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Application of the differential GPS technique to monitor landslides: A case study of Dutti Landslide, Nepal

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ABSTRACT

Landslides are a major natural disaster in Nepal, particularly during the monsoon season. This study focuses on the Dutti Landslide in Kavrepalanchok District, Bagmati Province, which has been active for over 80 years, damaging farmland, displacing communities, and depositing sediment into rivers. The objective is to monitor the Dutti Landslide's movement using differential GPS (DGPS) technology to analyze its slip rate and direction while examining the correlation between rainfall patterns and landslide dynamics, specifically how seasonal precipitation affects the landslide's behavior. Thirteen Global Positioning Systn (GPS) monitoring stations were installed along the landslide's crown and surrounding areas to record topographic movement from December 2021 to December 2022 using DGPS technology. Findings show a peak slip rate of 14.7 cm in August, correlating with high rainfall, suggesting that ground saturation plays a significant role in landslide acceleration. Additionally, agricultural practices, such as wet farming, contribute to the upward migration of the landslide crown. This study highlights the importance of DGPS in understanding landslide dynamics, revealing how seasonal rainfall and human activities intensify landslide movement. Results emphasize the need for ongoing monitoring and targeted risk mitigation strategies to address the challenges posed by landslide activity in this region.

Keywords: Dutti Landslide; DGPS; Landslide monitoring; Slip rate; Risk mitigation

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INTRODUCTION

The Himalayas, the youngest and most fragile terrain of the Cenozoic orogeny, are shaped by unique meteorology, geology, and topography, making them highly susceptible to natural hazards (Le Fort, 1975). Hazards are natural events that can lead to property damage, loss of life, or service disruptions. Nepal's Disaster Risk Reduction and Management (DRRM) Act 2074 classifies natural disasters as those arising from natural causes like landslides, earthquakes, floods, inundations, and glacial lake outburst floods (GLOF). Landslides represent a major hazard in the Himalayas, resulting in significant fatalities and damage, with approximately 70% of Nepal's mountainous terrain (Hasegawa et al., 2009; Pradhan et al., 2012; Kargel et al., 2016). As per the Ministry of Home Affairs, Government of Nepal, data resource, from 1971 to 2019, the number of landslides that occurred was 3787. The subsequent events that occurred were floods (3443), excessive precipitation (822), snowstorms (179), avalanches (126), and GLOF (14). These hazards caused property damage totaling 514.53million United State Dollar (USD), highlighting Nepal's vulnerability as a global hotspot for mountain hazards, especially landslides (Kincey et al., 2024). Given the high frequency and devastating impacts of landslides in Nepal, it is necessary to adopt newly developed technology for reliable and precise examining methods that can provide timely data to support early warning systems and risk reduction management.

Significant advancements have been made in landslide research over the last three decades. Monitoring landslides is essential for assessing landslide risk (Auflič et al., 2023). It provides quantitative data on landslide activity with varying levels of precision, depending on the methods and equipment used. Traditional methods for monitoring landslides, such as geotechnical instruments and aerial surveys, have contributed valuable data but face limitations in terms of accuracy, cost, and accessibility, particularly in remote and rugged terrains. More advanced methods, including Light Detection and Ranging (LiDAR), Differential Interferometric Synthetic Aperture Radar (DInSAR), and Unmanned Aerial Vehicle (UAV) photogrammetry, have improved our ability to assess landslide movement (Nikolakopoulos et al., 2017). Wieczorek and Snyder (2009) has analysed the advantages and drawbacks of these different methodologies for landslide monitoring. However, these methods often require sophisticated equipment and specialized expertise, which may not be feasible for resource-limited condition. Hence, there is a growing need for more accessible, precise, and adaptable techniques that can provide real-time, continuous monitoring in challenging environments with affordable costs as well as easily available manpower resources.

Attention must be given on effective landslide monitoring that encompasses measuring various parameters of landslide and understanding how they change over time, which is crucial for analyzing the spatial and temporal dynamics of landslides and identifying their driving factor (Abidin et al., 2004; Gili et al., 2000; Kang et al., 2021). Groundwater level on the slope, the mass movement involved, the failure plane's depth, the landslide's direction, and the landslide's amplitude and pace of movement are a few of the monitoring important parameters of landslide (Kane and Beck, 1999). To effectively mitigate the risk of landslides, monitoring landslides is crucial to developing strategies that enhance the planning, design, and implementation of preventive measures (Abidin et al., 2007; Hu et al., 2019).

