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ORIGINAL PAPER

Geomorphological analysis and early warning systems for landslide risk mitigation in Nepalese mid-hills

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Abstract

The Nepal Himalayas is one of the world's most active mountain belts and home to widespread natural hazards of various types, including landslides, which claim numerous lives and result in massive property damage in the country. Landslides occur due to the combined effects of seismic activity, monsoon rainfall, and improper land-use practices. The prevention and mitigation of landslides are challenging for countries such as Nepal. However, low-cost techniques such as bioengineering combined with affordable early warning systems have been implemented in recent decades. The Methum landslide in Lalitpur district, central Nepal, was selected as a case study to investigate the landslide geomorphology along with triggering factors and to evaluate the effectiveness of a landslide early warning system (LEWS). Multiple field visits were conducted to learn the patterns of landslide evolution, assess landslide risk, and identify potential triggers. This study analyzed aerial photos, satellite images, and precipitation records. Heavy rainfall and past earthquake events have been major landslide triggers, while sloped terrace farming has acted as a preparatory factor. LEWS, installed, measures rainfall, soil moisture, and displacement activity and generates an alarm to alert nearby inhabitants if any of these parameters exceed the threshold set. This monitoring system is a cost-effective technique and exemplifies the reduction of landslide risk at the community level in the landslide-prone mid-hills of Nepal.

Keywords Landslide · Triggering factor · Monitoring system · Risk reduction

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1 Introduction

The Nepal Himalaya lies in the central part of the Himalayan range that was formed by a collision between the Indian and Eurasian plates approximately 55 million years ago (Dhakal 2015). Five physiographic regions are distinguished based on Nepal's climatic and geomorphic conditions: the Terai, Siwaliks, Hills, Middle Mountain, and High Mountain (Adhikari and Ojha 2021). Approximately 40% of the country's population lives in the hills, albeit in a scattered manner across poorly defined areas (Central Bureau of Statistics 2021). After each rainfall event during the summer monsoon season, these hill slopes suffer from soil erosion and landslides (Dahal and Hasegawa 2008). Slope failures and landmass collapses occur as a result of the combined influence of internal and external factors (Miao et al. 2021). Various internal factors that may destabilize slopes are landforms, rock structures, and rock and soil properties. External factors such as precipitation intensity, reservoir water levels, seismic events, and human activity can also trigger a slide (Wang et al. 2022). Landslides often occur due to a continual process of geomorphic evolution (Thapa 2015), and it is thus necessary to understand their geomorphological changes prior to applying landslide measures.

For landslide risk mitigation, both structural (e.g., bioengineering, retaining walls, check dams, prop walls, gabion toe walls, drainage management) and nonstructural (e.g., landslide early warning systems, awareness, capacity building, resettlement to safer areas) measures have been adopted globally (Sultana and Tan 2021; Thapa and Adhikari 2019; Lacasse et al. 2009). A country with weak economic conditions, such as Nepal, cannot allocate a budget sufficient for the construction of large infrastructure projects to control landslides, and communities are left to survive under the risk of landslides in hilly landscapes (Jones et al. 2014; Malla et al. 2020). Moreover, in cases where settlements near landslide-prone areas are unprepared, the safety of the community becomes an immediate priority (Alcántara-Ayala and Moreno 2016). This necessitates a method of landslide of prediction that would minimize landslide risk and reduce casualties by alerting vulnerable communities in advance.

Globally, early warning and monitoring systems have been developed and used to predict landslides and protect properties and livelihoods. The government of Japan in 2005 started an early warning system in the country that relied mainly on hourly cumulative precipitation and the soil water data (Osanai et al. 2010). In Italy, a regional landslide forecasting system has been developed that integrates both temporal forecasting (which considers the rainfall amount) and spatial forecasting (which considers susceptibility maps) (Segoni et al. 2015). The Norwegian Water Resources and Energy Directorate initiated an early warning system for rainfall-induced landslides based on real-time observations of precipitation and groundwater levels (Krøgli et al. 2018). The United States of America started a debris flow early warning system in 1975 based on rainfall intensity and has since been improved and has issued multiple warnings for potential debris flows (Baum and Godt 2010).

Only limited applications of the landslide early warning system (LEWS) are known in Nepal (Dahal and Hasegawa 2008); furthermore, authorities in the Nepalese government have also largely overlooked the potential of early warning techniques for landslide risk reduction (Adhikari and Tian 2021). The LEWSs used earlier were simple and based on a single sensor, as they were designed to forecast landsides based on single metric, such as rainfall or ground displacement, and were not real-time forecasting systems. A landslide early warning system was installed during road construction to monitor potential landslides near the village of Kabilash, Chitwan district (JICA 2009). However, this system used only the rainfall threshold to predict landslides. Another LEWS was tested in Sundrawati village (Kalinchowk Rural Municipality, Dolakha district) and used a displacement sensor to predict the Mehle landslide (Thapa and Adhikari 2019). A few other LEWSs were launched on a project basis, but most of these instruments diminished once those projects were completed.

It is of utmost necessity to develop a cost-effective yet robust LEWS that uses multiple parameters to predict landslides in the country. In this context, we established a low-cost LEWS with three sensors (namely, a rainfall sensor, displacement sensor, and soil moisture sensor) to monitor the deep-seated and active landslide on a real-time basis. The LEWS has demonstrated that it can significantly reduce landslide risk to nearby inhabitants by raising an alarm. Additionally, this system can be replicated within other landslide-prone areas once the necessary thresholds of the measured parameters have been customized.

