From disaster to conservation: Geoheritage potential of the 2024 Wayanad landslide, India

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Abstract

The 2024 Wayanad landslide in the Western Ghats of India, which occurred on 30 July, is one of the most significant and devastating landslides in India, and stands as a compelling candidate for designation as a geoheritage site. This landslide, initiated as a rockslide and transformed into a massive debris flow, travelled 8 km causing widespread destruction across three villages, altering the course of the Punnapuzha River, and resulting in over 266 fatalities. This tragic event underscores the urgent need for management of natural hazards, particularly rain-induced landslides in the Western Ghats region. Thus, the Wayanad landslide site offers a unique opportunity to establish a field segment for guided exploration and a museum segment for research and education on landslide dynamics and geological processes, benefiting students, researchers, and disaster management professionals. Hence, this study evaluates the geoheritage potential of the site through a combined approach of Strengths, Weaknesses, Opportunities, and Challenges (SWOC) analysis, and a comprehensive stakeholder-informed survey. Results from the survey revealed especially high educational and tourism potential, despite major social, environmental, and economic disruptions. Recommendations include establishing real-time monitoring systems, controlled public access, and a digital platform to engage broader audiences. By recognizing the geoheritage significance, it could serve as a platform for scientific investigation, public awareness, and disaster risk reduction strategies. Furthermore, such a designation would foster geotourism, supporting sustainable development and benefitting the local community. Thus, this study aims to highlight the scientific value of the 2024 Wayanad landslide site and its potential to educate future generations while promoting both

conservation and geotourism, aligning with UNESCO’s initiatives to preserve dynamic geomorphosites that reveal Earth's active geological history.

Keywords: Wayanad landslide, the Western Ghats, Geoheritage, Geotourism

1 Introduction

Geoheritage, often termed as geological heritage, refers to unique geological formations, minerals, fossils, tectonic structures, and geomorphological landscapes that hold significant scientific, educational, cultural, or aesthetic value (Reynard and Brilha, 2017; Coratza and Hobléa, 2018; Chandran et al., 2022; Chavan et al., 2022, Sajinkumar et al., 2022). These natural features contribute not only to the understanding of the Earth’s history but also play a key role in geotourism and conservation efforts. The protection and sustainable management of geoheritage sites provide opportunities for public education, recreation, and economic benefits through geotourism (Bhargava et al., 2010; Hose, 2012; Gray, et al., 2013; Wadhawan et al, 2022). This focus on conservation, combined with promoting awareness on geodiversity, supports both the intrinsic ecological value of these sites and their broader societal value according to various UNESCO initiatives (McKeever, 2015). Moreover, sites classified as geomorphosites (cf. Reynard, 2005), the landforms with scientific, cultural, or historical significance, highlight the dynamic processes such as erosion and tectonic activities. The landforms shaped by active gravitational movements, such as landslides, rockslides, and debris flows, exemplify dynamic geomorphosites, showcasing the Earth's active geological processes (Coratza and Hobléa, 2018; Morino et al., 2022). Hence, landslides, which reshape landscapes, offer huge potentiality as geoheritage sites due to their geological and geomorphic significance.

Large-scale landslide events can reveal important insights into the Earth's dynamic processes and act as natural laboratories for studying the interaction between geological forces and ecosystems. Given the role landslides play in shaping terrains and influencing biodiversity, recognizing such regions as geoheritage sites could contribute to both scientific understanding and the conservation of fragile landscapes, particularly in areas like the Western Ghats where the interplay of geology, climate, and ecology is critical to sustain diverse ecosystems. Thus, recognizing large-scale landslides with significant geological features and impacts as geoheritage sites is essential for public education and awareness, as these sites provide insight into geological hazards, the processes shaping landscapes and conservation efforts. For example, the 1963 Vajont landslide in Italy, considered as one of the deadliest landslides in the European history, resulted from the collapse of a massive rock mass into a reservoir, generating a wave that overtopped the dam, caused catastrophic flood and led to nearly 2,000 fatalities (Barla and Paronuzzi, 2013). This tragic event, caused partly by human mismanagement of geological risks, serves as a poignant reminder of the need for better understanding and respect for natural processes (Coratza and De Waele, 2012; Morino et al., 2022). Another example is Canada's Frank Slide, where an enormous landslide destroyed a part of the town of Frank in 1903. Now preserved as a Provincial Heritage Site, the area educates visitors on the geological risks and factors that contributed to the landslide, enhancing public understanding of such hazards (Morino et al., 2022). Hence, by designating such massive-devastating landslides as geoheritage sites, the landslide can be preserved as educational resources, which can significantly improve risk perception among communities. When interpreted and presented as part of geoheritage, these sites can promote knowledge of Earth's history, encourage sustainable environmental planning, and reinforce the importance of geomorphology in hazard mitigation efforts. Today, the site serves as an educational resource, emphasizing the need for public awareness and effective risk management (Coratza and De Waele, 2012; Morino et al., 2022).

Thus, the landslide at Wayanad, occurred on 30^{th} July 2024 in the Western Ghats of India, killing 266 people with 32 missing and covering an area of 1 km^2 through a distance of 8 km, could be an ideal place for designating as a Geoheritage site, which could eventually create a natural laboratory for students, researchers, and disaster management professionals. This site could serve as a hands-on platform for studying landslide mechanisms, soil profiles, and stability, offering experiential learning through field studies, internships, and research projects. By fostering scientific research, education, and public awareness, the area could contribute to improved disaster risk reduction strategies and sustainable development. Additionally, recognizing the site's geoheritage significance would support geotourism, benefiting the local community while ensuring that the lessons from this tragic event are preserved for future generations. Despite increasing awareness of disaster risk in this region, the integration of geoconservation, public education, and community-based resilience strategies remains limited in both practice and literature. Most studies tend to focus on technical assessments or hazard mapping, with comparatively less emphasis on the long-term cultural, educational, and geoheritage value of landslide sites. Moreover, there is a notable absence of documented frameworks that translate post-disaster landscapes into platforms for awareness, research, and sustainable development.

Thus, this paper proposes designating the 2024 Wayanad landslide site as a geoheritage site to promote scientific research, education, and public awareness. Once recognized, this site would serve as a valuable resource for studying landslide dynamics and mechanisms, raising local awareness, and contributing to disaster risk reduction strategies. The brief Strength, Weakness, Opportunities, and Challenges (SWOC) analysis will highlight the importance of establishing this location as a geoheritage site. In the aftermath of this landslide, this proposal aims to ensure that the area is acknowledged not only for its scientific significance but also for its potential to support sustainable development and geotourism.

