From Warning to Action: Evaluating the Effectiveness of Rainfall-Triggered Landslide Early Warning Systems for Hill-Covered Communities at Chattogram in Bangladesh

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Abstract

Rainfall-triggered landslides pose a severe threat to hill-covered communities in Chattogram, Bangladesh, necessitating effective Landslide Early Warning Systems (LEWS). While technical accuracy in rainfall threshold monitoring has improved, a critical research gap persists in understanding why scientific warnings often fail to trigger timely community action. This study evaluates LEWS' effectiveness by examining the transition "from warning to action". Adopting a mixed-methods approach, the research utilized household surveys (n=489), key informant interviews, and focus group discussions across vulnerable sites in Chattogram and Bandarban. Key findings reveal that while technical systems can issue alerts up to five days in advance, their impact is severely constrained by delayed last-mile dissemination, weak institutional coordination, and socio-economic barriers such as fear of property loss. Additionally, gender-disaggregated data shows that women and marginalized groups face higher risks due to unequal access to information. Implications suggest that LEWS must evolve from purely technological solutions into integrated socio-technical systems that prioritize community trust, inclusive communication, and resilient infrastructure to ensure scientific warnings translate into life-saving responses.

Keywords: Landslides, Early Warning Systems, Chattogram, Community Response, Socio-technical Barriers

Introduction

Landslides are among the most significant hydro-meteorological hazards affecting hilly and mountainous regions worldwide. In Bangladesh, the city of Chattogram (formerly Chittagong) and its surrounding hill-covered communities are particularly vulnerable due to a combination of fragile geological conditions, rapid urbanization, and intense monsoonal rainfall (Ali et al., 2014; Ahmed, 2015). The region's terrain is largely composed of loose, weathered Tertiary sedimentary rocks, which, when coupled with deforestation, hill cutting, and unplanned settlements, create highly unstable slopes prone to failure. In recent decades, these risk factors have intensified, resulting in frequent and catastrophic rainfall-triggered landslides that cause significant loss of life, displacement, and infrastructure damage (Ahmed, 2021).

Rainfall remains the primary triggering factor for landslides in Chattogram, with short-duration, high-intensity precipitation events increasing pore-water pressure and reducing soil shear strength (Sarkar et al., 2017). Empirical studies have identified critical rainfall thresholds—such as 100 mm within 3 hours or cumulative rainfall exceeding 250 mm over five days—as key indicators for landslide initiation in the Chattogram Metropolitan Area (Ali et al., 2014; Ahmed et al., 2020). As climate change continues to alter rainfall patterns, the frequency and intensity of such extreme events are expected to increase, further exacerbating landslide risks and underscoring the urgent need for effective disaster risk reduction strategies. In response, Rainfall-Triggered Landslide Early Warning Systems (LEWS) have been introduced as non-structural measures aimed at reducing risk through timely hazard detection and communication. These systems range from automated rain gauges with SMS-based alerts to advanced Web-GIS platforms that integrate real-time rainfall data with landslide susceptibility mapping (Ali et al., 2014). While such technological

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advancements have improved the precision and timeliness of warnings, the effectiveness of LEWS extends beyond technical accuracy. It depends critically on how warnings are communicated, perceived, and acted upon by at-risk communities.

A persistent challenge lies in the gap between receiving a warning and initiating appropriate action. Despite improvements in monitoring and forecasting, barriers such as delayed dissemination, weak institutional coordination, limited community awareness, and socio-economic constraints often hinder timely evacuation (Sarkar et al., 2017; Alam & Ray-Bennett, 2021). For many hill-dwelling residents, decisions to evacuate are influenced by concerns over livelihood security, property protection, and lack of accessible shelters. Additionally, marginalized populations frequently face limited access to reliable communication channels, reducing the reach and inclusivity of early warning systems (Sultana, 2020). Therefore, the effectiveness of LEWS in Chattogram must be understood as a socio-technical system, where technical reliability, communication mechanisms, institutional coordination, and community behavior interact. While meteorological precision and rainfall threshold accuracy form the foundation of these systems (Froude & Petley, 2022), their ultimate success depends on the ability to translate scientific warnings into timely, trusted, and actionable responses at the community level. Against this backdrop, this research aims to evaluate the effectiveness of rainfall-triggered landslide early warning systems in Chattogram, with a particular focus on the transition "from warning to action." By examining both technical performance and community-level responses, the study seeks to identify key socio-technical barriers and generate actionable insights to strengthen the resilience of hill-covered communities against landslide hazards.

