Adoption of Four Pillars of Landslide Early Warning System in Bhimeshwor Municipality, Dolakha

1. Introduction

The United Nations Office for Disaster Risk Reduction (UNDRR) defines an Early Warning System (EWS) as the collective capabilities required to produce and distribute timely and relevant warning information[1]. This information empowers individuals, communities, and organizations facing hazards to undertake necessary preparedness actions and respond effectively in advance, thereby mitigating potential harms and losses. Hazard, as per the UNDRR, is defined as a dangerous phenomenon, substances, human activities, or conditions that may case loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption or environmental damage. The essential components of an EWS encompass (a) risk knowledge, (b) monitoring and warning services of hazard (c) communication and dissemination of alerts and warnings and (d) response capacity development.

Data compiled by the Ministry of Home Affairs (MoHA)[2] and Desinventar for the past 50 year suggest that there is an average of 112 deaths per year. The incidence of events is on the rise, primarily driven by the impacts of climate change. According to the Sixth Assessment Report (AR6) by the Inter-Governmental Panel on Climate Change (IPCC), future projections indicate a likelihood of more intense rainstorms, potentially resulting in increased landslides within Nepal's fragile mountainous terrain. Consequently, it becomes imperative to devise and execute various initiatives and measures aimed at safeguarding the lives and properties of the country's vulnerable population. Among these measures, the development and implementation of a Landslide Early Warning System (LEWS) have been recognized as one of the most effective strategies for minimizing loss of life and property.

The Landslide Early Warning System (LEWS) remains relatively new in Nepal and potentially globally, largely due to the complexity and uncertainty nature of its two primary components: (a) landslide hazard assessment and (b) monitoring and warning services for landslides. The first component primarily involves evaluating numerous factors contributing to landslides, including slope, soil, land use land cover, geology, rainfall patterns, and historical landslide data. These landscape characteristics exhibit spatial and temporal variability, compounded by the limited availability of historical landslide records, rendering landslide hazard assessment challenging[3]. The second component pertains to monitoring and warning services, which focus on understanding soil-water interactions during rainfall events—a highly complex process in estimation and prediction[4].

Considering these scenarios, there is a growing interest among decision-makers in the scientific and technical communities towards the design, implementation, and operationalization of Landslide Early Warning Systems (LEWS). Advancements in tools, techniques, and mathematical models have facilitated significant progress in understanding and predicting landslides, considered a crucial initial step in LEWS development. While cost-effective LEWSs are operational in various parts of the world such as the United States of America, Taiwan, Canada, Hong Kong, New Zealand, and Italy, many are still in the research phase. However, in Nepal, where a large portion of the country is susceptible to slope failures, there has been relatively little focus on research and development in this area. In response to this gap, the Institute of Himalayan Risk Reduction (IHRR), supported by USAID's Tayar Nepal program, has undertaken the design and implementation of a cost-effective LEWS in the Wosimpa research catchment area, located in Ward No. 1 of Bhimeshwor Municipality, Dolakha District.

2. The Research Catchment

Situated approximately 135 km east of Kathmandu, the research catchment lies within the Bhimeshwor Municipality of Dolakha District (**Figure 1**). This municipality is segmented into 9 wards, with the ward being the smallest administrative division in Nepal. Covering an approximate area of 7 km^2, the research catchment lies in the Ward Number 1 of the Bhimeshwor municipality.

The landslide inventory for the research catchment was compiled through a combination of field observations, community consultations, and analysis of time series remote sensing data. This inventory reveals a total of 170 landslides within the municipality, with the majority being shallow-type occurrences. Additionally, there are deep-seated landslides, debris flows, and slope failures induced by road construction activities.