Our focus is turned on the Global Navigation Satellite System (GNSS), which is a passive satellite-based positioning technique that is designed for precise three-dimensional positioning and has been primarily used for active crustal deformation measurements (Dixon, 1991; Hoffmann-Wellenhof, 1997). The GNSS has also been effectively used in landslide monitoring since the 1990s (Jinfeng, 1996; Gili et al., 2000; Matsushima and Takagi, 2000; Malet et al., 2002; Abidin et al., 2008; Li et al., 2011). Recent advancements showcase the accuracy of GNSS at centimeter levels across various scales, driving specific technical developments for precision (Blewitt, 1993). According to Lambiel and Delaloye, (2004) and Langbein and Bock, (2004), DGPS is a prominent GNSS positioning technique that enhances accuracy by using multiple reference stations with precisely known locations to correct errors in satellite signals. This method greatly improves GNSS positioning accuracy, especially in areas with limited satellite visibility or high levels of interference (Andreas et al., 2018). DGPS operates on the principle that nearby receivers encounter comparable atmospheric errors. Discrepancies are then adjusted in real-time through radio signals or post processing software, improving accuracy for roving receivers, which record data either on-site or for later analysis. In the DGPS survey, a base station, located at a precisely known location, serves as a reference station, and other reference stations are within the observable target i.e., landslide (Lin et al., 2021). DGPS monitoring offers precise, continuous, and weather-independent measurements for tracking landslide movement, making it a superior option compared to traditional methods like moving pigs, piezometers, and rainfall gauges, which provide limited surface movement data (Chrzanowski, 1986). Additionally, DGPS proves to be a more reliable and cost-effective solution for long-term ground deformation monitoring than conventional geotechnical techniques (Thomas et al., 2024).

The Dutti Landslide in Kavrepalanchok District, Bagmati Province, serves as a case study for DGPS monitoring due to its long history of activity and impact on local communities, agriculture, and infrastructure. Active for approximately 80 years, the Dutti Landslide exhibits seasonal movement patterns closely linked to monsoon rainfall and human activities, such as agriculture and irrigation. Understanding the factors driving this movement, including geo-hydrological and anthropogenic influences, is essential for developing targeted mitigation strategies and safeguarding vulnerable communities. This research aims to measure the landslide’s slip rate and direction with centimeter-level precision, providing insights into the spatial and temporal dynamics of the landslide. To achieve this objective the landslide is monitored over a year (December 2021–December 2022) using DGPS, deploying thirteen GPS stations throughout the landslide. The data reveal correlations between seasonal precipitation and landslide activity, particularly peak movement linked to rainfall-induced soil saturation, enhancing the potential for early warning systems in landslide-prone regions.

In addition to presenting high-precision data on landslide movement, this study also addresses gaps in the existing literature regarding landslide monitoring in Nepal. While most of the previous research has focused on and established the importance of rainfall and slope hydrology in landslide activity, few studies have applied GPS technology to study landslides in the Nepal Himalayas. This study relies on the DGPS in a resource-limited condition and a trustworthy monitoring technology of high-precision implementation, validating its efficacy for landslide monitoring as a strong instrument in previous studies. Additionally, the method's results evaluate whether it facilitates the installation of early warning systems to build landslide disaster resilience in regions that are vulnerable to landslides. Thus, it proceeds with an overview of the DGPS monitoring methodology, followed by a detailed analysis of the data collected, and concludes with a discussion of the implications for landslide management and future research directions.

GEOLOGY OF LANDSLIDE AND SURROUNDING AREA

The Dutti area in Kavrepalanchok District, in the eastern portion of central Nepal, has been experiencing a large-scale landslide due to poor geology with severe geomorphology, strong monsoonal rainfall, and improper agriculture techniques on the mountain slope. This landslide is termed the Dutti Landslide and has been active for the past 80 years (Fig. 1). In addition to uprooting the communities, it has harmed a huge tract of productive land.

The geology of the study areas reveals a dominance of soft rocks. Grey phyllites and grey meta-sandstones alternate in the landslide area. Mineralogical components of phyllites are represented by quartz of very fine grains and sericites. Fine-grained quartz mineral predominates in sandstone composition, with smaller amounts of fine micas and fine-grained feldspars. Geologically, these rocks belong to Kuncha Formation (Stöcklin, 1980). Dip of foliation planes range from 22° to 50° due N120 to N155. The landslide area and its surroundings do not reveal major geological tectonic structures like faults and folds.

Geomorphologically, landslides lie on slopes with aspects to the southeast, east, and northeast. Landslide scar slopes vary from 40° to 75°. The crown of the landslide areas is covered partly by forest and cultivated lands. Several dry gullies join the main, deeper gully, located in the southern part of the landslide. The main gully has a moist to very thin surface water flow towards the east that joins the Chauri Khola. The morphology of the Chauri Khola river bed exhibits a sharp morphological variation both upstream and downstream from the confluence of the tributary that drains the landslide and the Chauri Khola. The river has been aggrading rapidly to the downstream section of confluence, which reveals a convex upward floodplain morphology.