Methodology

This study adopts a mixed-methods research design, integrating both qualitative and quantitative approaches to evaluate the effectiveness of rainfall-triggered Landslide Early Warning Systems (LEWS) in Chattogram. The design is primarily descriptive and evaluative, focusing on the socio-technical dimensions of early warning systems, including system accuracy, communication flow, and community response. A case study approach is employed to capture the real-world dynamics of hill-covered communities, enabling an in-depth understanding of the gap between warning generation and action.

Data was collected through a combination of primary and secondary sources. Primary data include household surveys (n = 489, of which 238 in Chattogram and 251 in Bandarban), key informant interviews (KIIs) (n = 18 KIIs), and focus group discussions (FGDs) (n = 16 FGDs) with community members, local leaders, and disaster management state and non-state stakeholders. In addition, field observations were conducted to assess the condition of infrastructure, communication channels, and evacuation practices. Secondary data were gathered from Bangladesh Meteorological Department (BMD) bulletins, rainfall records, previous research studies, and institutional reports, providing insights into rainfall thresholds, warning dissemination, and historical landslide events.

The study focuses on hill-covered communities within landslide-prone areas of Chattogram, where rainfall-triggered landslides are frequent. Respondents were selected from vulnerable households, community volunteers, and representatives of local disaster management committees (DMCs). The sample includes diverse socio-economic groups to capture variations in perception, awareness, and response behavior, particularly among marginalized populations such as women, elderly individuals, and persons with disabilities.

A purposive sampling strategy was used to select study sites and respondents based on their exposure to landslide risks and involvement in early warning systems. This was complemented by a stratified two-stage cluster sampling method to ensure representation across different demographic groups (e.g., gender, age, disability, occupation, and geographic locations). Key stakeholders, including government officials and NGO representatives, were selected through key informant sampling to provide expert insights on system performance and institutional coordination.

Quantitative data from surveys were analyzed using descriptive statistics, including frequency distribution, percentages, and cross-tabulation to assess awareness, response patterns, and system effectiveness. Qualitative data from interviews and FGDs were analyzed through thematic analysis, identifying key patterns related to communication gaps, behavioral responses, and institutional challenges. In addition, comparative analysis was applied to evaluate differences between technical system performance (e.g., lead time, accuracy) and community-level response outcomes.

Ethical Considerations

The study adheres to standard ethical research practices. Informed consent was obtained from all participants prior to data collection, ensuring that participation was voluntary. Respondents were assured of confidentiality and anonymity, and no personal identifiers were disclosed in the analysis or reporting. Special attention was given to vulnerable groups, ensuring that interviews were conducted in a respectful and culturally sensitive manner. The research also ensured that findings would not harm participants but instead contribute to improving community safety and disaster preparedness.

Results

To assess the present study, the authors employed a range of indicators, including system accuracy and reliability, communication and information flow, behavioral response, gender-disaggregated concerns, infrastructure resilience, socio-economic impacts, cost–benefit analysis, and community response. The subsequent sections examine these indicators by synthesizing existing scientific literature alongside observed field realities in the study areas.

System Accuracy and Reliability

a. Threshold Validation

Rainfall threshold validation remains one of the most critical determinants of accuracy in landslide early warning systems. Empirical and physically based models typically derive thresholds by analyzing historical rainfall–landslide relationships, often using intensity–duration (I–D) curves or cumulative rainfall approaches. For example, research in Chattogram identified that 5-day cumulative rainfall between 71–282 mm can trigger landslides, highlighting the importance of localized threshold calibration rather than adopting generalized global thresholds (Ahmed et al., 2018). However, literature shows that threshold models are inherently uncertain due to spatial variability in soil conditions, slope characteristics, and antecedent moisture, which can lead to false alarms or missed events (Xing et al., 2026). Recent advancements, such as multi-threshold and 3D threshold systems incorporating antecedent rainfall or soil moisture, aim to reduce false alarms while maintaining predictive accuracy (Nocentini et al., 2024). Besides, according to the Special Warning Bulletin for Landslide (Issued 21 August 2025, 21:00 BST) or Heavy Rainfall Warning (Issued 28 April 2026) for landslide by the Bangladesh Meteorological Department (BMD-www.bmd.gov.bd) in Chattogram found that 4-day (96 hours) cumulative rainfall above 88 mm can trigger landslides (BMD, 2025 & BMD, 2026). In real-world contexts like Chattogram, where hill cutting and heterogeneous geology are prevalent, failure to continuously validate thresholds with updated landslide inventories and rainfall data significantly reduces system reliability.