2 Objectives

Based on the potentiality of Wayanad landslide as a geoheritage site, the following main objectives are included in this study

i. To propose the 2024 Wayanad landslide site as a geoheritage site by showcasing its geological, educational, and disaster risk reduction significance.
ii. To promote safe and sustainable geotourism at the Wayanad landslide site through controlled public access, educational infrastructure, and real-time monitoring systems.
iii. Suggestions to establish institutional and digital support through an expert committee and a dedicated website for project planning, outreach, and educational engagement.

iv. To conduct SWOC analysis to the Wayanad landslide site, identifying its strengths, weaknesses, opportunities, and challenges to guide geoconservation, education, and community engagement strategies.

v. To assess the geoheritage potential of the Wayanad landslide site by evaluating social, environmental, economic, educational, tourism, and cultural impacts through a stakeholder-informed survey.

vi. To promote sustainable development in the region through education, disaster preparedness, conservation, and geotourism, aligning with national and UNESCO geoheritage frameworks.

3 Study Area

The Western Ghats of India (Fig. 1a), having appeared on the UNESCO World Heritage List in the year 2012 (Kurian and Vinodan, 2023), exemplifies the rich biological diversity crucial to understand the Earth's ecological processes. The region is considered as one of the world's eight 'hottest hotspots' for biological diversity while supporting numerous threatened species (Laladhas et al., 2013). These unique characteristics make the Western Ghats an essential site for conservation efforts on a global scale (https://whc.unesco.org/). Older than the Himalayan Mountain range, the Western Ghats play a vital role in regulating the Indian monsoon system and nurturing a variety of ecosystems, including some of the world's most significant tropical evergreen forests (Karuppusamy, 2024). This prominent physiographic feature facilitates the orographic lifting of monsoon winds: both the southwest monsoon (June to September) and the northeast monsoon (October to November), resulting in heavy rainfall. This heavy rainfall frequently triggers catastrophic landslides on the highlands and steep slopes of the Western Ghats (Sajinkumar et al., 2011; Mathew et al., 2021; Ajin et al., 2022; Sharma et al., 2022; Yesubabu et al., 2024), especially debris flows (Thampi, 1997; Kuriakose et al., 2009), which are known for their devastation, with frequent occurrences in the recent years (Ajin et al., 2022; Vishnu et al., 2022). In 2018, Kerala (a southwestern state in India, sharing its border with the Western Ghats) faced severe ecological, financial, and humanitarian consequences due to the most extreme monsoon rainfall, which triggered widespread landslides and floods, causing significant loss of life, widespread property damage, ecological disruption, and major economic losses (Agarwal, 2018; Sankar, 2018; Megha et al., 2019; Martha et al., 2019; Vishnu et al., 2019, 2020; Sajinkumar et al., 2022; Parsa and Zehra, 2023). According to Hao et al. (2020), the state witnessed approximately 4728 landslides in the single storm event of August 2018, with around 2800 of them being debris flows initiated by slope failures (Fig. 1a). This pattern continued in the monsoon seasons of following years (Ajin et al., 2022).

Of these recent landslides, the 2024 Wayanad landslide stands as one of the most catastrophic landslide events in recent Indian history (Fig. 1b), illustrating the severe risk factors faced by the mountainous regions in Kerala, particularly during monsoon seasons. This landslide was triggered by an intense rainfall of 572.8 mm over 48 hours (i.e., 572.8 litres of water to each square metre), with 372.6 mm recorded in a single day (recorded July 30, 8:30 a.m.), which was the highest within that period (Fig. 1c). Originating at an elevation of around 1620 m above the mean sea level (amsl) in the densely vegetated region at the headwaters of the Chaliyar River, the landslide travelled over 8 km, descending 768 m in elevation before reaching the low-lying villages, including

Punchirimattom, Mundakkai, and Chooralmala (Fig. 1b). The event stands out as one of the most significant and devastating landslides in India, both in terms of volume, estimated as 5.17×10^6 to 5.72×10^6 m^3 (~0.5 million trucks full of soil) of depleted material using DEM of difference and in terms of destruction (Yunus et al., 2025), with 1555 buildings reported destroyed. The landslide wiped out three villages and altered the course of the Punnapuzha River. This high-velocity landslide caused widespread devastation, resulting in over 266 fatalities and 32 people reported missing (official record as on 29 July 2025), highlighting the critical need for improved understanding and management of such natural disasters. It originated as a rockslide (Fig. 2a) and quickly transformed into a massive debris flow (Fig. 2b,c), reshaping the landscape and highlighting the vulnerability of this region to rain-induced landslides (Krishnapriya et al., 2024, 2025). The event serves as a textbook example of mass movement types including slumps (Fig. 2d), demonstrating the region's potential to be developed as a field museum for research and education (Fig. 2). It captured global attention, not only due to the magnitude of the disaster but also because of the efficient post-slide rescue and relief operations (Business Standard, 2024).

The scale of this disaster makes it a compelling candidate for designation as a Geoheritage site, where the geological features and the chain of events that unfolded offer invaluable insights into the triggering mechanisms of landslides, exacerbated by extreme climate events. The landslide site offers numerous opportunities for scientific investigation, educational programs, and public awareness efforts, especially in terms of understanding landslide dynamics and preventing future disasters, befitting the characteristics for a geoheritage site.

4 Methodology

To propose the 2024 Wayanad landslide site as a geoheritage location, a systematic and multidisciplinary methodology was adopted. Initial field investigations mapped the landslide’s geological and geomorphological features, from the crown failure zone to the toe, highlighting key elements like the vanished Sitammakundu waterfall and identification of shear zones. These features were evaluated for their scientific relevance and educational value.

A general survey with local communities, geologists, and disaster management authorities revealed the site’s planning, ensuring both community engagement and practical feasibility. In view of this, relevant case studies and UNESCO guidelines were reviewed to align the proposal with international standards for geoheritage designation.

Based on the field and community insights, the landslide site was zoned into two segments: a field segment for guided exploration and a museum segment in Chooralmala for educational exhibits, research facilities, and public awareness. An integrated monitoring plan was proposed, including real-time instrumentation (GPS, piezometers, AWS) to support ongoing research and early warning systems. These instruments would not only aid in future landslide prediction but also serve as a practical training resource for students and researchers.