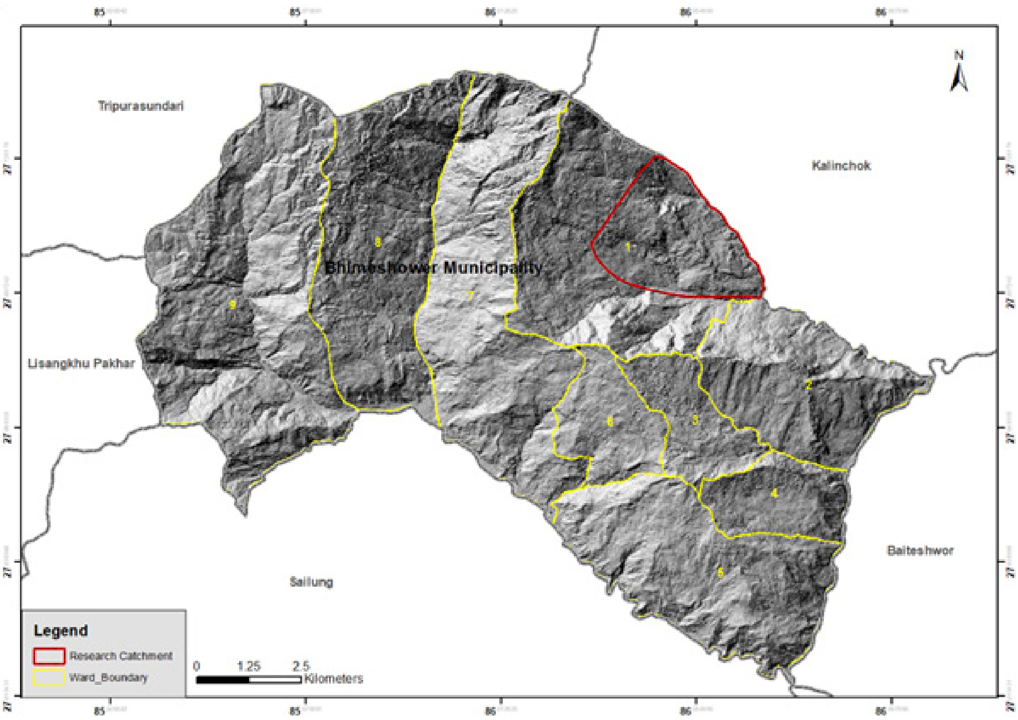

Figure 1: Location Map of the Research Catchment

An Unmanned Aerial Vehicle (UAV), commonly known as a drone, was employed to survey the catchment area and generate high-resolution data. This survey facilitated the creation of a detailed Digital Terrain Model (DTM) and Orthophoto with a resolution of 40 cm. The resulting data revealed that the elevation within the research catchment ranges from approximately 770 meters to 1654 meters above mean sea level (masl). Additionally, the Orthophoto was utilized to identify additional landslides and validate previously mapped slope failures.

From a geological perspective, the area is shaped by the influence of the Main Central Thrust (MCT) Zone, characterized by exposed rock masses of Schist and Gneiss in the upper regions, and Phyllites and Schistose-Phyllites with intercalated Quartzite layers in the lower areas. Additionally, the terrain is marked by varying degrees of weathering in the Phyllitic and Schistose-Phyllitic bedrock. The influence of the MCT has resulted in extensive fracturing, crossing, and shearing of the rock mass in the area. Moreover, factors such as groundwater and climatic conditions significantly impact terrain stability.

Field measurements indicate the presence of three primary soil types: Silty Loam, Loam, and Clay-Loam, with a notable presence of coarse fractions. Soil depth varies from a few centimeters to over 2.5 meters across the area. Similar to other regions of the country, fine-resolution rainfall data is unavailable within the municipality.

The research catchment is equipped with a set of automated monitoring instrument, including (1) rain gauges, (2) soil moisture sensors, and (3) extensometers. Tipping bucket rain gauges have been strategically placed—one at Wosimpa (research catchment) in Ward No. 1 and another at Sherpa Basti in Ward No. 7 of the municipality—to accurately measure rainfall. Additionally, two sets of soil moisture sensors have been installed, with each set consisting of three sensors positioned at depths of 0.30 m, 0.80 m, and 1.30 m below the earth's surface. This setup allows for the observation of soil moisture dynamics at various depths during precipitation events, aiding in the understanding of soil-water interactions and landslide behavior.

Furthermore, a set of extensometers has been deployed in Wosimpa to monitor ground movement, with a total length of 55 meters. These instruments play a crucial role in detecting any changes in ground stability within the catchment area.