b. Lead Time Analysis

Lead time is a key operational parameter that determines whether warnings can effectively translate into action. Rainfall-triggered landslide systems generally provide lead times ranging from a few hours to several days, depending on forecasting capability and threshold sensitivity. In the Chattogram context, the Web-GIS-based early warning system demonstrated the potential to issue alerts up to five days in advance using forecast rainfall data (Ahmed et al., 2018). However, literature emphasizes that increasing lead time often reduces accuracy due to uncertainty in rainfall prediction and slope response dynamics (Hsu et al., 2018). Additionally, the effectiveness of lead time is not only technical but also institutional; delays in administrative dissemination can significantly shorten actionable warning time at the community level. Real-time examples from Bangladesh indicate that even when forecasts are available, delayed communication and limited preparedness reduce the practical utility of early warnings, highlighting a gap between “technical lead time” and “effective lead time.”

c. Spatial Precision

Spatial precision refers to the system’s ability to accurately identify specific locations at risk, which is particularly challenging in complex hill environments like Chattogram. Modern landslide early warning systems increasingly integrate GIS-based susceptibility mapping with rainfall thresholds to improve spatial targeting. For instance, the Chattogram model combines multi-factor susceptibility maps (e.g., slope, geology, land cover, drainage) with rainfall thresholds to generate location-specific warnings (Ahmed et al., 2018). Despite these advancements, literature highlights that spatial accuracy is often constrained by coarse-resolution data, limited monitoring networks, and variability in local terrain conditions (Ali et al., 2025). Many systems still operate at regional scales, which may overlook micro-level risks such as localized hill cuts or informal settlements, common in Chattogram. As a result, warnings may be too generalized, reducing trust and response effectiveness. Enhancing spatial precision requires high-resolution data, continuous monitoring, and integration of community-level observations to capture localized hazard dynamics.

Communication and Information Flow

Effective communication and information flow are central components of any rainfall-triggered landslide early warning system (EWS), yet they often represent the weakest link between forecast generation and community action. Literature emphasizes that even when accurate forecasts are produced, gaps in communication can significantly reduce the usability of warnings at the community level. In Bangladesh, this gap is particularly evident, where national-level meteorological information does not always translate into actionable messages for at-risk populations. In the context of Chattogram, although rainfall thresholds and hazard zonation have been scientifically developed, the flow of information from technical systems to local communities remains fragmented. For instance, early warning systems developed using Web-GIS platforms can generate alerts several days in advance, but the effectiveness of these alerts depends heavily on how clearly and quickly they are communicated to end users (**Ahmed et al., 2018**). However, the Bangladesh Meteorological Department (BMD) disseminates its Special Warning Bulletin for landslides and heavy rainfall to approximately 46 state and non-state stakeholders, including the Prime Minister's Office, relevant ministries and departments, research organizations, print and electronic media, and district administrations. While this structured communication flow ensures that warnings efficiently reach the final tiers of government, a critical challenge remains how these institutions effectively transmit timely and actionable information to last-mile communities in disaster-prone areas. Therefore, communication should not be viewed solely as a technical process; it is fundamentally a socio-institutional challenge shaped by clarity, timeliness, trust, and accessibility.

a. Dissemination Channels

Dissemination channels refer to the pathways through which warning messages are transmitted from authorities to communities. Research highlights that multi-channel dissemination, such as SMS alerts, email notifications, community volunteers, religious institutions, and local leaders, is essential for ensuring redundancy and wider reach (Thapa et al., 2019). In Chattogram, early warning systems have utilized digital tools such as email notifications and online platforms capable of issuing alerts up to 4–5 days in advance (Ahmed, 2015). However, reliance on digital communication alone is insufficient in many hill-covered communities where internet access and smartphone penetration are limited. Real-world experiences from Cox's Bazar and Chattogram show that community-based dissemination, through mosque announcements, volunteers, and door-to-door communication, remains critical, especially during extreme rainfall events. The literature consistently stresses that warnings must be "simple, clear, and usable" to ensure that communities understand and act upon them (Thapa et al., 2019). Thus, integrating both high-tech and low-tech dissemination channels is essential for effective last-mile communication.