To guide implementation, the formation of a multidisciplinary expert committee was recommended. This committee would be responsible for conducting a detailed feasibility assessment and preparing a Detailed Project Report (DPR) addressing geological significance, infrastructure needs, and potential collaborations. A SWOC analysis and a comprehensive stakeholder-informed survey (includes socio, environmental, economic, educational, tourism, and cultural aspects) were conducted to evaluate the proposal's viability. This survey employed both field-based and online methods to capture through the perspectives of these groups, the internal capacities and resources available and also identify gaps and limitations. The field surveys targeting local natives directly impacted by the disaster and online surveys aimed at gathering insights about potential opportunities that can be addressed constructively and how the barriers and problems could be resolved. Each group provided ratings for each parameter, which were then averaged to yield a final score, reflecting the multidimensional impact and future potential of the site for geoheritage recognition. Conservation measures, such as limiting vegetation regrowth, maintaining the debris expanse in its current state, minimal site disturbance, and seasonal visitor control, were integrated to preserve the site's integrity while promoting education and sustainable geotourism.

5 Results

5.1 Wayanad Landslide: a Geoheritage Site for landslide study

The proposed geoheritage site could have two segments, including:

i. a field segment, and

ii. a museum segment

Together, they provide access to key geological features and dedicated infrastructure for studying landslide mechanisms, impacts, and mitigation strategies. This categorization ensures both preservation of sensitive field areas and wider accessibility for education and outreach, accommodating varied visitor needs while maintaining scientific and conservation integrity.

5.1.1 Field segment

The entire landslide area together with the villages of Punchirimattom, Mundakkai, and Chooralmala, located on either side of Punnapuzha and Padavettipuzha, are considered the field segments to serve as an informative and educational space for both tourists and researchers. Since the area is susceptible to future landslides, no civil work should be permitted except for the construction of a simple, non-invasive walkway up to the end of Punchirimattom village, which is 2 km downstream from where the slide/flow originated. This village provides a safe vantage point to view the scarp of the landslide. The walkway would be constructed with the guidance and consent of geotechnical engineers after thoroughly assessing the stability of the surrounding area. Additionally, a zip line could offer visitors an aerial view of the landslide-affected zone, allowing for a unique and immersive experience. Visitors can be guided by geology-trained volunteers of Aapda Mitra or Kudumbasree. For researchers, controlled access to the landslide source area should be allowed for in-depth studies, and geologists can volunteer as field guides, drawing on examples like the Barringer Crater where geologists serve as site volunteers. Trained field volunteers will be stationed at the site to ensure consistent maintenance and conservation support. Thus, to support these efforts, two types of volunteers are proposed: (a) guides for general visitors (trained in geology) and (b) guides for academic researchers (geologists). While the guides for general visitors support visitor navigation and provide interpretive information about the site, geologists and specially trained volunteers can assist researchers in conducting field studies.

The key field components to be studied from the crown to the toe of the debris flow include (Fig. 3a):

(a) Planar failure at the landslide crown: To analyze the nature of the failure mechanism and investigate the structural features of the bedrock, providing insights into the geological conditions that contributed to the landslide (Fig. 3b).

(b) Sitammakundu waterfall site: Once a tourist attraction, this vanished waterfall offers a unique opportunity to study the topographic and geomorphic changes caused by the landslide, revealing the impacts of the catastrophe on the landscape (Fig. 3c).

(c) Bailey bridge: After the landslide event, the Indian Army built a 58 m long Bailey bridge at Chooralmala village, to rescue the stranded population in the Punchirimattom and Mundakkai villages. This area, where flooding and damming impacted the downstream Chooralmala village, provides an essential field segment for examining the hydrological changes and flood risks in landslide non-susceptible zones. The affected area includes the Mundakkai school (Fig. 3d).

(d) Shear zones along the landslide run-out: The flanks of the landslide's flow path expose shear zones, which are critical for studying the lithological and structural features, helping to understand the underlying geological forces that contributed to the event (Fig. 3e).

5.1.2 Museum segment

Museums, usually, form an integral part of a geoheritage site. Such a museum has several implications when established in a natural hazard site. For example, the Pompeii volcano site hosts an observatory museum 'Osservatorio Vesuviano' (Scandone and Giacomelli, 2014; Di Vito et al., 2023), which aids in research activity as well as entertaining tourists. Similarly, the Oso Slide Memorial in Washington, USA, commemorates the 43 lives lost in the 2014 landslide, one of the deadliest in U.S. history, through a thoughtfully designed space that combines remembrance, public education, and awareness of landslide hazards and disaster preparedness. Spanning two acres, the memorial honors the victims, the heroic efforts of first responders, and the grief and resilience of survivors. Developed collaboratively by families, responders, scientists, and local authorities, it features interpretive panels, reflection areas, and educational elements, serving as both a tribute and a platform to promote understanding of landslide risks and the geological event (https://www.slidememorial.com/thememorial). As far as Wayanad is concerned, the museum unit should be located in a safer part, outside the main landslide and run-out zones, ensuring both visitor accessibility and long-term safety. This segment should require the following facilities:

(a) Disaster Museum/Geoheritage Museum: This museum will focus specifically on the 2024 Wayanad landslide and other major events in the region, documenting the extent of destruction, number of lives lost, and stories of rescue and recovery. A dedicated section to honour the victims of the landslide disaster, featuring tributes, memorials, and information about the lives lost, ensuring that their stories are preserved with dignity and respect. This will serve as a poignant reminder of the human loss owing to such natural events, reinforcing the importance of disaster preparedness, risk awareness, and resilience-building in vulnerable regions. An exclusive audio-visual can be included, which will provide visitors with an audio-visual experience showcasing the landslide-affected area before and after the event, using video presentations, news articles, and photographs to illustrate the scale of the disaster and the recovery efforts. An adjoining awareness hub will host regular programs and meetings for local residents, focusing on

disaster preparedness, risk reduction, and geoheritage conservation, thereby fostering community resilience and informed engagement.

(b) Interactive scientific museum with models, samples, and posters: Exhibiting models, geological samples, and informative posters, this scientific museum will offer an engaging and educational experience about the scientific aspects of landslides, including their triggers, causes, effects, warning signs, preventive measures, emergency response strategies and the roles of key rescue and relief agencies. This will also highlight the different types of landslides.

(c) Research scholars' section: A section where researchers and scholars can conduct studies and further investigations into the geological, hydrological, and environmental aspects of the region's landslide history.

(d) Meteorological station: Equipped with gadgets for real-time weather monitoring, this station will track meteorological data relevant to landslide early warning systems.

(e) Services section with cafeteria for refreshments and space for limited accommodation: This section will offer visitors refreshments and a space for limited accommodation, ensuring a comfortable experience for both tourists and researchers. It will also provide essential services to support the museum's operations.

5.2 Other requirements

5.2.1 Preservation of the landslide site

To preserve the landslide site for geotourism, the accumulated landslide debris and ruins would remain undisturbed, with efforts made to prevent vegetation from regrowing - an issue common in tropical climates where plants quickly reclaim disturbed areas. However, during the monsoon season, tourism would be restricted due to safety concerns, limiting access to the landslide site. Visitors would instead be directed to the on-site museum dedicated to the landslide, featuring information on the event, geological context, and ongoing efforts to study and preserve the area.