2 Materials and methods

2.1 Study area

The Methum landslide (Fig. 1) selected as the study area lies near a settlement in the Sankhu watershed (latitude 27°28′ 35″– 27°32′ 23″ and longitude 85°16′ 51″–85° 21′

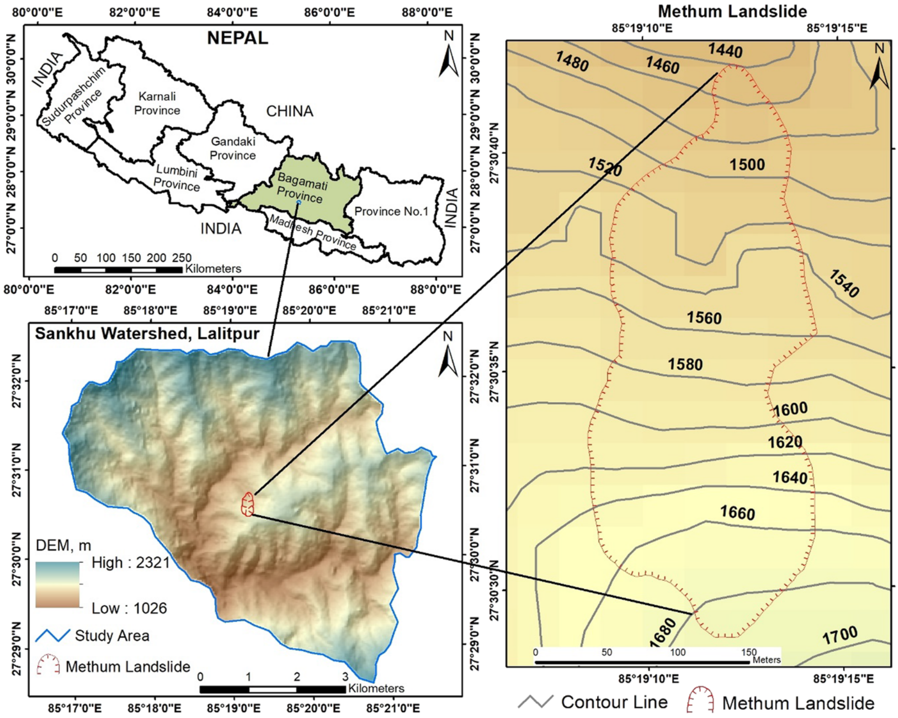


Fig. 1 Study area: Methum landslide location in Sankhu watershed, Lalitpur district

33″) of the Lalitpur district in the mid-hills of Nepal. The Sankhu watershed covers approximately 33.69 square kilometers and has a population of 4978 (2428 males and 2550 females) (Central Bureau of Statistics 2021). The climate in this watershed is subtemperate, with an average humidity of 50–80%. The region's average annual temperature is 14.80 °C, and the annual average rainfall is 1697 mm (Konjyosom Rural Municipality 2019). Major land uses in the study area include forest and non-forest (built-up, agricultural land, grassland, shrubland, water body, and barren land). The area's vegetation comprises numerous species, such as khote salla (*Pinus roxburghii*), gobre salla (*Pinus wallichiana*), katus (*Castanopsis indica*), chilaune (*Schima wallichi*), thulobanjh (*Quercus lanata*), phalant (*Quercus lamellosa*), khasru (*Quercus semecarpifloia*), and laligurash (*Rhododendron sps.*) (Divisional Forest Office, Lalitpur, 2021). Geologically, this area consists of Lesser Himalayan and Higher Himalayan rocks. Paleozoic granite (Phulchoki Group), Chandragiri limestone, the Chitlang formation, the Markhu formation, the Sopyang formation, and the Tistung formation can be observed in the Sankhu area (DMG 1994; Acharya and Paudyal 2019). Several low-grade metamorphic rocks dominate the study area, including metasandstone, phyllite, argillaceous limestone, orthoquartzite, and slate. A succession of highly weathered calcareous rocks is exposed throughout the region.

2.2 Methodology

2.2.1 Geomorphological analysis of the Methum landslide

The geomorphology was studied with the help of aerial photographs, satellite images, and digital elevation model (DEM) data (Siart et al. 2009). Aerial photos collected in 1954 and 1972 were obtained from Nepal's Forest Research and Training Center and converted into mosaic images, which were analyzed in the ArcGIS Pro 2.7.0 Geographic Information System Environment. High-resolution satellite images for 2005 (Quickbird), 2010 (George-1), 2014 (WorldView-2), and 2020 (WorldView-3) were obtained from the Remote Sensing Technology Center (RESTEC) of Japan. AW3D high-definition terrain data for 2019 from the Maxar satellite constellation (obtained from RESTEC, Japan) were used to prepare the DEM (which has a 2 m × 2 m resolution). Using the DEM, various geomorphological characteristics, such as longitudinal and cross sectional profiles, and average advancing rate, were extracted.

2.2.2 Potential triggers of the Methum landslide

We examined three major factors that triggered (but are not necessarily limited to) this landslide: monsoon precipitation and severe earthquake tremors as natural factors and terrace farming on outward slopes as an anthropogenic preparatory factor.

To assess the respective roles played by those factors, we analyzed precipitation records, temporal earthquake events, and sloping terrace farming-related information relevant to the study area. We acquired precipitation records of three meteorological stations nearest to the study area, namely, Chapagaun, Khokana and Lele, for the 1976–2020 period from the Department of Hydrology and Meteorology (DHM), Nepal. For earthquake-related information, we assembled information gathered from peer-reviewed articles published globally and from the website hosted by the National Earthquake Monitoring and Research Center, Nepal, which were analyzed for visual interpretation. Interaction with locals and field investigation enhanced the understanding of the role that the cultivation of outward sloping terraces plays as a preparatory factor for landslide initiation and was used to support the findings. No primary data were generated for sloping terrace farming; however, the discussion was triangulated with previous studies conducted in similar geological settings. The quantitative data related to precipitation and earthquake events were analyzed and presented using Excel sheets on Windows 11 Pro.

2.2.3 Establishment of the landslide monitoring system

Site visits and interaction with locals confirmed that the Methum landslide had been expanding at an accelerated rate since the Gorkha Earthquake in 2015 and had been jeopardizing the settlements and a recently expanded rural road at the landslide's crown (Fig. 2). As agricultural terraces were destroyed and the landslide approached their homes, three households (Ha- 27°30′29.63″N, 85°19′3.20″E, Hb- 27°30′32.88″N, 85°18′59.55″E, and Hc- 27°30′34.97″N, 85°18′58.34″E) abandoned the area in fear of new slope failures (Fig. 2).