Figure 2: Installed Automated Rain Gauges at Wosimpa and Sherpa Basti

Ministry of Home Affairs (MoHA) data portal (i. e. Bipad Portal)[5] show that there were 12 landslide events between 2002 and 2022 affecting the municipality. The data however is heavily underreported.

3. LEWS Components

3.1 Landslide Risk Knowledge

Landslide Susceptibility Model

Landslide susceptibility mapping serves as the initial phase in understanding landslide risk. Within the research catchment, the Landslide Susceptibility Map (LSM) was developed using Geographic Information System (GIS) tools. High-resolution Digital Terrain Model (DTM) data obtained from UAV surveys, featuring a spatial resolution of 40 cm, were utilized to extract various topographical attributes like slope, aspect, and curvature. These attributes were then integrated into GIS to formulate the LSM.

Digital datasets encompassing DTM, land cover, soil type, and geology were employed to derive additional factor maps, including distance to drainage, land use, Normalized Difference Vegetation Index (NDVI), terrain wetness index, among others. The Frequency Ratio (FR) technique, a widely used bivariate statistical method for assessing landslide susceptibility, was employed in LSM preparation. This method correlates past landslide occurrences with various contributing factors, thereby estimating the likelihood of future landslides.

The resulting LSM, depicted in **Figure 3**, reveals that approximately 28% of the research catchment exhibits a high susceptibility to slope failure, with 34% and 26% respectively displaying moderate to low susceptibility. Evaluation of the model indicates a predictive accuracy of about 82% for observed landslides, with an overall success rate of 86%.

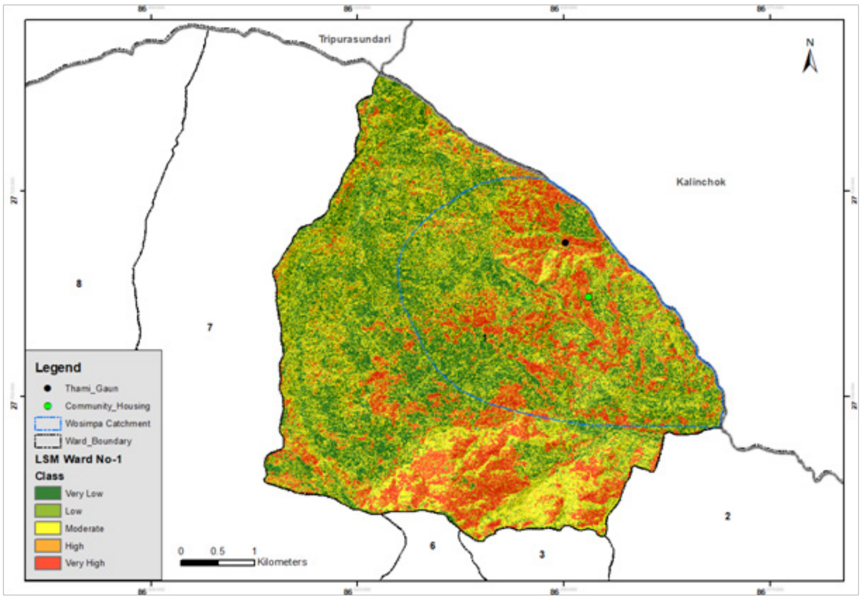

Figure 3: Landslide Susceptibility Map of Ward No 1 indicating the research catchment, Wosimpa area in blue polygon

Physically-based Landslide Hazard Modelling using Factor of Safety

The catchment-scale Factor of Safety (FoS) map was developed utilizing the physically-based Infinite Slope Stability Model (ISSM), which calculates the factor of safety of the slope. The FoS represents the ratio of the soil's shear strength to the developed stress. Employing the FoS aids in assessing the stability conditions of a slope amidst varying wetting fronts during real-time rainfall events or forecasted rainfall from DHM (Department of Hydrology and Meteorology).

By understanding the geotechnical properties (such as soil cohesion, angle of internal friction, soil texture, soil depth, etc.), land cover data (root cohesion), DTM data (slope, upslope contributing area, etc.), and rainfall characteristics, the FoS of a landscape can be estimated. Landscapes with an FoS below a specified threshold (1.50 in this instance) are generally considered potentially unstable slopes that may be susceptible to failure (**Figure 4)**.