5.2.2 Constitution of an Expert Committee

A multidisciplinary team should be formed, comprising geologists, disaster management experts, environmental scientists, civil engineers, and urban planners. This committee will conduct a comprehensive survey of the landslide-affected area, assess its geological value, and prepare a feasibility report for establishing the geoheritage site. The expert committee will also create a Detailed Project Report (DPR) outlining the geological significance of the area, its research potential, infrastructure requirements, and budget. Additionally, this report will include a framework for collaboration with educational institutions and disaster management agencies. This geoheritage site could be managed by the Kerala State Disaster Management Authority (KSDMA), with technical and financial support from the National Disaster Management Authority (NDMA) or any other stakeholders like the Geological Survey of India (GSI).

5.2.3 Installation of landslide monitoring equipments

The Wayanad landslide is a significant event that provides a unique opportunity to study the complex processes and mechanisms that lead to landslides in the Western Ghats region. To better understand these processes and improve future landslide prediction and mitigation strategies, it would be ideal to install a comprehensive monitoring system in the affected area. This system will gather precise, real-time data on various environmental and geological factors that influence landslide activity, including ground movement, soil conditions, and rainfall patterns. Such a system will help to improve the early warning systems and landslide prediction models.

(a) Tiltmeters and GNSS Sensors: These instruments can be strategically installed across various critical locations within the landslide-prone area around the 2024 Wayanad landslide zone. Site selection will be based on a combination of past landslide records, current field assessments, slope failure precursors, and expert recommendations. These will monitor minute changes in the angle of the slope and detect any movement or deformation of the ground with respect to the coordinates. This data will help in identifying early signs of slope failure and provide valuable insights into how the terrain responds over time.

(b) Piezometers: This is deployed to measure the pore water pressure within the soil layers. Elevated pore pressure can weaken soil strength and increase the likelihood of landslides. Monitoring these pressure levels will allow us to understand the critical thresholds that trigger landslide events and identify similar patterns in other areas. The spatial distribution of piezometers will be carefully planned based on expert assessment, site-specific geotechnical conditions, historical landslide activity, and the presence of precursors such as tension cracks or persistent seepage zones. Instruments will be strategically installed in areas with known instability to ensure representative and early detection of potential failure zones.

(c) Soil moisture sensor: This can be installed at varying depths across the site in different elevations, lithology, soil types and land use to monitor the saturation levels of the soil. The spatial extent for sensor installation will be determined based on expert assessment and the presence of landslide indicators. The soil moisture content is a key conditioning

factor that affects slope stability, and continuous monitoring will provide insights into how water infiltration impacts the potential for slope failure.

(d) Automated weather stations (AWS): AWS with rain gauges can be placed at strategic locations to collect data of temperature and humidity, along with monitoring the intensity and duration of rainfall, which is a primary triggering factor for landslides in this region. Given that landslides can occur across different areas, the placement of AWS will be guided by expert assessment, historical landslide records, elevation gradients, and hydrological catchment characteristics to ensure coverage of both active and high-risk zones. The data will be used to correlate rainfall events with pore pressure, soil moisture levels, and ground movements to better understand the direct role of precipitation in landslide initiation.

Deploying the above instruments in the field will not only facilitate precise data collection but also offer a valuable real-time learning experience for interns and researchers with hands-on experience. It enhances their understanding of environmental and geological factors, instrumentation, and data interpretation, which is crucial for future research and mitigation efforts.

5.2.4 A dedicated website

A dedicated website for the geoheritage site would serve as a comprehensive platform for booking as well as for providing detailed information about the landslide event, its geological significance, including photos, videos, and virtual tours to allow visitors worldwide to explore the site remotely. A critical component of the website would be the early warning, displaying real-time data collected from monitoring stations in Wayanad and its hinterland to inform and protect the local community and visitors. Additionally, the website would include educational materials, interactive maps, and updates on conservation efforts, serving as a helpful resource for locals, visitors, and researchers creating awareness, education, and sustainable tourism.

5.3 Expected outcomes

Once the 2024 Wayanad landslide site is declared as a geoheritage site, it would attract not only geoenthusiasts but also scientists and students interested in studying landslides and related natural processes. By preserving the area as it is and promoting sustainable tourism, the site could serve as a living laboratory for geological research and education. The zip line and viewing points would offer a safe, controlled way to experience the power and aftermath of such a natural event, while the museum would provide a wealth of information on landslide mechanisms, local geology, and climate factors.

Designating this site as a geoheritage site would highlight its exceptional educational and scientific value, as one of the few such sites in the world, and is likely to attract significant interest from the international scientific community across various disciplines. This recognition could foster greater collaboration, unlock new research opportunities, and ensure its long-term conservation. Moreover, it would create opportunities for local economic development through responsible tourism, while ensuring minimal environmental impact. By restricting tourism to the non-monsoon season and focusing on controlled, educational visits, the area would remain safe for tourists while serving as a crucial resource for understanding natural hazards.

In addition to the provisions mentioned above, it should be ensured that any buildings or constructions on-site are eco-friendly, with an architect who specializes in sustainable design being engaged. Unskilled jobs should be offered to people from the affected area. The maintenance of such areas will require field staff, for which local residents can be employed. A few youths, preferably those who have worked as Aapda Mitra, can be trained to serve as guides. Through Kudumbashree's community-driven model, more opportunities for social empowerment and economic support can be provided to local women, helping build resilience and sustainable livelihoods in the affected community.

5.4 Geotourism

Wayanad district, characterized by distinctive geological formations, holds immense potential for geotourism, a form of tourism that emphasizes the appreciation and preservation of significant geological features. By establishing this region as a geoheritage site, Wayanad can offer visitors a unique perspective into the Earth's geological history and processes, promoting both educational and environmental awareness.