METHODOLOGY

DGPS technology was used in this study to track the Dutti Landslide's path and identify ground deformation using both

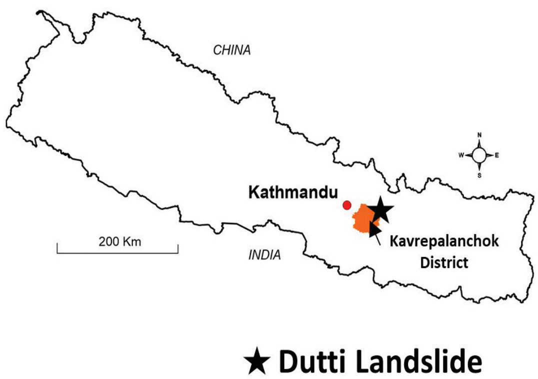

Fig.1: Location maps of the landslide under study in the Dutti area, Kavrepalanchok District, Bagmati Province, Nepal, are displayed in a and b, while Google pictures and photographs of the landslide are displayed in c and d.

static and real-time GPS measurements.

The methodology was divided into three phases. In the first phase, literature review was conducted, accompanied by a preliminary site visit to select appropriate locations for monument stations. The second phase involved installing these monuments, or reference stations, at strategic points in the study area and collecting DGPS data. In the final phase, the collected data were analysed and processed, leading to a comprehensive discussion and conclusion based on the results. The flowchart in Fig. 2 outlines the entire methodology for DGPS methods for landslide movement monitoring.

Site Selection and Monumentation

The preliminary field visit, literature review and interaction with local stakeholders provided the initial insight into the landslide, i.e. past qualitative spatial and temporal activity of landslides, topography and local geology, current and past aerial extent history and socioeconomic impact of landslide etc., based on these data and information the appropriate position and numbers of reference stations were determined. A high topographical location with no physical obstacles, a good view of the sky to prevent interference with GPS signals, and the absence of above-ground utility lines to prevent signal disruption are among the criteria used to select rover stations (Fig. 3). A safe and secure setting is also essential; avoid places close to roadways, rivers, or streams where the monuments can be moved or jeopardized. Except these criteria, there are no hard and fast rules regarding selecting the location and number of reference stations for this method of landslide movement monitoring. Thirteen rover stations were installed to cover the crown and landslide area. And one fixed based base station was outside the landslide at stable ground. Concrete pillars embedded with grooved metal rods were used to securely position GPS receivers (Fig. 4). These monuments ensured stable and consistent measurement points throughout the study period.

DGPS Setup and Data Acquisition

The DGPS system included two types of stations: a permanent base station on stable ground outside the landslide area and rover stations across the landslide. The base station served as a reference point, while the rover stations measured ground displacement relative to it. GPS antennas were mounted on the monuments or station, and GPS data were collected from the each of the reference station on each turn up to 1 year. Where the mode of data collection was static, data observation time was 30 minutes, and data collection occurred at 30-second intervals with a 15-degree elevation mask to minimize signal noise.

The DGPS system used both static and kinematic methods for monitoring depending on the accessibility of stations and the desired accuracy. The static method was preferred for monitoring long-term displacement, ensuring precise data over extended periods. The rover stations provided real-time updates on ground movement, while static data captured larger time-scale changes.

Data Processing and Post-Processing

The GPS data were collected in a Topcon GNSS receiver (Fig. 5) and stored in Topcon Positioning System (TPS) format. To ensure compatibility and ease of analysis, the raw data were converted into Receiver Independent Exchange Format (RINEX) format, allowing further error corrections. This conversion generated various data files, including observation and navigation files, which contained atmospheric and clock error information. The below flow chart (Fig. 6) shows the details procedure for DGPS data processing.

The RINEX data were processed using South Geomatics Office (SGO) software, applying baseline corrections to remove errors and produce high-accuracy positional data. The slip rate of the landslide was calculated based on coordinate differences between consecutive surveys.