In anticipation of new slope failures within the Methum landslide area, a LEWS was installed at a relatively stable site close to the head scarp (27°30′29.49″N, 85°19′3.46″E) on July 1, 2021, to monitor landslide activity. The system comprised a precipitation sensor (rain gauge), two soil moisture sensors, a land displacement sensor (extensometer), and a data collection platform (DCP), as illustrated in Fig. 3 (representative sketch), and Fig. 4. The detailed specification of sensors used in the LEWS is shared in Online Resource 1 and circuit diagram of DCP is shown in Online Resource 3. The precipitation sensor (tipping bucket) was set to measure rainfall accumulated every 10 min; soil moisture sensors were installed at depths of 30 and 50 cm to detect the vertical moisture profile every 10 min, and a displacement sensor comprised of a wire attached to an extensometer was pegged along the potential crack zone in the crown area to measure landmass displacement (additional data are shared in Online Resource 2). A solar panel was installed on a stand facing toward the south to supply power to the battery inside the DCP system. An alarm speaker was attached to the stand facing the settlement area. Subscriber identity module (SIM) cards from two different communication companies (Nepal Telecom Corporation's Global

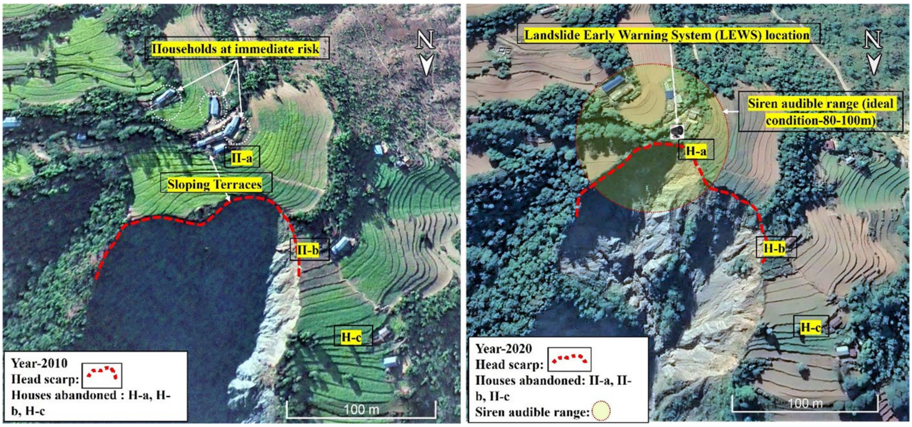


Fig. 2 Methum landslide head scarp region: Household at risk and sloping terraced farms in the crown area (left photo 2010) which has already collapsed in the right photo (2020) with the LEWS station; siren audible range, and H-a, H-b, and H-c represent three abandoned houses

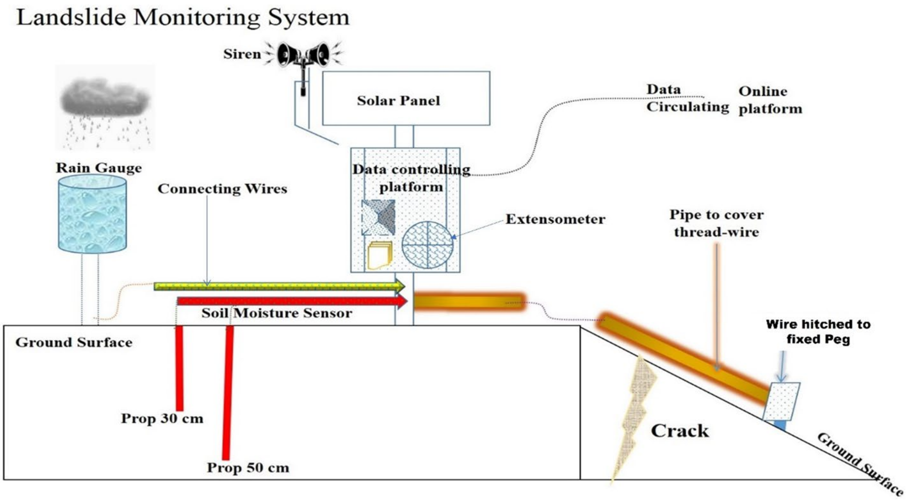


Fig. 3 Representative sketch of the LEWS installed to monitor the Methum landslide

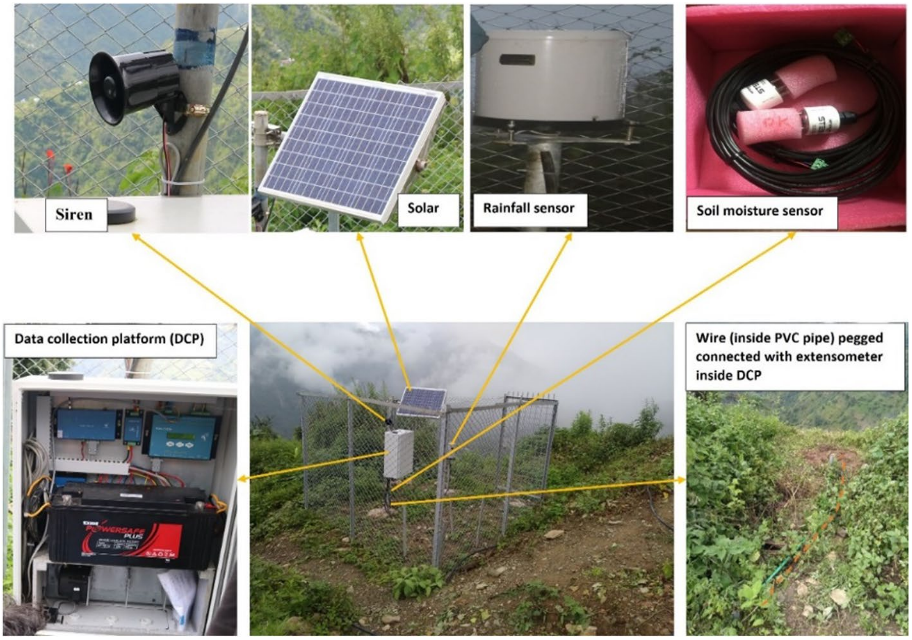


Fig. 4 Landslide monitoring system showing assembled sensors and accessories (located at the stable site near crown area for monitoring the Methum landslide)

System for Mobile [GSM] and Ncell Axiata's GSM) were used at the DCP to share the recorded data. The station was protected with wire mesh fencing, and polypropylene random copolymer (PPR) pipe was used to protect the land displacement sensor wire that was hitched with multiple pegs along the landslide's crack zone.