The Moyar (Bhavani) shear zone, crossing through Wayanad district, has several emplacements like the Kalpetta Granite, Amabalavayal Granite, and Kartikulam Gabbro (Fig. 4a-e). These geological emplacements represent key magmatic events associated with the region's tectonic evolution, influenced by continental collision, subduction, different phases of Precambrian magmatism and mid-Neoproterozoic magmatism and shear-related processes (Kumar, 1986). The granites and gabbro serve as geological markers of the shear zone's reactivation and tectonic history in the Southern Indian shield (Rajesh, 2000), which shaped its unique geological character (Santosh & Nair, 1985; Kurian et al., 2001). The Kalpetta Granite (Fig. 4a), an elliptical pluton with an oblique crustal exposure, reveals evidence of a deep-level emplacement, with its arcuate contacts and inward dipping surfaces suggests a diapiric origin (Kurian et al., 2001). Similarly, the Ambalavayal Granite (Fig. 4b,c), a high-temperature emplacement characterized by the presence of molybdenite, further enriches the area's geological appeal. This Pan-African granite, emplaced within high-grade metamorphic terrain and associated with significant lineaments, reveals two distinct compositional zones that suggest an A-type granite, indicative of extensive crystal fractionation and partial melting processes (Rajesh, 2000). The Kartikulam Gabbro (KG) (Fig. 4d,e) is a key site with tholeiitic characteristics and subduction-modified mantle origins (Kumar, 1986). The presence of rare trace element patterns, including large-ion lithophile elements (LILE) enrichment and high field strength elements (HFSE) depletion, showcases its subduction-related tectonic history where the mantle was metasomatized by subducting slab-derived fluids or melts (Prabhakaran & Prasannakumar, 2015; Uthup et al., 2020). Each of these formations provides insights into the area's tectonic events and magmatic processes, forming an integral narrative of Earth's history that, if supported by interpretive resources and guided access, could foster sustainable tourism and a greater appreciation of the region's natural geological heritage.

Apart from the geological significance of Wayanad, there are several cultural, historical, social, and environmental characteristics that make this region unique. The nearby attractions such as Cheengeri Mala and the historically significant Edakkal Caves (Fig. 4f,g), which contain ancient petroglyphs, add to the cultural richness of Wayanad. Meenmutty Waterfalls (Fig. 4h) offers a stunning, multi-tiered cascade reached through a scenic trek, and Pookode Lake (Fig. 4i), an ideal site for boating, is surrounded by serene green forests. Banasura Hill, part of the Western Ghats, is a popular trekking destination and offers panoramic views of the region's high-altitude terrain. It is situated near the

Banasura Sagar Dam (Fig. 4j), India's largest earthen dam, offering insights into both natural and human-engineered environments. Another significant site is the Soochipara Waterfalls (Fig. 4k), 3 km from Chooralmala village, where layered rock formations and cascading waterfalls provide an example of natural erosion and rock weathering processes. Trekkers are drawn to Chembra Peak, where they can find a unique heart-shaped lake near the top (Fig. 4l). Adding to Wayanad's spiritual significance, the Thirunelli Temple offers insight into the area's sacred history. Kuruvadweep (Fig. 4m), a group of uninhabited islands, located in the Kabini River delta, is famous for diverse flora and fauna. Lakkidi Pass, with its steep, winding roads, offers beautiful views of surrounding mountains and valleys. The Wayanad Wildlife Sanctuary is rich in biodiversity, providing a safe habitat for elephants, tigers, and other species. Additionally, the Phantom Rock in Ambalavayal, resembling a human skull, is a popular tourist site. Lastly, the Pazhassi Raja Tomb honors a local freedom fighter and adds a historical dimension to Wayanad's rich heritage (Fig. 4n). Wayanad also hosts indigenous tribal communities like Paniyas, Kurumas, Adiyars, Kurichyas, Ooralis, Kattunaikkans and Uraali Kurumas (Fig. 4o), who have their own traditional dance, music, and crafts. Thus, altogether, these sites make Wayanad an ideal place for exploring nature, culture, and history. All these geological and non-geological attractions can convert the proposed Wayanad geoheritage site to a geopark, which can be further upgraded to the Global Geopark Network of the UNESCO.

5.5 SWOC Analysis

A SWOC analysis is an essential tool for evaluating the internal and external factors, supporting strategic alignment and resource allocation within an organization's environment (Aithel and Kumar, 2015). It identifies strengths, weaknesses, opportunities, and challenges; guiding institutions like educational and conservation organizations in planning and decision-making (Shahabadkar et al., 2019). When strengths focus on intrinsic site qualities, weaknesses reveal limitations, opportunities highlight external growth potential, and challenges assess barriers. A SWOC analysis is applied for the Wayanad landslide site to assess its unique geological attributes, potential for geotourism and education, while addressing challenges like accessibility and preservation needs. This analysis highlights pathways for promoting geoconservation and community engagement, positioning the site as a valuable hub for scientific study. The SWOC analysis is given in Table 1.

The social impact (score: 45) (Fig. 5a,b) has been devastating due to the landslide event, with numerous fatalities, injuries, mental health issues, and a significant demographic collapse due to migration. The environmental impact (score: 20) is extensive, with landscape changes, ecological loss, and destruction of forested areas. The environment has been heavily altered. Economically, with a score of 25, the area faces challenges, as locals have lost livelihoods in agriculture and small businesses. Loss of breadwinners adds to the economic distress. Educationally, the area scored high (85), indicating its strong potential as an educational hub for geological studies, training programs, and disaster preparedness, offering learning opportunities for youth and researchers. With a score of 70 in tourism, the site holds long-term potential for geotourism despite an initial decline due to safety concerns; a well-developed geoheritage site could become a significant draw for tourists. The cultural score of 50 reflects the loss of some religious and cultural sites; however, the community retains its cultural identity, and the area’s rich tribal culture remains significant. Community pride would be fostered by involving residents as custodians of their heritage. Cultural preservation would also be prioritized, with resources to restore and celebrate religious and tribal heritage, showcasing Wayanad's unique traditions to visitors.

Geoheritage recognition would promote conservation efforts and stabilize affected areas, enabling the landscape to recover and minimize future risks. Although the impact on the social aspect is severe, designating the Wayanad landslide area as a geoheritage site could benefit local residents by fostering a sense of local pride and create new employment opportunities. Additionally, it would provide a platform for locals to share their unique cultural heritage with visitors, thereby contributing to improved socio-economic conditions. The designation would attract tourism, drive economic revitalization, and create job opportunities in conservation, hospitality, and guiding. This, in turn, would diversify income sources for locals. Overall, transforming Wayanad into a geoheritage site could elevate the community from the aftermath of disaster by fostering resilience, enhancing cultural pride, and promoting sustainable growth, ultimately positioning Wayanad as a landmark of both natural and cultural significance. The entire process of converting this disaster site into a geoheritage site is shown in the form of a flow chart (Fig. 6).

6 Discussions

6.1 Geoheritage - based Conservation strategy for the Wayanad Landslide

The Wayanad landslide is notable for its large scale, composite type, and the significant impact. While eco-restoration could be considered for the affected area, such efforts would leave the riverbed, its banks, and the adjacent land characterized by steep slopes, shear zones, and intense weathering still vulnerable to future catastrophic landslides during heavy downpours or cloudbursts, putting lives at risk. A government appointed committee has recommended designating go and no-go zones within the affected area (Mathai et al., 2024). This would result in large sections of land lying idle without proper upkeep or maintenance.