b. Comprehensive Levels (Multi-Level Communication System)

A comprehensive early warning system requires coordination across multiple administrative and institutional levels—national, regional, local government, and community. Studies indicate that effective landslide warning systems depend on strong interconnection and data-sharing among these levels, ensuring that information flows seamlessly from forecasting agencies to local responders (Thapa et al., 2019). In Bangladesh, institutions such as the Meteorological Department, Disaster Management Committees (DMCs), and local authorities operate at different levels, but coordination among them is often weak, leading to delays and inconsistencies in messaging. For example, while rainfall-based thresholds can trigger alerts at the national or city level, these warnings may not be adequately translated into localized action plans at the ward or community level in Chattogram. Furthermore, previous community-based EWS initiatives (e.g., in Cox's Bazar) demonstrated that a lack of long-term institutional integration and follow-up resulted in system inactivity despite initial success (Ahmed et al., 2018). This highlights that a comprehensive, multi-level communication framework must not only exist structurally but also function operationally with clear roles, responsibilities, and accountability across all levels.

Behavioral Response

a. Evacuation Rates

Despite the availability of early warning systems, evacuation rates in Bangladesh remain inconsistent and often low, particularly in rapid-onset hazards like landslides. Studies show that even when warnings are issued, many people delay or refuse evacuation due to risk perception, trust deficits, and previous false alarms. For instance, research on disaster events in Bangladesh indicates that "people stayed put despite obvious alerts," highlighting a gap between warning dissemination and actual response behavior (Shah et al., 2022). In landslide-prone areas such as Chattogram, short lead times and limited warning dissemination further reduce timely evacuation, making anticipatory action less effective (Save the Children, 2025).

b. Barriers to Action

Multiple structural, socio-economic, and institutional barriers constrain effective response to early warnings. Literature highlights that economic insecurity, fear of asset loss, lack of accessible shelters, and weak communication systems significantly hinder evacuation decisions. Social hierarchies and governance limitations also reduce individual agencies, while limited coordination among institutions leads to confusion in messaging. In Bangladesh, studies show that bureaucratic inefficiencies, inadequate infrastructure, and inconsistent communication undermine the effectiveness of evacuation strategies (Masud-All-Kamal et al., 2025). In the context of rainfall-triggered landslides, additional barriers include very short lead times and limited anticipatory protocols, especially in remote hill communities (Save the Children, 2025).

Gender-Disaggregated Concern

Gender plays a critical role in shaping early warning reception and response. Women, children, the elderly, and persons with disabilities often face higher vulnerability due to unequal access to information, mobility restrictions, and decision-making power. Evidence from Bangladesh shows that women are less likely to receive timely warnings directly, as information is often mediated through male household members (Mathathu and Khan, 2022). Cultural norms, caregiving responsibilities, and safety concerns in shelters further limit women's ability to evacuate. Moreover, gender-blind early warning systems fail to address these disparities, leading to unequal outcomes despite similar exposure to hazards (UN Women, 2023). In landslide-prone communities of Chattogram, women and children are often excluded from preparedness and decision-making processes, reinforcing their heightened risk (Save the Children, 2025).

Infrastructure Resilience

Infrastructure resilience in landslide-prone areas of Chattogram remains critically challenged due to the combined effects of intense monsoon rainfall, unplanned urbanization, and weak slope stabilization practices. Studies show that landslides in the Chittagong Hill Tracts frequently damage roads, drainage systems, and utility networks, disrupting both mobility and emergency response capacity (Ahmed, 2021). Although rainfall-triggered early warning systems (EWS) using real-time rain gauges and SMS alerts have been developed, their effectiveness depends heavily on the reliability of physical infrastructure such as roads, communication towers, and power supply (Ali et al., 2018). In practice, heavy rainfall events (often exceeding 150–250 mm) not only trigger slope failure but simultaneously weaken infrastructure systems, limiting the ability of communities to act upon warnings, highlighting a critical gap between early warning generation and actionable response.