This system was designed to share a real-time database with the server, designated organizations (Department of Forests and Soil Conservation, Konjyosom Rural Municipality Ward Number 2), and specific persons (nearest residents). The system was also designed to sound an alarm when the set threshold of any parameter under observation was exceeded. The thresholds for this system were calibrated with some customization referring to the warning-level limits used by the Japan International Cooperation Agency (JICA), DHM and previous research findings (JICA 2009; Dahal and Hasegawa 2008; Thapa and Adhikari 2019) and aided by researchers' experience in this field (see Table 1 below).

3 Results

3.1 Geomorphological assessment of the Methum landslide

An aerial photo from 1954 revealed the Methum landslide in its initial stages, with only small scar and gully like structures (Fig. 5A). Vegetation was visible on the left flanks of the small collapsed area. Terraced land was also a prominent feature along the landslide's left and head regions. No significant changes were observed in the landslide's shape based on an aerial photo captured in 1972, despite the 18 years that had elapsed (Fig. 5B), although the vegetation on the landslide's left flank appeared to have increased. However, it is evident from high-resolution satellite images captured in 2005, 2010, and 2020 (Fig. 5C, D, E) that the small collapse structure had developed into a massive landslide, with considerable evidence of incremental failure in the upper region that expanded to both side flanks of the landslide in 2020. The 2005 image shows that multiple large ravines also appear to have formed along with the collapses. Nevertheless, in the landslide's crown zone, a few terraced landmasses appear to have remained intact up to 2010. Based on the 2020 image, it is evident that all vegetation on the slopes, in addition to several terraces that were cultivated in the landslide's crown region, moved downward (Fig. 5E). By the year 2020, the landslide's crown almost approached the houses.

The Methum landslide is an active landslide with concave longitudinal slope failure that has expanded to an area of 4.3 hectares. The landslide's main scarp is at an elevation of 1,685 m, and its toe is found at 1455 m above sea level, with an elevation difference of 230 m. Geomorphological analysis (Fig. 6) has revealed that the Methum landslide has become a large and deep-seated landslide, with a length of approximately 537 m extending from crown to toe and a breadth of approximately 170 m in its

Table 1 Threshold set for three parameters in the LEWS (as of July 2021)

Parameter (Sensor)	Rainfall (Rain gauge)	Displacement (Extensometer) (mm)	Soil moisture (Props) (%)
Threshold	1 h–60 mm, 3 h–80 mm, 6 h–100 mm, 12 h–120 mm, 24 h–140 mm	≥ 500	75
Initial reading	~ 0 mm	~ 4000	~ 0

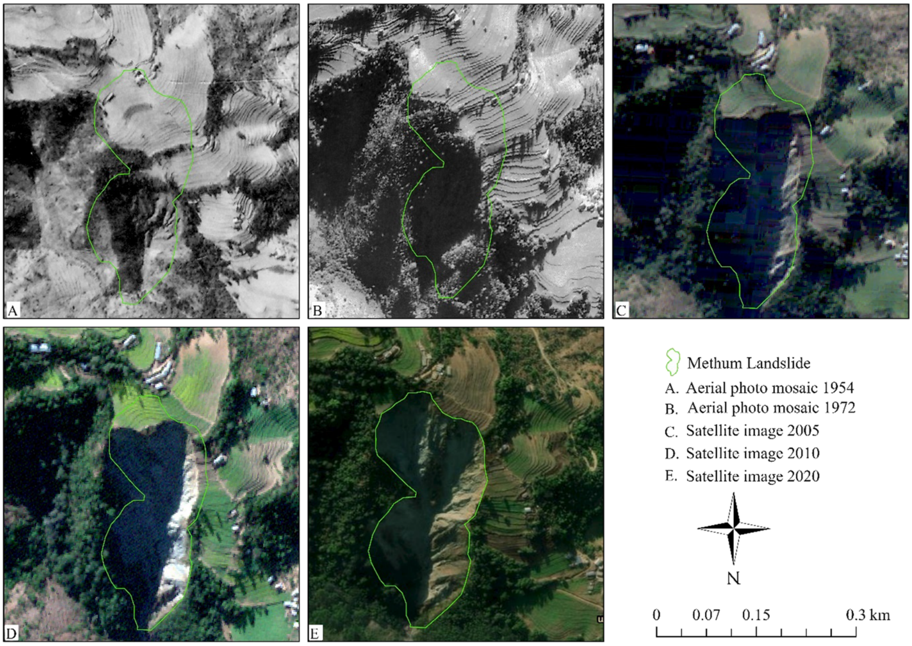
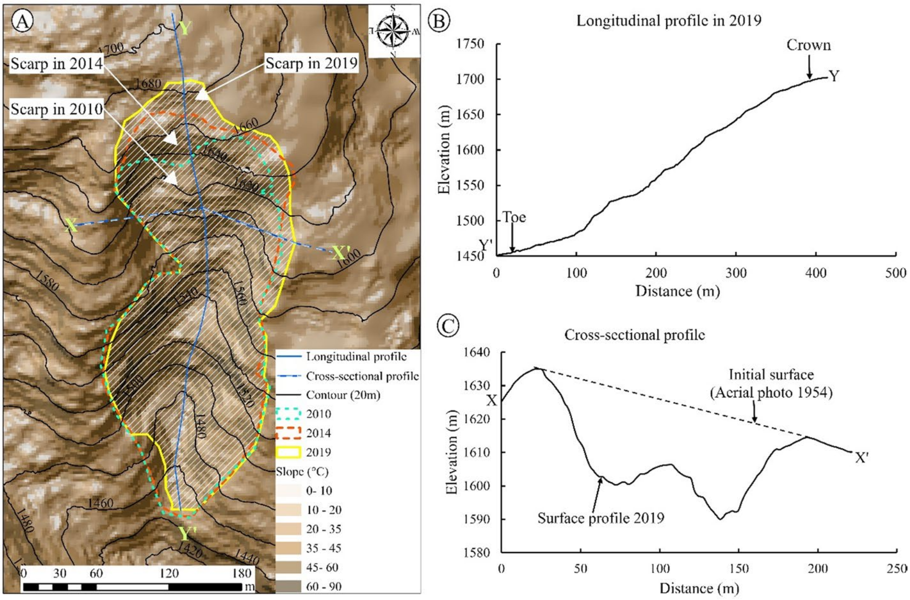


Fig. 5 Temporal increment in the size of the Methum landslide scar (**A**, **B**, **C**, **D**, and **E**) between 1954 and 2020



Source: Maxar Satellite imagery from 2010 and 2014, and AW3D-DEM derived from Maxar Satellite constellation, 2019.

