing, they remain irregular and focus mainly on landslide prevention. Broader participation and more diverse educational content will be essential to strengthen behavioural change and collective preparedness.

From an institutional perspective, coordination between village governments, BPBD, and community forums has strengthened but remains reactive and leadership-dependent. FGD results show that both villages maintain contact lists and evacuation routes, yet response protocols vary significantly based on the leadership capacity of village heads. In Gunungsari Village, for instance, coordination improved markedly during the tenure of proactive village leaders but declined thereafter, indicating institutional fragility and dependence on individual leadership cycles rather than system-based governance.

Community-driven initiatives continue to demonstrate strong potential in Punten and Gunungsari Villages. Mutual aid (gotong royong) remains a key mechanism for collective action, especially in post-disaster clean-up. Gotong royong embodies the spirit of cooperation that strengthens unity and resilience in Indonesian communities (Suwignyo, 2019; Depari & Lindell, 2023; Sasongko et al., 2025; Schäfer et al., 2025). In Punten Village, emerging proposals to link slope conservation with tourism, such as eco-trails, tree-planting tourism, and volunteer reforestation programmes, reflect a shift towards integrating environmental management with livelihood enhancement. Moving forward, cross-sector collaboration among stakeholders, i.e., village government and relevant government agencies, academia, private institutions, non-government organisations, and public communities, is essential to develop a sustainable participatory mitigation system (Karlina et al., 2024). Participatory landslide risk mapping, training on conservation-oriented slope farming, and strengthening farmer groups as community change agents represent feasible strategies that can be implemented progressively to build long-term resilience.

CONCLUSION

This study demonstrates that landslide risk in Punten and Gunungsari Villages arises from a complex interaction of geomorphological vulnerability and anthropogenic drivers. The DPSIR analysis clearly shows that steep volcanic terrain and intense rainfall interact with agricultural expansion, tourism-driven land conversion, and

weak spatial planning to generate significant environmental pressures on slope stability. These pressures have altered the state of the socio-ecological system, reflected in declining vegetation cover, increased surface runoff, deteriorating soil structure, and heightened livelihood fragility among households dependent on climate-sensitive agriculture. The impacts are multidimensional, encompassing physical, economic, social, and psychological losses, with uneven recovery capacities that further exacerbate vulnerability. Current responses, such as early warning systems, selective slope rehabilitation with vetiver and bamboo, community mutual aid, and disaster education, indicate awareness and initial progress. However, these measures remain fragmented, intermittent, and insufficiently institutionalised, with limited community engagement beyond project implementation stages. Sustainable reduction of landslide risk requires a shift from reactive and campaign-based interventions to preventive, long-term, and community-centred risk governance.

Recommendations:

1. Strengthen practical land-use control at the local level: Village and sub-district governments should gradually improve enforcement of existing spatial regulations by prioritising high-risk zones for strict control, introducing simple community-based slope assessment checklists for land-use decisions, and requiring basic slope-stability considerations before approving new agricultural plots or tourism facilities on steep terrain.
2. Embed community-led risk reduction into routine village activities: Instead of one-off disaster campaigns, awareness sessions, early warning practices, and slope maintenance (e.g., clearing drains, monitoring cracks) should be integrated into regular community meetings (musyawarah desa) and annual village work plans, supported by periodic training facilitated by local BPBD officers and schools.
3. Promote scalable and low-cost eco-engineering practices: Expansion of vetiver and bamboo planting should focus first on the most erosion-prone slopes, supported by community-managed nurseries, practical demonstrations on planting and after-care, and simple incentives such as integrating vetiver into existing farming systems (e.g., hedgerows or boundary planting) to reduce labour burden.
4. Improve coordination through clear role-sharing: Collaboration between government agencies, Perhutani, TNI, local universities, and farmer groups should be structured through defined roles, e.g., Perhutani for technical guidance on vegetation, TNI for mobilisation support, universities for monitoring and evaluation, and village authorities for community engagement and maintenance.
5. Enhance Resilience Through Contextual Livelihood Options: Economic vulnerability can be reduced through targeted support for climate-smart agriculture (e.g., intercropping deep-rooted species), small-scale agroforestry, and value-addition training (such as processing local produce for tourism markets), ensuring that alternative income streams are compatible with local cultural and economic realities.
6. Establish simple and community-friendly monitoring: A practical monitoring system should be co-designed with communities to record survival of planted vegetation, visible slope changes, rain-induced incidents, and preparedness activities, using easy-to-use tools (e.g., village logbooks, photo documentation, or mobile reporting) to support continuous improvement.

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