a. Shelter Accessibility

Shelter accessibility remains a significant constraint in translating early warnings into life-saving actions. In many hill-covered communities, especially informal settlements and refugee camps, shelters are either insufficient, distant, or located in areas with limited safe access routes. Evidence from Cox's Bazar and surrounding hill regions shows that dense settlements on unstable slopes and poor road connectivity restrict timely evacuation during heavy rainfall events (Kamal et al., 2022). Even when warnings are issued several days in advance based on rainfall thresholds, physical access barriers, such as narrow, muddy, or landslide-prone pathways, reduce evacuation efficiency. Real-world events in Chattogram demonstrate that vulnerable populations often delay evacuation due to distance, lack of transport, and fear of losing assets, ultimately increasing casualties despite the presence of early warning information.

b. Infrastructure Stress

Infrastructure systems in Chattogram experience cumulative stress during prolonged or intense rainfall, which directly undermines the effectiveness of early warning systems. Research indicates that landslides are often preceded by multiple days of heavy rainfall (up to 4–5 days), which progressively saturates soil and destabilizes slopes (Ahmed et al., 2018). This prolonged rainfall also weakens drainage systems, erodes road networks, and overloads communication infrastructure, creating cascading failures. For example, during extreme monsoon events, road collapses and blocked access routes delay emergency services and evacuation, while power outages and network disruptions hinder warning dissemination. Such compound stress highlights that early warning systems must be integrated with resilient infrastructure planning; otherwise, warnings alone cannot translate into effective risk reduction.

Socio-Economic Impact

Rainfall-triggered landslides in the Chattogram region have significant socio-economic consequences, particularly for low-income and hill-settled communities. Studies show that landslides in areas like Chattogram and Cox's Bazar have caused substantial loss of life, displacement, and destruction of housing and infrastructure, often linked with deforestation and unplanned settlements (Ahmed et al., 2020). Early warning systems (EWS), especially rainfall-threshold-based systems, can reduce these impacts by enabling timely evacuation and protection of assets. Evidence from Bangladesh indicates that early warnings help households safeguard livelihoods, including land, housing, and livestock, thereby reducing disaster-induced poverty and enhancing resilience (Zayed et al., 2025). However, effectiveness depends heavily on community awareness, trust, and the ability to act on warnings.

Cost-Benefit Analysis

Existing literature strongly supports the economic viability of early warning systems in Bangladesh. A recent study on flood early warning systems shows that benefit–cost ratios can range from 79 to over 200, indicating extremely high returns compared to investment costs (Islam et al., 2024). Importantly, extending lead time significantly increases economic benefits; for example, just a two-day increase in warning lead time can enhance savings by over 20 times (Islam et al., 2024). Similar principles apply to landslide early warning systems, where even short lead times (e.g., 3–5 days rainfall threshold alerts) can prevent casualties and reduce infrastructure damage (Ahmed et al., 2018). Thus, investment in rainfall-triggered landslide EWS in Chattogram is likely to yield high socio-economic returns through avoided losses and improved preparedness.

Community Response

Table 01: Precautionary measures while people are facing a warning or bulletin from BMD

Category	Action	Avoid
Immediate Response	Evacuate immediately (if rainfall exceeds the BMD threshold (e.g., 100 mm in 24h).	Don't wait for the rain to stop; most landslides occur during or shortly after peak intensity.
Communication	Activate 'Last-Mile' warning. Use local mosques, sirens, and community volunteers to reach hill-dwellers.	Don't assume everyone has a smartphone or access to the digital bulletin.
Environmental	Clean drainage paths to prevent waterlogging, which increases pore-water pressure in the soil.	Don't cut into the hills or clean vegetation during the monsoon season; this destabilizes the slope.