Fig. 6 Methum landslide profile: **A** representation of head scarp advancement (to south) in 2010, 2014, and 2019, **B** longitudinal profile of the landslide from toe to crown, and **C** cross sectional profiles showing degradation of the surface topography along the middle cross-section of the landslide

Table 2 Yearly cumulative rainfall with high intensity in the study area

Year	Cumulative yearly rainfall (≥ 1700 mm year^{-1})
1985	1900 mm year^{-1}
1998	2274 mm year^{-1}
1999	2293.7 mm year^{-1}
2002	2329 mm year^{-1}
2004	2022 mm year^{-1}
2014	2151 mm year^{-1}
2019	1750 mm year^{-1}

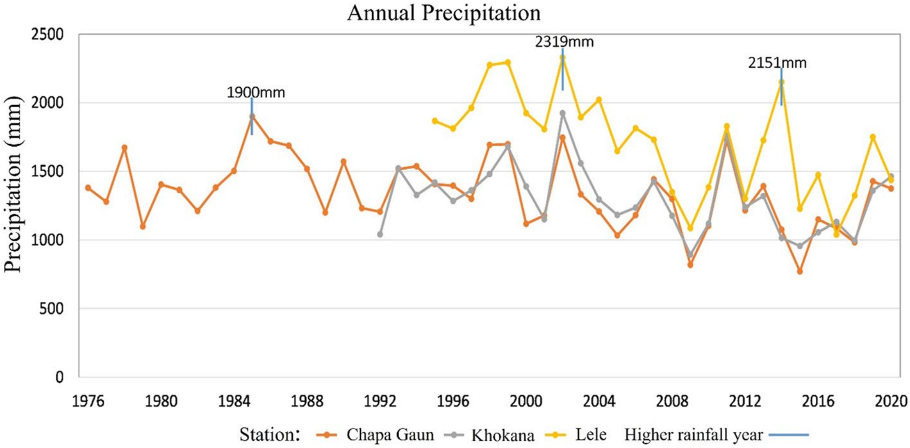


Fig. 7 Precipitation data from three meteorological stations (Chapagaun, Khokana, and Lele), with vertical blue marks indicating years (1985, 2002, and 2014) that recorded higher rainfall than the annual average of 1697 mm in the study area

mid-section. The landslide was slow-moving in the past, but recent satellite image analysis indicated that the Methum landslide appeared to have advanced by approximately 6 m yr^{-1} between 2010 and 2019. Ravines approximately 30–35 m deep have formed in the middle section of the landslide, and steep slopes have developed at the head scarp, which seems unstable.

3.2 Triggering factors for the Methum landslide

During the field observation, local residents frequently remarked that past earthquakes, especially the 1934 Bihar-Nepal event, reactivated the landslide, and since then, this landslide has advanced every year. Furthermore, they mentioned that the slopes of the Methum landslide descended further whenever heavy rainfall occurred in the area. Earthquakes and monsoon rainfall are identified as the main factors triggering the occurrence of the Methum landslide. The available records for the 1976–2020 period revealed that the cumulative annual rainfall in 1985, 2002, 2014, and 2019 was higher than the area's annual average (1697 mm) (Table 2 and Fig. 7). Daily rainfall was highest on July 23, 2002

Table 3 Daily cumulative rainfall with high intensity in the study area

Day	Cumulative daily rainfall (≥ 140 mm day^{-1})
6/29/1986	150.5 mm day^{-1}
10/20/1987	172 mm day^{-1}
7/23/2002	280 mm day^{-1}
7/23/2002	200.5 mm day^{-1}
7/23/2002	249.2 mm day^{-1}
7/9/2004	165 mm day^{-1}
7/12/2019	149.2 mm day^{-1}

(280 mm day^{-1}), and daily rainfall higher than 140 mm was recorded on five occasions from 1976 to 2020 as detailed in Table 3.

Seismic activity that occurred over the last century was identified as another triggering factor for this landslide. Table 4 below presents a list of major earthquake events (local magnitude scale [ML] ≥ 7, which struck close to the study area during the last century in chronological order. These past earthquake events were of sufficient intensity to shake the hillslopes and trigger several landslides.

Earthquake magnitude values in Table 4 were referred from previous scholarly archives (Bollinger et al. 2016; Okamura et al. 2015; Ader et al. 2012).

The continuation of unsuitable agricultural practices around the landslide has also contributed to landslide advancement. The field visit confirmed that the area's local inhabitants had been farming on the outward sloping terraces for multiple generations, producing rice, wheat, mustard, and vegetables. For agricultural crops, such as rice and wheat, local farmers plow and hoe the sloping terraces to loosen the soil, as shown in Fig. 8. Most of the landslide region has a slope of more than 50%, which is more susceptible to erosion.

On such steep slopes, practicing outward sloping terrace farming increases the susceptibility of the surface to erosion following plowing and hoeing activities. The Asian monsoon rainfall then erodes these soil surfaces, forming gullies.

3.3 Landslide monitoring system

On August 16, 2021, one and a half months after the LEWS was installed, a new collapse occurred in the Methum landslide's head scarp region. On this occasion, this system generated an alarm that alerted locals to the landslide. The siren was heard by locals residing near the landslide crown area. On the day of the slope failure event, residents heard the first alarm at 05:35 a.m., and key individuals received alert messages notifying them about the displacement parameter that had exceeded the set threshold. The LEWS recorded 4550 mm (initial reading 4000 mm + 550 mm) of displacement and initiated the siren on the speaker attached to the system, as intended. In this case, the displacement sensor exceeded the set threshold limit of 500 mm. Another siren was sounded at 16:55 p.m. later that same day. This alarm was triggered based on the data recorded by the rainfall sensor. By this time, the cumulative rainfall reached 66 mm hr^{-1}, which exceeded the set threshold limit of 60 mm hr^{-1}. During both alerts, the alarm sounded for 20 s. During this period, the monitoring system recorded the displacement of land and rainfall, as illustrated below (Fig. 9).