Mathematical Calculation of Landslide Movement

Landslide movement was determined using the Haversine formula and the spherical law of cosines, both of which account for Earth's curvature. These formulas calculate the distance between two GPS coordinates, providing the basis for

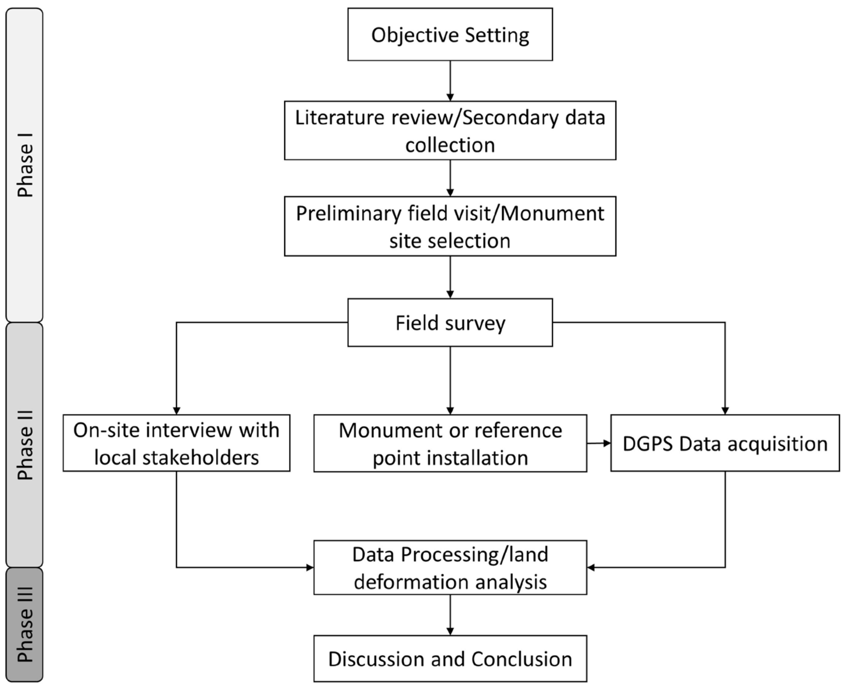

Fig. 2: Comprehensive flowchart of the research methodology.

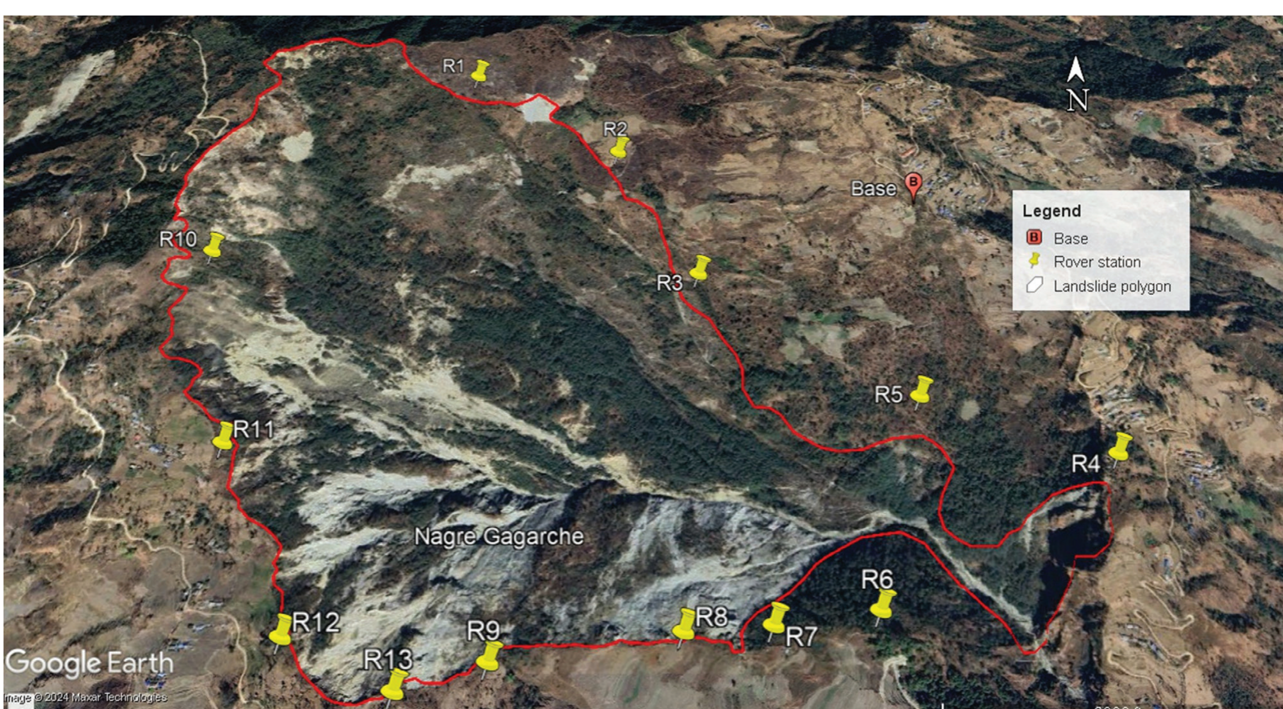

Fig. 3: Location of rover GPS and base stations at the Dutti Landslide.