But by establishing a geoheritage site with systematic maintenance, the area could be transformed into a valuable platform for scientific research and education. It would offer on-site opportunities for earth scientists, students, and disaster managers to study landslide dynamics and disaster mitigation strategies. It would also benefit prospective students and disaster managers by helping them understand every aspect of a disaster - from hazard and risk to mitigation. Additionally, geoparks and geoheritage sites worldwide have successfully engaged the public, and the success stories of various global geoparks and geoheritage sites highlight the potential of such initiatives to support the local economy through sustainable development (Farsani, 2012; Morino et al., 2022). In the case of Wayanad, this could also create livelihoods for the landslide-displaced population, making it a pioneering initiative in the country. For e.g., the Aapda Mitra scheme, introduced by the National Disaster Management Authority (NDMA) in 2016 to enable volunteers for assisting affected communities after disasters (Kaur, 2024), can be effectively utilized to deploy the specially trained volunteers at geoheritage sites for immediate response and support in times of need. Another success story is of Kudumbashree (a poverty eradication and women empowerment programme implemented by the State Poverty Eradication Mission (SPEM) of the Government of

Kerala) in disaster management efforts during the COVID-19 pandemic, which is evident through its wide range of community-driven initiatives, such as mask and sanitizer production, care for the elderly, and agricultural support, a testament to the empowerment of women across Kerala to become a resilient support system (Thomas and Prakash, 2020). This accomplishment highlights Kudumbashree's potential for deployment in geoheritage sites, where its community-based approach could foster social empowerment and support sustainable economic development.

6.2 Challenges

Designating the landslide site in Wayanad as a geoheritage site also comes with significant challenges, with fast-growing vegetation being a primary concern. Wayanad, being part of the Western Ghats Ecosystem, has a tropical climate that promotes rapid plant growth, particularly after disturbances like landslides. While this resilience reflects the area's natural ecological progression, it complicates the preservation of the site’s geological features, which are essential for its value as a geoheritage site. The exposed soil surfaces provide fertile ground for vegetation—plants that are the first to colonize disrupted environments—quickly establish themselves on these open landscapes. By the consistent monsoon rainfall that creates ideal growing conditions, plant life can cover significant portions of landslide-affected areas within a matter of months. Shrubs, and grasses often proliferate, and invasive species may even accelerate this process by monopolizing open ground, further speeding up vegetative coverage (Sajinkumar, 2015). Previously, using NDVI as proxy, studies have shown that vegetation growth in landslide-affected sites takes less than a year to reach 40% recovery, while full recovery can take over 18 years (e.g., Lin et al., 2004; Yunus et al., 2020; Aman et al., 2024). If vegetation obscures the site, the visibility of strata, slip surfaces, and rock fractures—which are essential to understand the landslide's cause and dynamics—diminishes the site's scientific and educational value.

One another challenge is the development of gullies and sediment erosion that alter the original geomorphology of the landslide site (Dou et al., 2024). Without plant cover, the site may experience erosion from rain and running water, exposing it further to downcutting and landsliding. A balance would have to be struck between preserving geological features and allowing natural vegetation process. Therefore, for a viable project implementation, policy support, combined with community engagement, would be essential for sustainable management that respects both the geoheritage significance and the ecological needs of the area.

A key challenge lies in the region’s continued vulnerability to landslides, which could pose risks to any geoheritage infrastructure. However, this can be addressed through careful site selection, hazard zonation, and resilient construction. Rather than deterring the initiative, this highlights the opportunity to develop a model for disaster-resilient heritage preservation and community-based risk management. In fact, the presence of such infrastructure could enhance local preparedness and scientific understanding, making the site a living example of adaptive and sustainable development in a hazard-prone region.

7 Conclusions

The 2024 Wayanad landslide, characterized by its long run-out debris flow and the immense impact on both landscape and community, holds significant potential for being designated as a geoheritage site. As a geoheritage site, the area would not only serve as a living laboratory for geoscientific research but also as a focal point for education, awareness, and sustainable geotourism. This designation would promote the conservation of signatures of this unique geological event, ensuring that the lessons learned from the landslide contribute to future risk mitigation strategies while fostering socio-economic benefits for the local community through responsible geotourism. Recognizing the 2024 Wayanad landslide as a geoheritage site is thus a step forward towards blending scientific study with heritage conservation, benefiting both current and future generations.

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Declaration of competing interest

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

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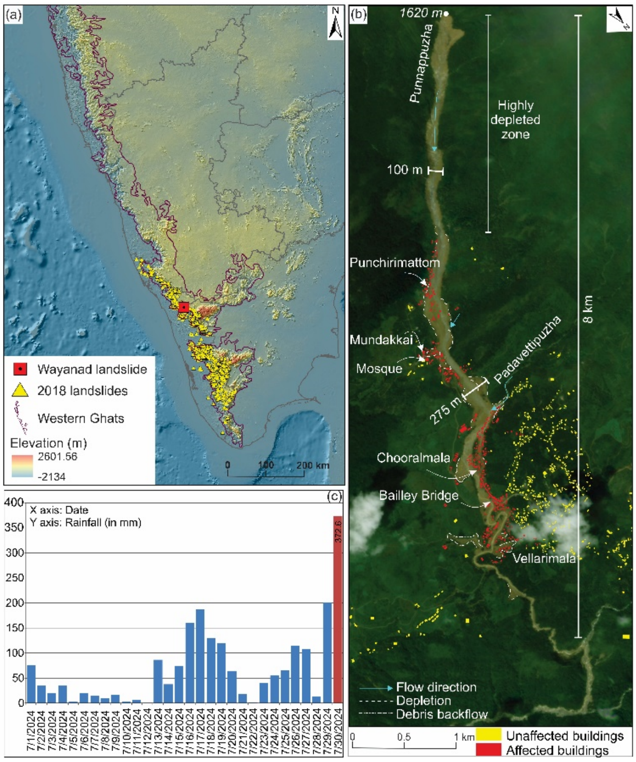

Figure 1 (a) The Western Ghats in Peninsular India showing the Wayanad landslide location along with the 2018 landslide inventory (Source of 2018 landslide inventory: Hao et al., 2020) (b) the affected villages of the 2024 Wayanad landslide: Punchirimattom, Mundakkai and Chooralmala (Background image: Planet Lab) (c) One month rainfall data from the Kalladi rain gauge, which is the nearest rain gauge to the Wayanad landslide location

Figure 2 Field photographs showing (a) the crown part of the landslide, which is planar rock slide (b,c,d) the subsequent debris flow depletion zone