Table 4 Earthquake events occurring in proximity to the study area

Year	1905 (Kangara-earthquake)	1934 (Bihar–Nepal earthquake)	1950 (Assam earthquake)	2015 April 25 (Gorkha earthquake)	2015 May 12 (Aftershock of Gorkha earthquake)
ML	7.8	8.1	8.6	7.8	7.3

This recent collapse occurred on the head scarp of the Methum landslide (Fig. 10). The displacement sensor wire hitched with pegs was also found to have been breached along with the slide. The slide area was almost 3 m wide, and a landmass with an arc of 10 m had collapsed from the crown region of the landslide. Following this slope failure, the Methum landslide advanced toward the nearby rural road and the houses of the small community, which increased the risk of landslide in these areas.

4 Discussion

4.1 Landslide evolution and triggering factors

Geomorphological analysis reveals that the Methum landslide became a deep-seated giant landslide within the last 65 years, having developed from small gully like structures. The available aerial photos confirmed that the landslide remained at an almost dormant stage between 1954 and 1971. However, the image from 2005 shows that its size has significantly expanded. This landslide was reactivated between 1971 and 2005. The Methum landslide experienced continued incremental advancement from 2005 to 2021, with multiple collapses when the last displacement at the crown was also recorded by LEWS. Consequently, terraces in the crown section were disrupted, and the continuous landscape to the landslide's right and left became fragmented. This reactivation of large landslides in the Nepal Himalayas has been a major cause for concern within the communities of Nepal's mid-hills (Hasegawa et al. 2009) owing to the potential of these events to destroy communities or structures over time if left unchecked (Timilsina et al. 2017).

Both natural and anthropogenic triggering factors played a crucial role in reactivating the Methum landslide, as earlier studies have reported similar findings regarding several landslides in the hillslopes of Nepal (McAdoo et al. 2018; Gnyawali et al. 2020). Erratic rainfall during the monsoon season has emerged as the foremost natural factor that may have reactivated the Methum landslide. This area has received heavy rainfall in excess of 140 mm day^{-1} several times during the monsoon season, which is considered the potential threshold for rainfall to trigger landslides in the Nepal Himalayas (Dahal and Hasegawa 2008; Kanungo and Sharma 2014; Dikshit et al. 2019). In 2002, the study area received daily rainfall amounts of 280 mm and a cumulative yearly rainfall of 2329 mm, which was sufficient to trigger landslides by weakening the soil surface through excessive infiltration of water. Such torrential rainfall events are sufficient to trigger landslides. For example, in 2002, monsoon rainfall triggered several landslides in many parts of Nepal (Bajracharya et al. 2017; Sharma et al. 2020).

The Nepal Himalayas is a seismically active zone that experiences recurring large-scale earthquakes, with a remarkable cluster of seismic events occurring in the twentieth and twenty-first centuries. Specifically, earthquakes with seismic intensity values higher than

Fig. 8 Overview of the Methum landslide; looking from north to south: outward sloping terraces farming practiced around the Methum landslide

7 occurred in 1905, 1934, and 1950. These earthquakes generated numerous landslides and weakened the region's geology. The recent Gorkha earthquake (2015) triggered more than 19,332 coseismic landslides (Gnyawali and Adhikari 2017). The Post-Disaster Needs Assessment (PDNA) report included the Methum landslide area in the severely affected category, with an average intensity of VII on the Modified Mercalli Intensity scale (World Bank Group 2015). Although the Methum landslide was first initiated many years ago, in

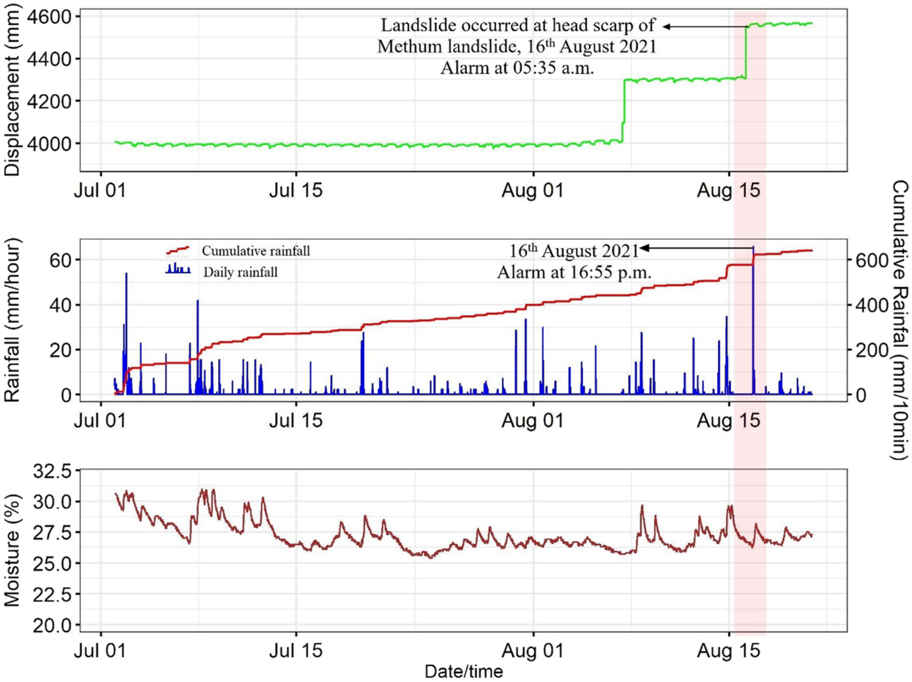


Fig. 9 Displacement, rainfall, and moisture measured by LEWS for the Methum landslide