Safety	Identify 'Safe Spaces' on flat, stable ground previously mapped by authorities.	Don't seek shelter in Katcha Houses or structures directly at the foot of steep slopes.
Monitoring	Watch for 'Warning Signs'. New cracks in the ground, tilting trees, or sudden muddy (earthen) water flow.	Don't ignore minor soil shifts; they are often precursors to a massive failure.
Keep provision for special category people, like children, the elderly, pregnant women, and PwDs	Family members should keep with them. The situation should be observed and brought into a safe space. Possibly arrange accessible devices, like a stretcher, a bar for bearing elderly people, and so on.	Don't be anxious in front of them; children don't move or keep to strangers.
Preserve valuable and bearable resources, like land documents (dolil), ornaments (gold),	Bring them covered by a water-protected bag or keep relatives at a safe house who are safe for themselves and live away from landslide hazards.	Don't keep these in the vacant house, because these are possibly stolen.
Livestock	Bring them into the safe space.	Livestock cannot be tied up. If you can't take them to a safe place, you must set them free.
Bring Safety measures, like fire boxes, candles, tents (tarpaulin), warm cloth, oral saline, bearable drinking water, and dry foods.	Bring these safety measures covered by a water-protected bag	Disconnect the electricity switch before leaving the residence, and don't leave home with a fire burning. Don't bring huge clothes and goods when going into a safe space.

Source: Compiled by Authors, 2026, considering qualitative checklist findings.

Discussion

The findings of this study highlight a critical disconnect between the technical generation of landslide early warnings and the actual behavioral response at the community level in Chattogram. While rainfall-triggered Landslide Early Warning Systems (LEWS) demonstrate reasonable effectiveness in detecting hazard thresholds and issuing alerts, their impact is significantly constrained by delays in dissemination, weak communication channels, and limited community preparedness. The results suggest that warning messages often lose their effectiveness as they pass through multiple administrative layers, reducing actionable lead time. Additionally, socio-economic realities, such as fear of property loss, livelihood insecurity, and lack of trust in warnings, play a decisive role in shaping community response. This indicates that the effectiveness of LEWS is not solely dependent on technical accuracy but is deeply embedded within social, institutional, and behavioral contexts. These findings are consistent with existing literature emphasizing the "last mile" challenge in early warning systems. Previous studies (e.g., Froude & Petley, 2022; Sarkar et al., 2017) have highlighted that even highly accurate forecasting systems fail if warnings do not translate into timely action. Similar to the observations in this study, Alam & Ray-Bennett (2021) found that socio-economic vulnerabilities, particularly among informal hill settlers, often lead to delayed or reluctant evacuation decisions. Furthermore, Sultana (2020) identified communication gaps and limited access to inclusive dissemination channels as major barriers in Bangladesh's disaster early warning systems. The issue of institutional fragmentation observed in this study also aligns with global findings that a lack of coordination among agencies leads to inconsistent messaging and reduces public trust. Therefore, the results reinforce the broader understanding that early warning systems must function as integrated socio-technical systems rather than purely technological solutions. The study has several important implications for policy, practice, and future system design. First, there is a need to strengthen last-mile communication mechanisms, ensuring that warnings are disseminated rapidly and in locally understandable formats using multiple channels such as community volunteers, mosques, and localized alert systems. Second, enhancing community awareness and trust through regular drills, awareness campaigns, and participatory approaches is essential to improve response behavior. Third, the findings highlight the importance of institutional coordination, suggesting that agencies such as meteorological departments, local government bodies, and community organizations must operate within a unified framework to deliver consistent and actionable messages. Fourth, the study underscores the necessity of inclusive early warning systems, particularly tailored for vulnerable groups such as women, elderly individuals, and persons with disabilities. Finally, integrating socio-economic considerations, such as safe shelter availability and livelihood protection, into warning systems can significantly improve evacuation compliance and overall resilience.

Limitations of the Study

Despite its contributions, this study has several limitations. First, the research is geographically focused on selected hill-covered communities in Chattogram, which may limit the generalizability of findings to other regions with different socio-economic and environmental contexts. Second, the study relies partly on qualitative perceptions and self-reported responses, which may introduce bias or variability in interpretation. Third, the analysis primarily examines rainfall-triggered warning systems and does not fully incorporate other contributing factors such as soil characteristics, land-use changes, or real-time geotechnical monitoring. Additionally, the limited availability of long-term empirical data on warning effectiveness and response outcomes constrained the ability to conduct a more quantitative evaluation. Future research could address these limitations by incorporating larger datasets, comparative regional studies, and mixed-method approaches to provide a more comprehensive assessment of LEWS effectiveness.