Fig. 4: Photographs showing the monumentation process, including A) digging the hole, B) concrete pillar installation, C) inserting the pillar, and D) rod setup for GPS device.

Fig. 5: Data acquisition by Topcon GPS receiver in the field.

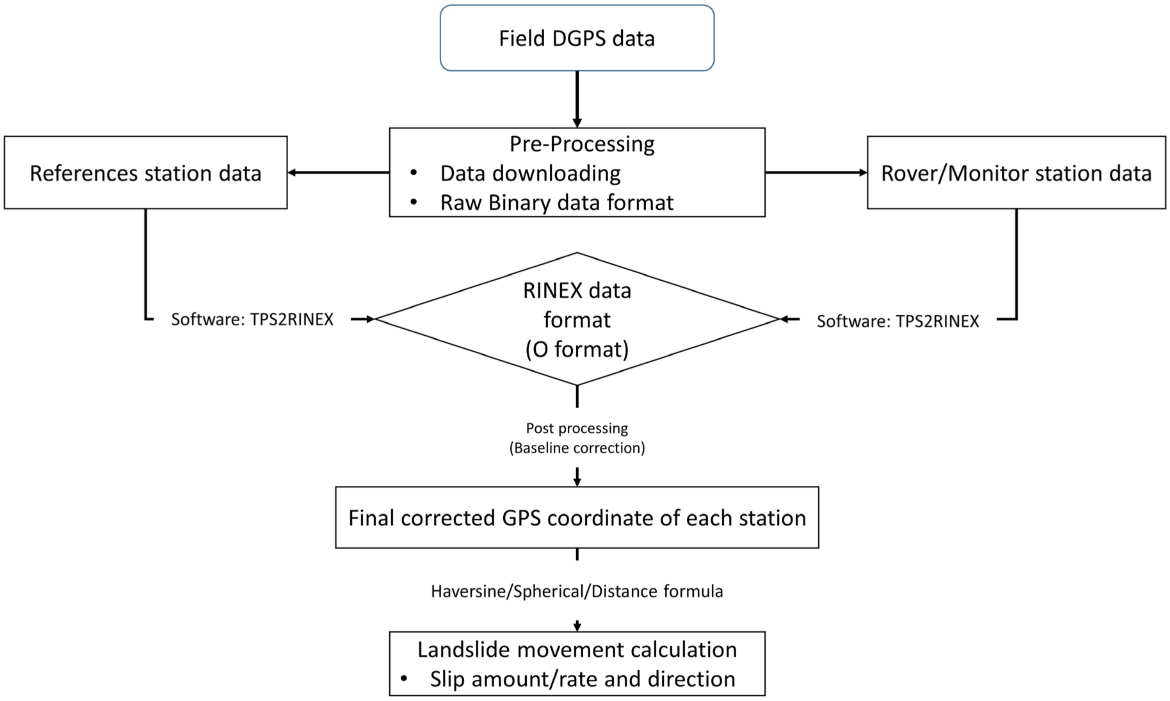

Fig. 6: Flow diagram of the processes used for the analysis of GPS data.

determining the slip rate and direction of ground movement. The formulas used include: (1)

Haversine formula: (2)

$$Distance = 2.R.\arcsin\sqrt{sin^2(\frac{\Delta lat}{2}) + \cos(latitude2).\cos(latitude1).sin^2(\frac{\Delta long}{2})} \quad (3)$$

Δlat = latitude2 - latitude1

Δlong = longitude2 - longitude1

where R in Eq. (3) is the radius of the Earth, which is 6371 km.

Spherical law of cosines:

According to the spherical law of the cosine,

Distance (d) = acos (sin.sin φ2 + cos φ1.cos φ2+cos Δλ).R (4)

where φ1 = lat1 * π/180, φ2 = lat2 * π/180, Δλ = (lon2-lon1) * π/180, and R = 6371 km.

These calculations enabled the research team to determine the extent and direction of the landslide's movement (Azdy and Darnis, 2020).

To assess the slip direction at each reference station within the Dutti Landslide, GPS data were collected monthly throughout the study period. By comparing the first and last measurements of each station, the slip direction was determined in ArcGIS software based on the relative movement of point data from its initial position. This approach allowed for the slip direction at each station to be mapped accurately in ArcGIS using various extrapolation tools.