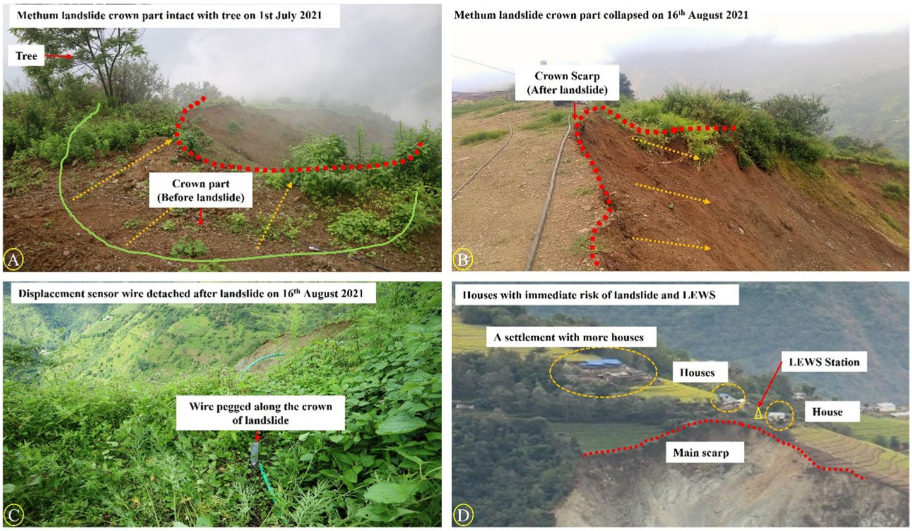


Fig. 10 Methum landslide crown failure and vulnerable households: **A** head scarp of the Methum landslide as of July 1, 2021; **B** the scarp following the collapse on August 16, 2021; **C** detached wire from the displacement sensor on August 16, 2021; **D** houses and settlement above the landslide's main scarp

recent years, it remains in an active state and is advancing at an increasingly faster rate. Several further internal and external triggering factors (McColl 2015) may have influenced the reactivation of this landslide, but owing to limited data availability, a more detailed analysis of these factors is required.

Anthropogenic factors, such as outward sloping terrace cultivation, have also contributed to the intensified erosion in the study area. An intense tillage system has been adopted to cultivate cereal crops on sloping terraces in the area. Earlier studies have indicated that poorly managed sloping terraces cause higher erosion (West et al. 2015; Chalise et al. 2019), which leads to gully formation. Moreover, the Methum landslide surrounding the cultivated land has a slope greater than 75%, although terraces with more than a 50% slope are not recommended for cultivation (Green 1978), given the high annual degradation of sloping terraces. Many researchers have already noted that improper management of agricultural practices can lead to landslide occurrence or reactivation of old landslides and damage to villages and farms (Pandit and Balla 2004; Devkota et al. 2014). Another study estimated the average erosion rate of gently sloping terraces cultivated with rain-fed irrigation at approximately 2 mm yr^{-1} (Ghimire et al. 2013). It is estimated that the mean annual soil erosion for Nepal was 8.76, 6.55 and 7.49 t ha^{-1} yr^{-1} in 1990, 2000, and 2010, respectively (Uddin et al. 2018). The physiographic regions, namely the middle mountains, High Mountains, and High Himalayas of Nepal, have mean erosion rates of 38, 32 and 28 t ha^{-1} yr^{-1}, respectively, and barren lands have the highest erosion rate of 40 t ha^{-1} yr^{-1}, which is followed by agricultural lands at 29 t ha^{-1} yr^{-1} (Koirala et al. 2019). A recent study reported mean erosion rates of 23.2 t ha^{-1} yr^{-1} and 21.4 t ha^{-1} yr^{-1} from barren land and agricultural land, respectively, at the watershed scale in the mid-hills of Nepal (Pandey and Gurung 2022). Higher slopes and intensive tillage practices in outward sloping terraces expose soil to erosion, while creating the preparatory conditions that may trigger landslides. Torrential rainfall events in such fragile landscape conditions may have contributed to the reactivation of the Methum landslide.

While it is not possible to control rainfall and seismic activities, anthropogenic factors can be managed with appropriate assistance from experts and government authorities. Specifically, sloping terraced farming systems can be replaced with agroforestry or developed as seed orchards, which require less hoeing and plowing. Although it is cost-intensive, the reduction of tillage work and the alteration of sloping terraces into level terraces are useful strategies for reducing erosion (Mupangwa et al. 2007).

4.2 Monitoring system for landslide risk reduction

The LEWS installed for the purpose of monitoring the Methum landslide can detect landslide activities using three sensors (rainfall, displacement, soil moisture), making it a robust (Michoud et al. 2013) yet simple system. These three sensors can independently produce alarms or alert messages based on the provided threshold limit. If activity occurs on dry days, the landslide displacement sensor is mainly responsible for detecting the movement and generating alert signals, while on rainy days, all three sensors can equally and independently initiate an alarm. Moreover, on rainy days, even if the wire attached to the displacement sensor is breached or the displacement sensor becomes nonfunctional, the other two sensors—the rainfall and moisture sensors—will also produce alert alarms independently should threshold exceedance occur.

This LEWS performed effectively in the event that occurred on August 16, 2021, when alarms sounded twice during the day as rainfall and displacement thresholds were exceeded. This event increased the local communities' and other stakeholders' confidence in the LEWS. The closest inhabitants, who were among the most anxious about the prospect that a landslide disaster would occur, felt safer (Dixon et al. 2018) than they had prior to the LEWS's installation. By properly operating and sharing alarms, LEWS could mitigate the risks associated with landslides. However, sensitization is necessary to reduce overdependency on LEWS, which may cause communities to develop a false sense of security for landslide disaster (Rogers and Tsirkunov 2010).