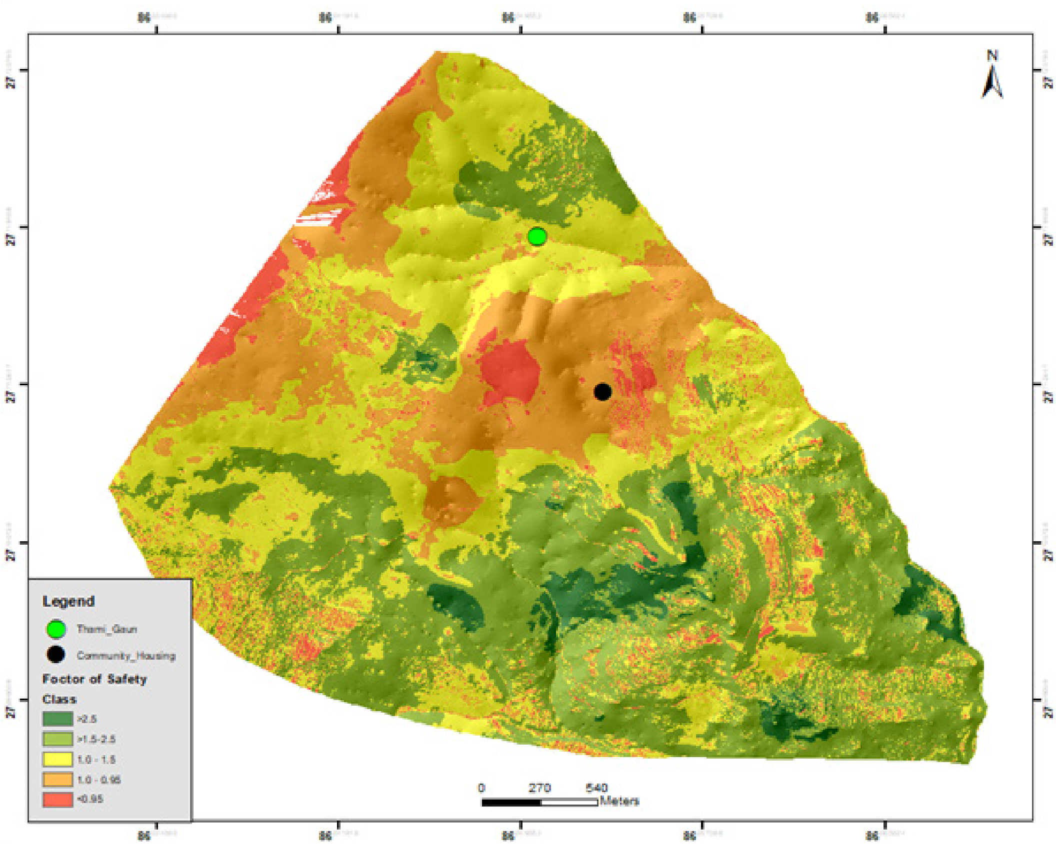

Figure 4: Landslide Hazard Modelling by using Factor of Safety Assessment

The FoS model has yielded results that are reasonably representative and have effectively identified the majority of observed landslides. According to the FoS model, approximately 27% of the catchment area exhibits an FoS below 1, with 32% falling within the range of 1 to 1.5, and the remaining 39% displaying an FoS greater than 1.5. It's worth noting that an FoS greater than 1.5 signifies slope stability, while an FoS between 1 and 1.5 indicates moderate stability, and an FoS below 1 suggests susceptibility to failure during rainfall.

These two maps are anticipated to enhance the understanding of landslide risk assessment among local communities and municipal authorities. They offer valuable insights into households, land cover, and infrastructure situated within landslide-prone areas. Additionally, various training programs and capacity-building activities have been conducted at both the municipal and community levels to bolster awareness and understanding of landslide risks.