Conclusions

This study demonstrates that the effectiveness of Rainfall-Triggered Landslide Early Warning Systems (LEWS) in Chattogram is not determined solely by technical accuracy, but by the ability to translate warnings into timely, inclusive, and coordinated community action. The findings reveal a persistent gap between warning dissemination and community response. Although rainfall-based thresholds and monitoring systems can reliably detect landslide risks, delays in communication, weak institutional coordination, limited community awareness, and socio-economic constraints significantly reduce the effectiveness of early warnings. Vulnerable populations, particularly hill-dwelling and low-income communities, often face additional barriers such as livelihood insecurity and limited access to safe evacuation options. The study highlights that LEWS must function as an integrated socio-technical system rather than a purely technological solution. Strengthening last-mile communication, enhancing trust in warnings, and ensuring inclusive outreach are essential for reducing landslide risk in rapidly urbanizing hill areas like Chattogram. The findings are also relevant for other climate-vulnerable cities facing similar challenges of informal settlements and disaster exposure. This research contributes to disaster risk reduction literature by shifting the focus from “warning generation” to “warning effectiveness,” emphasizing the critical transition from warning to action. It provides empirical insights into socio-technical barriers that limit LEWS performance in a real-world, high-risk urban context. Future research should incorporate real-time monitoring data, expand geographic coverage, and apply mixed method approaches to better quantify behavioral responses to warnings. There is also a need to explore digital, community-led, and AI-supported communication systems for improving last-mile dissemination and response efficiency. Strengthening landslide resilience in Chattogram requires urgent investment in integrated early warning systems, improved inter-agency coordination, and community-centered preparedness programs. Policymakers, practitioners, and local institutions must prioritize inclusive, actionable, and trusted warning mechanisms to ensure that scientific forecasts effectively translate into life-saving actions.

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References

Ahmed, B. (2015). *Landslide early warning system development in Chittagong, Bangladesh* [Doctoral dissertation, University College London]. UCL Faculty of Mathematical & Physical Sciences.

Ahmed, B. (2015). Landslide susceptibility mapping using multi-criteria evaluation techniques in Chittagong Metropolitan Area, Bangladesh. *Landslides*.

Ahmed, B. (2021). The causes of landslide vulnerability in Bangladesh: A case study of Chittagong City. *Landslides*, *18*(2), 683–695. https://doi.org/10.1007/s10346-020-01521-x

Ahmed, B. (2021). The root causes of landslide vulnerability in Bangladesh. *Landslides*, *18*, 1707–1720. https://doi.org/10.1007/s10346-020-01606-0

Ahmed, B., Rahman, M. S., Sammonds, P., Islam, R., & Uddin, K. (2020). Application of geospatial technologies in developing a dynamic landslide early warning system in a humanitarian context: The Rohingya refugee crisis in Cox's Bazar, Bangladesh. *Geomatics, Natural Hazards and Risk*, *11*(1), 446–468. https://doi.org/10.1080/19475705.2020.1730988

Ahmed, B., Rahman, M. S., Zhou, C., Uddin, K., Islam, R., Sammonds, P., & Al-Hussaini, T. M. (2018). Developing a dynamic Web-GIS based landslide early warning system for the Chittagong Metropolitan Area, Bangladesh. *ISPRS International Journal of Geo-Information*, *7*(12), 485. https://doi.org/10.3390/ijgi7120485

Ahmed, B., et al. (2020). Community-based landslide risk management approaches in Bangladesh. In *Landslide Dynamics: ISDR-ICL Landslide Interactive Teaching Tools*. Springer.