Final Analysis and Interpretation

Post-processing and error correction allowed for the precise determination of the landslide's movement in both space and time. The results provided valuable insights into the relationship between precipitation levels, ground saturation, and landslide activity. This methodology ensures an accurate and reliable understanding of the landslide dynamics, offering essential data for disaster risk management and early warning systems.

RESULTS

The results of this study demonstrate a systematic approach to understanding the dynamics of the Dutti Landslide through DGPS monitoring. Throughout the 2021–2022 study period, DGPS measurements from 13 stations indicate that the highest slip rate of 14.7 cm occurred at Rover-9 in August, a period with the most rainfall. Data from January to August show a progressive increase in movement across most stations, which aligns with rainfall patterns and suggests that ground saturation significantly impacts landslide activity. Figure 7 presents these monthly slip measurements, highlighting the peak displacements during the monsoon season.

Slip rate variations across different stations further reveal that localized factors, such as hydrogeological conditions, slope orientation, and human activities, influence movement. Higher slip rates, particularly in the southern landslide area near Nagre village, correspond with the presence of natural springs and

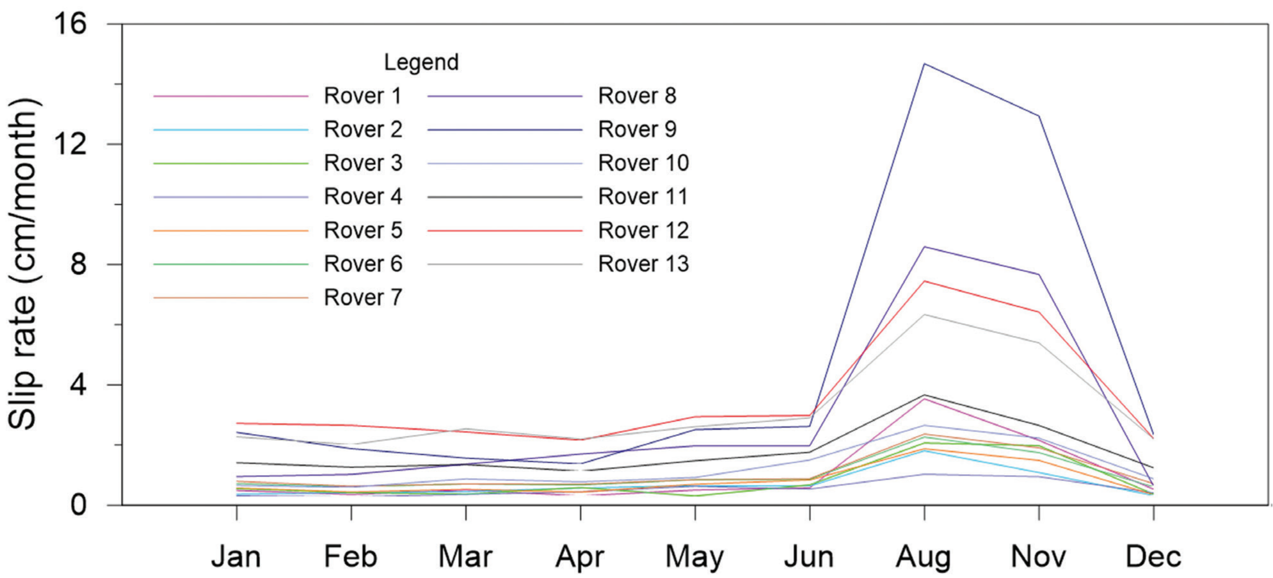

Fig. 7: Graphs show each rover station's monthly slip amount in the Dutti Landslide area.

wet agricultural practices that increase soil moisture. Figure 8 provides average monthly slip rates, indicating higher values at stations near water sources, supporting the notion that groundwater infiltration accelerates landslide processes.

Figure 9, which displays the slip rate and direction of movement, shows how local hydrogeological conditions, slope gradient, and human activities contribute to this differential movement pattern. The map emphasizes that zones with steeper gradients and increased water exposure, especially near Nagre village, exhibit higher slip rates. This mapping allows for a detailed examination of the landslide's spatial variability, offering a clear depiction of the area's most susceptible to expansion. By pinpointing high-risk zones within the landslide, this spatial analysis provides critical information for implementing localized risk reduction strategies, such as drainage improvement and slope stabilization efforts.

The strong correlation between rainfall and landslide slip rates, supported by rainfall data from the nearby Thokarpa gauge station (Fig. 10), further establishes seasonal precipitation as a primary driver of landslide dynamics in the region. The alignment of peak slip rates with heavy rainfall months demonstrates that landslide movement is strongly influenced by groundwater saturation following intense rainfall, which loosens soil and weakens slope stability. This relationship suggests that future landslide activity in the region may be forecasted by monitoring rainfall and groundwater levels.