3.2 Monitoring and Warning Services of Landslide Hazard

Monitoring near real-time or potential rainfall events is a crucial aspect of the Landslide Early Warning System (LEWS). Near Real-time monitoring is conducted using rain gauges, soil moisture sensors, and extensometers installed within the research catchment. Data collected from these stations and sensors are instantly accessible through a web-based dashboard installed within the Municipal Emergency Operation Centre (MEOC). Additionally, forecasted rainfall from the Department of Hydrology and Meteorology (DHM) and other open sources is integrated into the dashboard, allowing for advanced visualization of upcoming threshold rainfall events.

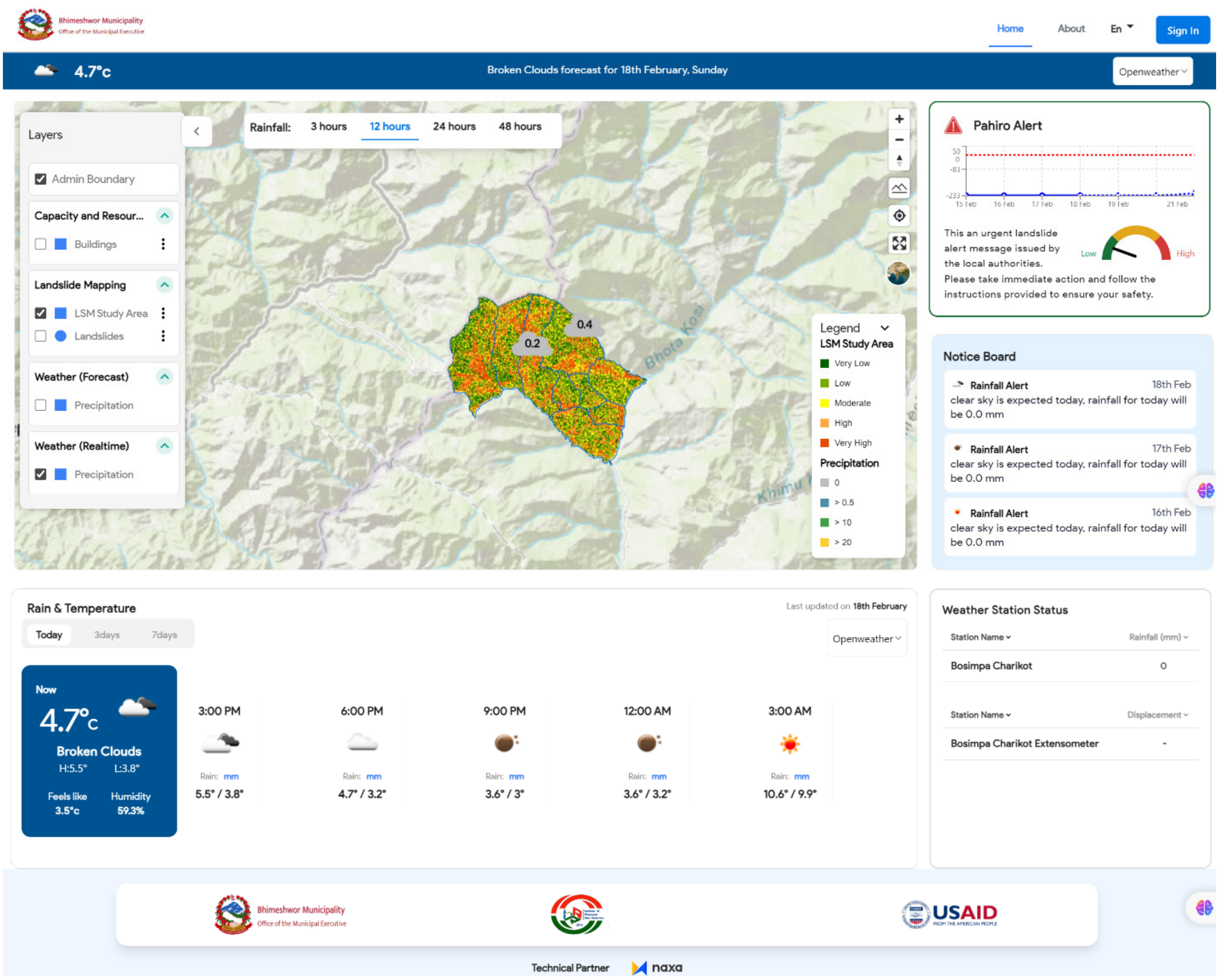

Figure 5: Alert Bhimeshwor Dashboard Interface (Top) and Real Time and Forecast Rainfall Visualization in the Dashboard (Bottom).