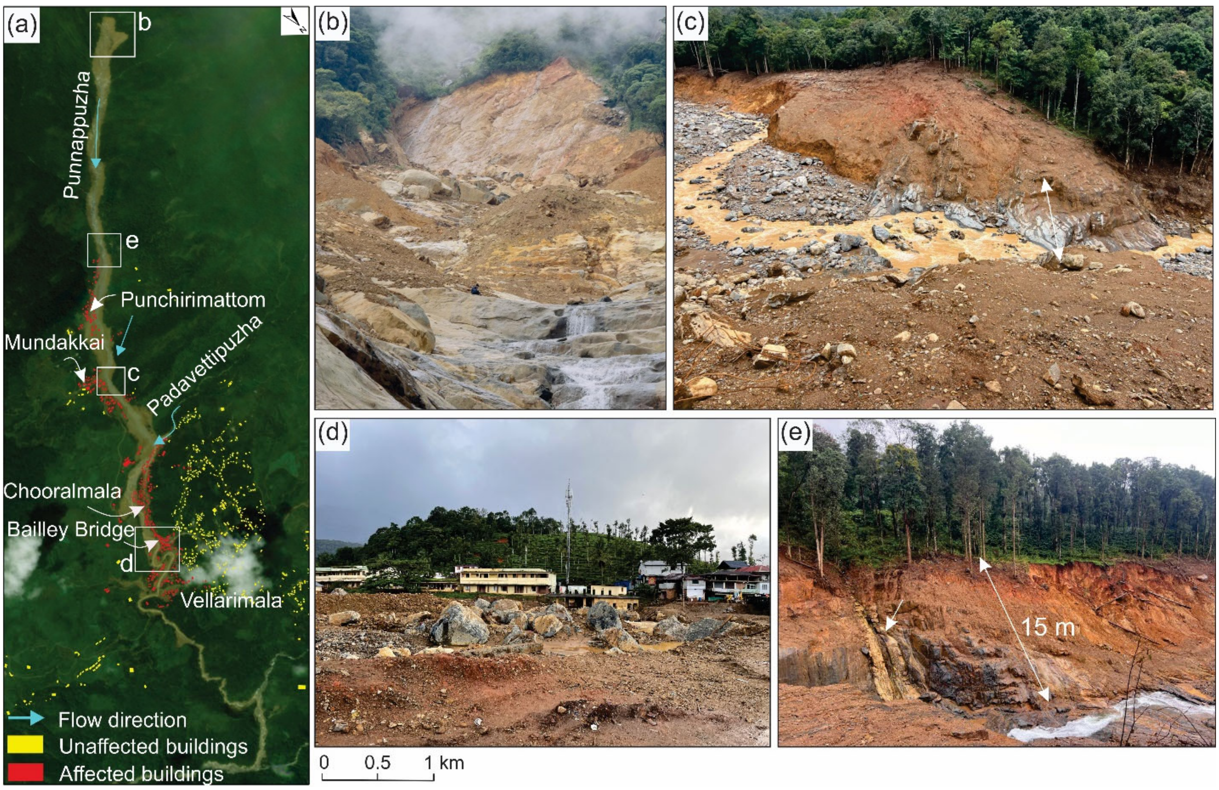

Figure 3 Figure showing the key field components throughout the flow path (a) Planet Lab image of the 2024 Wayanad landslide showing the affected villages and other details (b) Crown of the landslide (c) the vanished Sitammakundu waterfall (white arrow) (d) the zone of accumulation with the Mundakkai school in the backdrop (e) A thickness of 15 m debris was eroded by this landslide. Highlighted part is a shear, manifested as the weathered hornblende gneiss (white arrow).


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Figure 4 Figure showing the major geological and non-geological attractions in the Wayanad district (a) Kalpetta granite (b,c) Ambalavayal granite (d,e) Kartikulam gabbro (f,g) Edakkal caves (h) Meenmutty Waterfalls (i) Pookode lake (j) Banasura Sagar dam (k) Soochipara Waterfalls (l) Chembra Peak with its heart-shaped lake (m) Kuruvadweep (n) Pazhassi Raja Tomb (o) a hamlet of indigenous people in Wayanad (Photo courtesy: Shamil, Deeju, Sanjayan, Ramith).

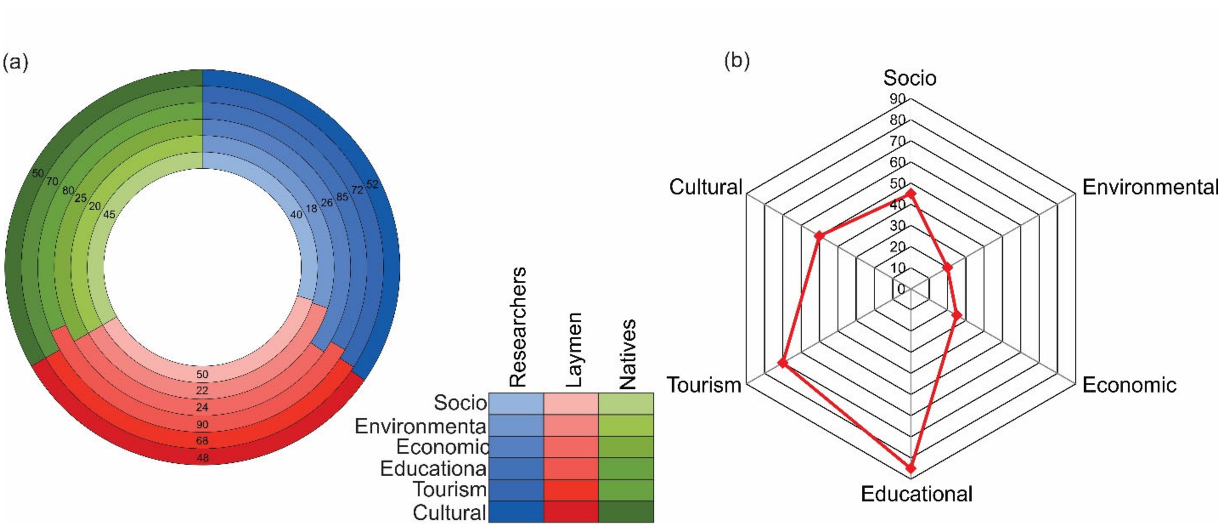

Figure 5 (a) Pie chart showing the score given for six parameters through the survey of researchers, laymen, and natives, (b) Qualitative analysis showing the average score of the six parameters – Socio, Environmental, Economic, Educational, Tourism, and Cultural