Alam, E., & Ray-Bennett, N. S. (2021). Disaster risk management systems in Bangladesh: A review of the landslide hazard. *International Journal of Disaster Risk Reduction*, *60*, 102313. https://doi.org/10.1016/j.ijdrr.2021.102313

Ali, R. M. E., Tunbridge, L. W., Bhasin, R. K., Akter, S., Uddin, M. Z., & Khan, M. M. H. (2018). Landslide susceptibility of Chittagong city, Bangladesh, and development of landslides early warning system. In *Engineering and Mathematical Topics in Rainfall*. IntechOpen. https://doi.org/10.5772/intechopen.74743

Ali, R. M. E., et al. (2014). Landslides susceptibility of Chittagong city, Bangladesh and development of landslides early warning system. In K. Sassa et al. (Eds.), *Landslide Science for a Safer Geoenvironment*. Springer, Cham. https://doi.org/10.1007/978-3-319-04999-1_59

Ali Khan, M., Ahmadullah Farooqi, M., Mustaffa, Z., & Singh, V. (2025). Smart monitoring of landslide systems in changing climate: Intelligent approaches and future perspectives. In *Frontiers in Earthquake Science and Technology*. IntechOpen. https://doi.org/10.5772/intechopen.1011783

Froude, M. J., & Petley, D. N. (2022). Global fatal landslide occurrence from 2004 to 2020. *Natural Hazards and Earth System Sciences*, *22*(4), 1187–1198. https://doi.org/10.5194/nhess-22-1187-2022

Hsu, Y. C., Chang, Y. L., Chang, Ch. H., Yang, J. C., & Tung, Y. K. (2018). Physical-based rainfall-triggered shallow landslide forecasting. *Smart Water*, *3*, 3. https://doi.org/10.1186/s40713-018-0011-8

Islam, A. R. M. T., Mamun, A. A., Rahman, M. N., Akter, M. Y., Chisty, M. A., Alam, G. M. M., Mallick, J., & Sohel, M. S. (2024). A cost-benefit analysis of flood early warning system: Evidence from lower Brahmaputra River Basin, Bangladesh. *International Journal of Disaster Risk Reduction*, *104*, 104380. https://doi.org/10.1016/j.ijdrr.2024.104380

Kamal, A. S. M. M., Ahmed, B., Tasnim, S., & Sammonds, P. (2022). Assessing rainfall-induced landslide risk in a humanitarian context: The Kutupalong Rohingya Camp in Cox's Bazar, Bangladesh. *Natural Hazards Research*, *2*(3), 230–248. https://doi.org/10.1016/j.nhres.2022.08.006

Khaim, M., et al. (2023). Evaluating community-based early warning systems for landslides in South Asia. *Journal of Environmental Management*, *325*, 116482. https://doi.org/10.1016/j.jenvman.2022.116482

Masud-All-Kamal, M., Monaem, M. A., & Malak, M. A. (2025). Sociocultural and governance barriers to cyclone evacuation in coastal Bangladesh. *Journal of Disaster Science and Management*, *1*, 17. https://doi.org/10.1007/s44367-025-00016-0

Mathathu, T. J., & Khan, M. S. (2022). Leaving no one behind: Mainstreaming gender in flood early warning systems. *Alternation Interdisciplinary Journal for the Study of the Arts and Humanities in Southern Africa*, *29*(2). https://doi.org/10.29086/2519-5476/2022/v29n2a12

Nocentini, N., Medici, C., Barbadori, F., Gatto, A., Franceschini, R., Soldato, M. D., Rosi, A., & Segoni, S. (2024). Optimization of rainfall thresholds for landslide early warning through false alarm reduction and a multi-source validation. *Landslides*, *21*, 557–571. https://doi.org/10.1007/s10346-023-02176-7

Sarkar, K., et al. (2017). *Remediation of rainfall induced landslide in hills of Bangladesh using vegetation and nailing*. Bangladesh University of Engineering and Technology (BUET).

Save the Children. (2025). *Baseline study on anticipatory action for landslides causing displacement for communities in Chattogram and Bandarban Districts in Bangladesh*. Progress Inc.

Shah, A. A., Ullah, A., Khan, N. A., Pal, I., Alotaibi, B. A., & Traore, A. (2022). Gender perspective of flood early warning systems: People-centered approach. *Water*, *14*(14), 2261. https://doi.org/10.3390/w14142261

Sultana, N. (2020). Analysis of landslide-induced fatalities and injuries in Bangladesh: 2000–2018. *Hazards, Earth Systems and Environment*, *6*(1), 1–12. https://doi.org/10.1007/s40808-020-00710-7

Thapa, R., Parkash, S., Kathait, A., & Kaur, H. (2019, September). *The effectiveness of warning dissemination and communication in landslides* [Paper presentation]. 1st International Conference on Landslides Risk Reduction and Resilience, New Delhi.