In accordance with the Standard Operating Procedures (SOP) established for the Landslide Early Warning System (LEWS) in Bhimeshwor, municipality officials, typically comprising the LEWS task force, regularly monitor both real-time and forecasted rainfall. The dashboard displays a 3-day forecast of rainfall, continually updated to align with updates from the Department of Hydrology and Meteorology (DHM) and other open sources. Additionally, the MEOC officials can monitor the landslide hazard map and Landslide Susceptibility Map (LSM) to pinpoint landslide-prone zones during extreme events. They will also be able to evaluate the rainfall threshold required to trigger landslides.

Once the cumulative real-time or forecasted rainfall surpasses the threshold, the municipality issues warnings through the communication channels outlined in the SOP. The SOP designates various stakeholders at federal, provincial, district, municipality, and community levels, all of whom play roles during landslide events.

The municipality's rainfall threshold model has been formulated using regression rainfall analysis based on historical landslide events, considering cumulative antecedent rainfall over five days. The threshold rainfall is determined by a regression equation, as illustrated in **Figure 6**.

*"**Threshold Rain ≥ 146 - 0.85 x 3 days antecedent rainfall**"*

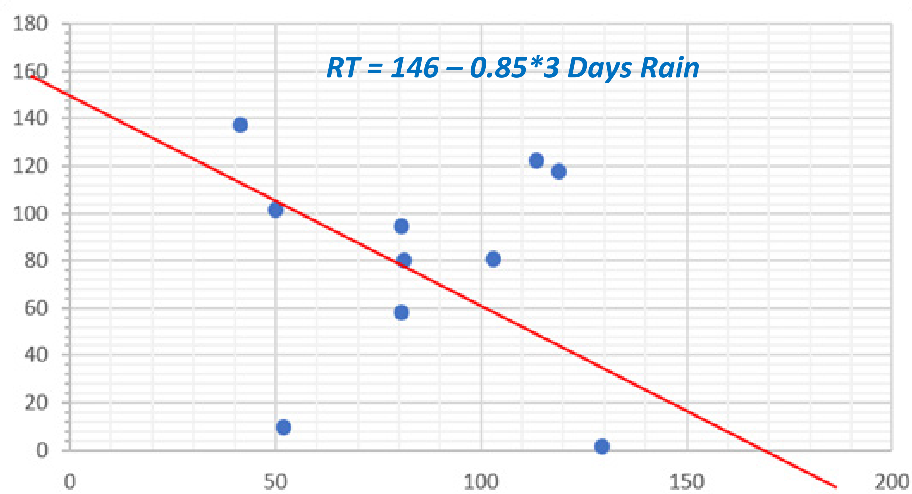

Figure 6: Daily vs. 3-Day Rainfall to Trigger Landslides in Wosimpa and Bhimeshwor Municipality.

The relationship of threshold rainfall indicated that the daily cumulative rainfall equal to or greater than 146 mm could trigger landslides in the research catchment. Deducting the daily rain (or real time rain or the forecast rainfall) to the threshold rain, shown above often turns negative values if it turns positive and greater than (or approached) to "0", the rain would potentially trigger landslides in the hilly terrain of the municipality. The Dashboard allows the user to graphically visualize on how the threshold rain approaches to the pre-defined threshold line in the dashboard (Figure 7).