This system has only a single-level alarm that sounds immediately after the threshold limit of any of the three sensors has been exceeded. To overcome this limitation and differentiate the state of landslide occurrence (Piciullo et al. 2018), a two-level (ordinary, escape alarm) or three-level (ordinary, pre-alarm, escape alarm) LEWS may be installed (Intrieri et al. 2013), although this will inevitably make the system more complex. In the case of multi-level alarm LEWS, the parameters need to be set to produce signals for each required level. The ordinary alarm indicates a lower increment in the observed parameter with less risk, while the pre-alarm signifies a significant increase in the parameters under observation, requiring locals to be cautious about landslide movement; and finally, the escape alarm or final alarm indicates the exceedance of the highest-threshold set, signaling locals to leave the landslide-prone area cautiously and move to safer places (Guzzetti et al. 2020). The different level alarm may also require unique sound-producing devices for each level alarm and different messages with clear information about landslide movement to retain the credibility of the system as more false alarms could be generated. A further limitation is that the landslide's displacement will be measured only in a single direction, while movement in other directions remains undetected. Moreover, false alarm activation may occur due to disturbances along the pegged wires linked to the displacement sensor caused by animal or human movement, considering the proximity of the nearest settlement. Should false alarms occur, the locals may begin to lose trust in the system. Although this system utilizes double SIM cards to ensure reliable communication and data sharing, in the absence of the telemetry network, this system will not share any data in real-time or may not generate an alarm. The system is operated using multiple sensors and electronic equipment, such as batteries, wires, and solar panels; therefore, maintenance work grounded in technical expertise is necessary at certain time intervals. Thus, the adequate sensitization of local communities and the provision that the operator (a local caretaker) be trained appropriately is of the utmost importance in reducing maintenance costs.

The threshold setting for the LEWS requires careful consideration. For this system, the rainfall thresholds set in this system were close to the threshold used in Nepal by to predict debris flow in mid-hills. While the threshold for soil moisture and displacement was set based on earlier studies and the researchers' own experiences from LEWS piloted sites. Considering the area's higher susceptibility to landslide reactivation, the threshold for the displacement sensor is 50 cm. In the case of a particular slope failure event, this low threshold will provide local inhabitants with more time to escape or to take the necessary actions. During such landslide events, in addition to the siren, an alert message will be delivered to local designated persons, assigned authorities, and local elected bodies, thus increasing real-time interaction among stakeholders and response activities if deemed essential.

Following the collapse on August 16, 2021, the landslide advanced further toward the settlement and rural road. We repaired the system by re-establishing the detached sensor wire, and two additional displacement sensors were installed to record the displacement of the landslide crown in three directions from the station. This time, the threshold for displacement was set at 300 mm, as the slope of the landslide's head scarp became steeper and reached just below the rural road. This new threshold for displacement was set based on the idea that even a 30-cm displacement would generate an alarm and increase lead time. The monitoring system's findings with lowered threshold will be presented in a future publication.

4.3 Policies conducive to the sustainability of the early warning system

The early warning system is the most important phase for landslide disaster management, as with proper forecasting, the risk of disaster could be reduced. The government of Nepal has included disaster management programs in its 10th National Development Plan for the first time (GoN/NPC 2002). While Nepal is the pioneer country in South Asia for establishing a Disaster Management Act in 1982, it has considered natural disasters to be Divine Incidents and focused on response and rehabilitation activities rather than mitigation and risk reduction. This notion was amended in 2017 when the Disaster Risk Reduction and Management Act was formulated, which included the provisions of preparedness. Nepal's Ministry of Home Affairs is the Nodal entity for disaster management at the central level; however, a number of ministries are responsible for landslide management, including the Ministry of Forest and Environment, the Ministry of Industry, Commerce and Supplies, and the Ministry of Energy, Water Resources, and Irrigation. Furthermore, provincial- and local-level governments also have the authority to coordinate disaster preparedness and response activities. The National Policy for Disaster Risk Reduction 2018 envisages the establishment of a multi-hazard early warning system. The National Strategic Plan for Disaster Risk Reduction 2018–2030 elaborates on disaster risk forecasting and early warning systems for preparedness against multiple hazards, but no specific strategies are proposed for landslides. There is a brief mention in the Guideline on Landslide Treatment and Mitigation 2016, which was developed by the former Department of Soil Conservation and Watershed Management, about the establishment of an early warning system, but no mention of any pragmatic approach to LEWSs was made. Moreover, the lack of budgetary provisions, inadequately trained experts, weak coordination among different ministries, and limited publicity of the LEWS (Kafle 2017) has undermined the scope of LEWSs to minimize the landslide risk in Nepal. Based on the experience of the present landslide warning system at the Methum landslide, it can be recommended that forecasting landslides based on rainfall, soil moisture, and land displacement are possible and feasible in terms of small-scale budgets and available technical knowledge. Upscaling this type of LEWS can contribute to mitigating landslide risk and reducing fatalities and economic losses in the country. We encourage establishing LEWSs in landslide-prone areas where communities are at risk, but other structural treatments for landslides may not be possible immediately. It is recommended that a dedicated institution with legal, financial, and trained human resources is critical to design, implement, and manage LEWSs throughout the country. Thus, a conducive policy, specific legal instruments, financial support, and trained human resources are deemed necessary to establish and sustainably operate LEWSs in Nepal.

5 Conclusion

Landslide occurrences are common in the Nepalese mid-hills due to the combined effects of the intense Asian monsoon and seismic activities. Moreover, intense anthropogenic activities greatly impacted slope movement. The advancement of small gullies can create large-scale landslides under the continuous pressure of several triggering factors if not treated appropriately. The Methum landslide advanced significantly between 1971 and 2005. The landslide remained in an active state and posed a serious threat to nearby settlements after the 2015 Gorkha earthquake. Therefore, a low-cost LEWS was installed to monitor the active head scarp to reduce landslide risk. The LEWS installed on the Methum Landslide has communicated information relating to landmass movement to the area's inhabitants, demonstrating that it is a viable low-cost technology for landslide risk reduction at the community level. To operate the LEWS successfully, it is crucial to select stable sites, set the alarm threshold correctly, take precautions to minimize the occurrence of false alarms, build capacity, and sensitize locals. The application of LEWSs in Nepal is still in the pilot stage. Therefore, this study recommends that concerned authorities promote the technique with appropriate policy backing and popularize the use of the technology through regular budgetary programs to minimize landslide risk in vulnerable areas in the country. Replication of this system may require customizing the thresholds and parameters for each specific landslide condition and setting the audible range of the siren appropriately. Furthermore, we recommend that the LEWS should not be limited to forecasting but should also incorporate disaster response actions and encourage evacuations to safer places.

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Declarations

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