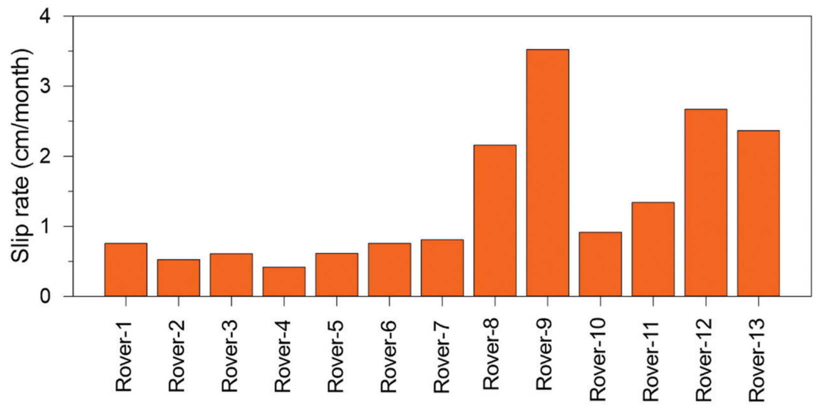

Fig. 8: Average monthly slip rate at each rover station established in the Dutti landslide.

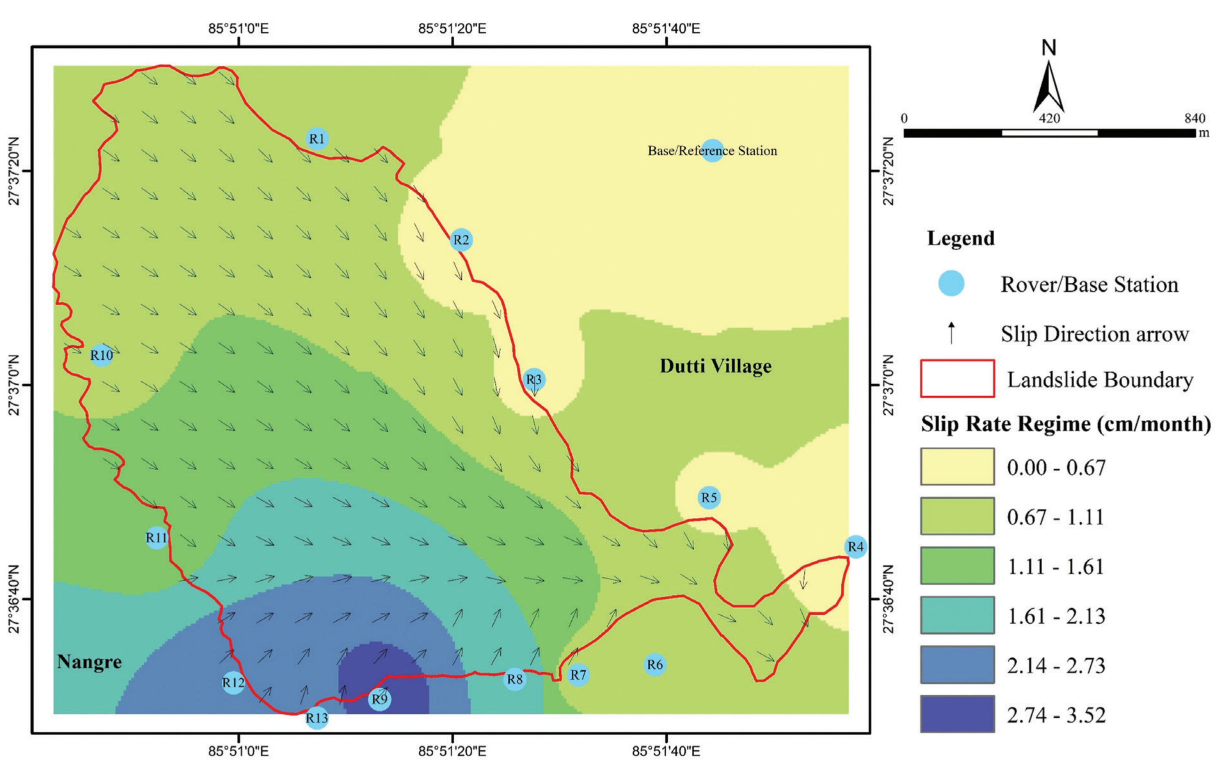

Fig. 9: Map shows slip rate and slip direction of the Dutti Landslide.