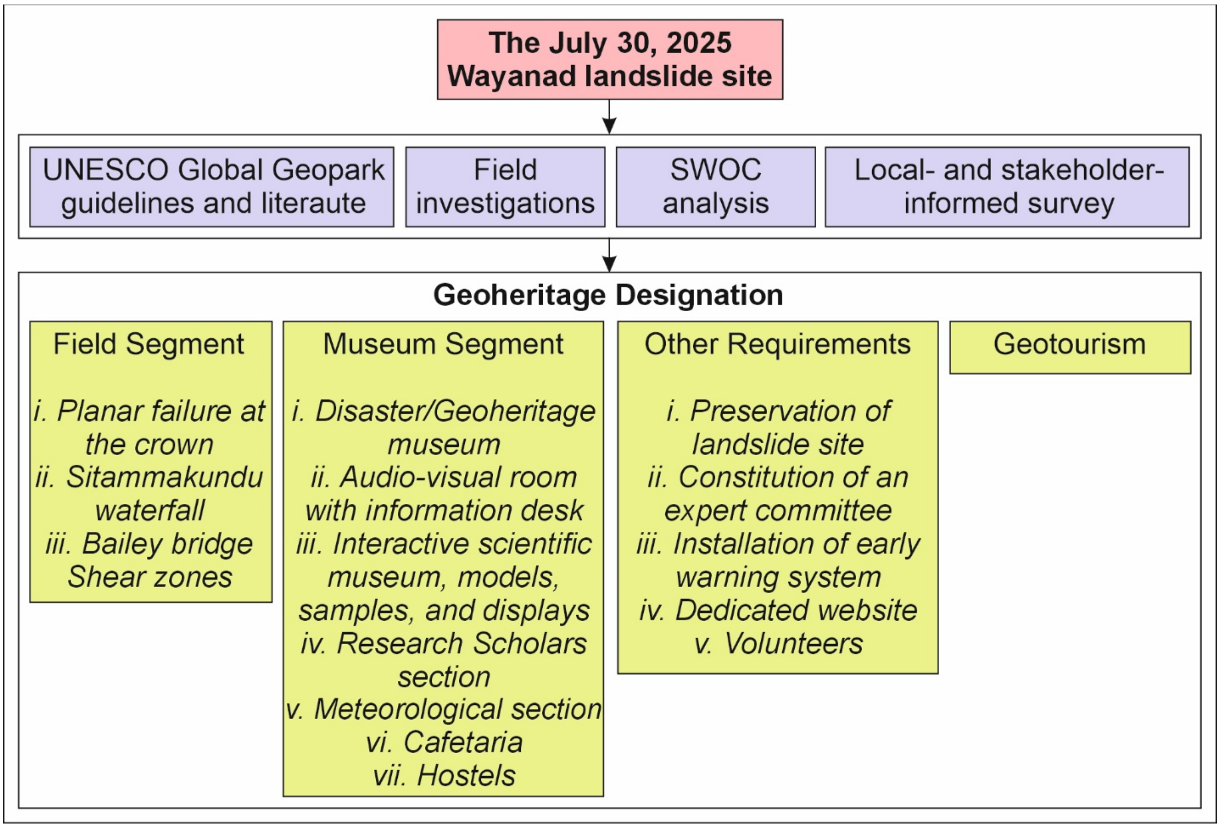

Figure 6 Flow chart showing the schema of converting the disaster prone Wayanad landslide site to a geoheritage site

List of Tables

Table 1 SWOC analysis for the Wayanad landslide as Geoheritage site

Sl No	Criteria & Indicators	Assessment
1	***Strength***	
1.1	Scientific and educational Value	Natural laboratory for earth science research and education.
1.2	Rarity	The landslide Geoheritage site would be the first of its kind in the country
1.3	Location	Landslide geoheritage site is located in the high ranges of the Western Ghats, the UNESCO World Heritage Site, recognized for their exceptional biodiversity, unique ecosystems, and status as one of the world's

		eight 'hottest hotspots' of biological diversity, which are vital for environmental sustainability in India. The site is having an elevation ranging from 700 to 2100 m.
1.4	Representation	Unique blend of geological and geomorphological processes coupled with a rich assemblage of flora and fauna. An opportunity to learn from the field joint patterns, foliation, and lineaments that could provide critical insights into the area's instability, which aids in understanding the mechanics of such composite landslides.
1.5	Showcase	Comprehensive documentation of fatalities and damages supports effective resource allocation and disaster response planning. The systematic response and documentation after the disaster show the region's ability to manage post-disaster efforts, including rescue, relief, and rehabilitation.
2	***Weaknesses***	
2.1	Vulnerability	The entire landslide affected area is still recovering from the massive landslide and the threat of minor slides are not ruled out.
2.2	Lack of Infrastructure	The terrain is characterized by steep slopes, weathered rock, and dense vegetation, makes the area susceptible to frequent landslides, posing a persistent challenge for infrastructure and settlement planning.
2.3	Inadequate local awareness	Many local communities lack awareness or preparedness for the scale and frequency of such composite landslides, making evacuation and safety measures difficult to implement effectively.
2.4	Weak structural resilience	The destruction of 259 buildings indicates that construction practices may not be well adapted to withstand landslide impacts in such high-risk areas.
3	***Opportunities***	
3.1	Preservation and showcasing	Preserve Wayanad landslide as a landslide geoheritage site to promote scientific research, education, and public awareness
3.2	Implementation of early warning systems	Installation of monitoring equipments could collect data on various geological and environmental factors of landslides and they can be analysed in real time. Information centre at the landslide geoheritage site could educate public how leveraging modern technologies such as remote sensing, real-time rainfall data monitoring, and ground

		sensors can provide early warning, helping to reduce fatalities and damage in future events.
3.4	Reinforcement of community resilience	Educating and training local populations about landslide risks, evacuation protocols, and disaster preparedness could minimize loss of life and property in future events.
3.5	International collaboration	Sharing and integrating global knowledge on landslide mitigation (such as successful models from Japan or Nepal) can help Kerala and other landslide prone areas around the world develop more effective mitigation and rehabilitation strategies.
4	***Challenges***	
4.1	Recurring landslides	The region remains vulnerable to future landslides, especially with overhanging colluvium, dislodged boulders, and newly formed gorges that could trigger subsequent slides or debris flows.
4.2	Climate change	Rainfall in the area has become extremely erratic. Increasing rainfall intensity could severely cause landslides, threatening both human settlements and ecological balance.
4.3	Environmental degradation	Promoting plantation in the vulnerable slopes, unchecked tourism and licensing quarrying could exacerbate the intensity of landslide impacts.
4.4	Biodiversity loss	Repeated landslides could result in loss of flora and fauna in the Western Ghats, a biodiversity hotspot, impacting the local ecosystem and livelihoods dependent on natural resources.

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