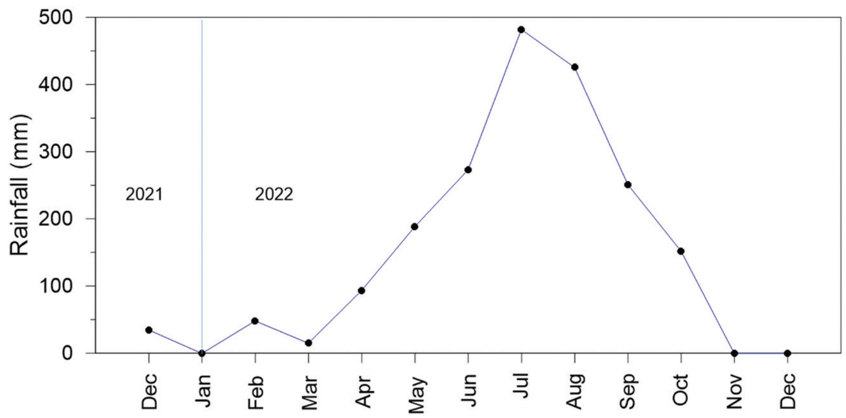

Fig. 10: Monthly rainfall data (DHM, Nepal), recorded at the nearby Thokarpa gauge station, to the Dutti landslide.

This study establishes DGPS as a reliable tool for continuous landslide monitoring, contributing to improved early warning systems and informing mitigation strategies to reduce risks in landslide-prone areas.

DISCUSSION

For the first time Gautam et al. in 2022 described the mechanism of the Dutti Landslide. This paper intends to provide a detailed insight into the movement patterns of the Dutti Landslide, revealing how seasonal rainfall and anthropogenic factors drive landslide dynamics. The data demonstrate a clear association between rainfall peaks and increased landslide slip rates, with the highest movement (14.7 cm) recorded during August, coinciding with peak monsoon rainfall (Fig. 10). These results align with Dahal and Hasegawa's (2008) findings that link monsoon precipitation to heightened landslide activity in the Nepal Himalayas. By highlighting this correlation, DGPS offers a high-precision, cost-effective approach for continuous monitoring of landslide-prone areas, especially in terrains similar to the Himalayan region, where factors such as heavy rainfall and geological vulnerability play a significant role in landslide occurrences.

Spatial variability in slip rates across the Dutti Landslide (Fig. 9) suggests that localized hydrogeological conditions and human activities, such as wet agriculture practice and irrigation on vulnerable, contribute to landslide risk. The southern portion near Nagre village displayed elevated slip rates, potentially due to groundwater infiltration from natural springs and irrigated surface water, consistent with findings by Kincey et al. (2024) and Javadinejad et al. (2020). Similar studies revealed that topographic factors and hydrogeological conditions intensify landslide dynamics by destabilizing soil layers, particularly during high rainfall. This site-specific landslide movement analysis corroborates the significance of slope hydrology in landslide development, consequently reinforcing the need for targeted mitigation measures in zones with higher water exposure.

The study's DGPS methodology, offering continuous and adaptable monitoring, proves advantageous over traditional methods, especially in the context of rainfall-triggered landslides in the mountainous regions of Nepal. Unlike manual surveying techniques or intermittent geotechnical measurements, DGPS continuously records landslide movement, enhancing data reliability. The technology's adaptability to various environmental conditions, including adverse weather, strengthens its use in early warning systems.

Ultimately, it underscores DGPS's role as a reliable monitoring tool that facilitates refined hazard assessment and landslide risk management in the Himalayas. By comparing landslide movement data against seasonal rainfall records, DGPS enables more precise forecasting of landslide activity, crucial for future planning and community protection. This technology used here to gather slipping ground data is an extra tool for the Himalayan region's continuous landslide study technique in order to manage the risk of landslides and ensure slope stability (e.g. Polemio and Sdao, 1999; Aleotti, 2004). Further expanding DGPS networks across vulnerable regions can enhance early warning capabilities, enabling localized interventions and contributing to Nepal's broader disaster risk reduction initiatives.

CONCLUSIONS

In conclusion, time-series DGPS monitoring of the Dutti Landslide from December 2021 to December 2022 highlights significant spatial and temporal variations in slip rates, with higher deformation rates (up to 3.5 cm/month) concentrated in the southern portion, particularly near Nagre village. The data revealed a strong correlation between seasonal rainfall and landslide movement, with slip rates accelerating during monsoon periods due to groundwater saturation. This study emphasizes the importance of DGPS as a valuable tool for landslide monitoring in Nepal, offering critical insights into landslide dynamics and informing risk management. Continuous monitoring aids in early warning systems, mitigation strategies, and future planning to minimize landslide risks and protect vulnerable communities.

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