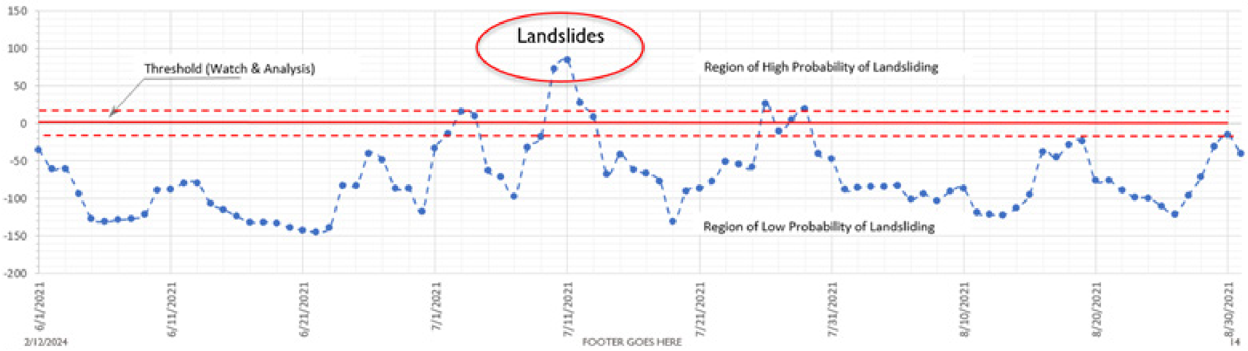

Figure 7: Graphical Visualization of Rainfall in the Dashboard

3.3 Communication and Dissemination of Alerts and Warnings

A LEWS taskforce led by the coordinator of the Local Disaster Management Committee (LDMC) has been provisioned in the SOP which is responsible for the communication and dissemination of alerts and warnings. The SOP's communication channel is presented in the Figure 8.

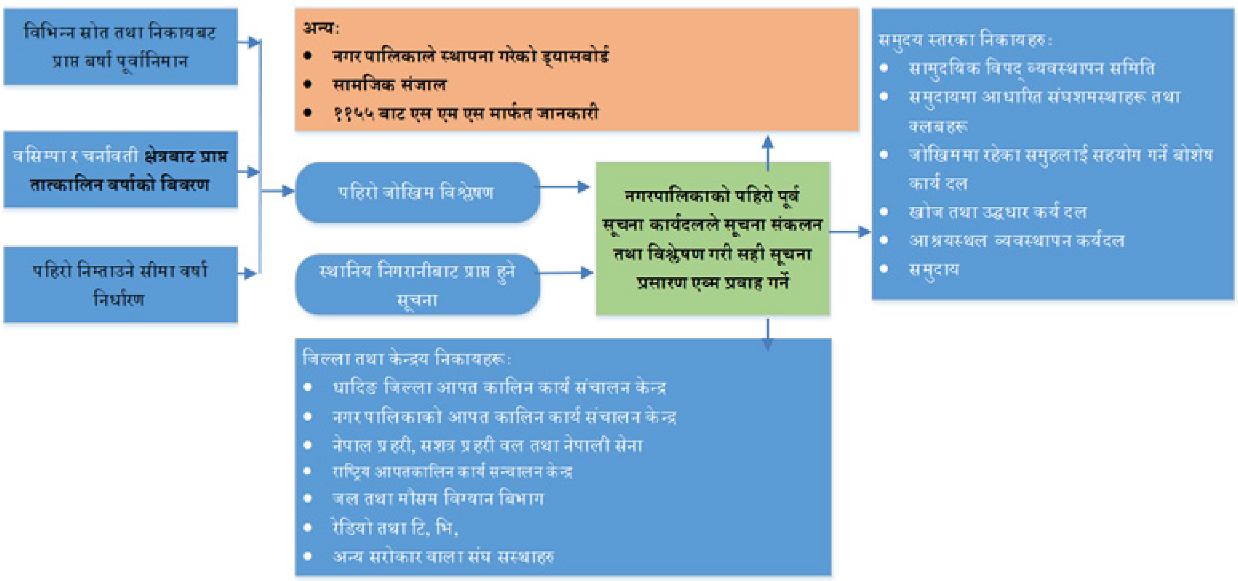

Figure 8: Communication Channel for the LEWS

The Dashboard will be the focal point of the communication because all the data and information related to the landslide hazard are collected, processed and displayed on the board. Sometimes, local level monitoring is also important and therefore information from the local communities is also gathered through the Local Disaster Management Committee (LDMC). Information from the LDMC typically includes cracks formation along hillslope, their expansion rate and other anomalies like tilting of electric pole, wall of buildings etc. Cracks across the hillslopes increase the infiltration of the water below ground leading to the slope failures. The LDMC, user committees and local communities regularly undertake such monitoring and subsequently inform the municipality.

Various training and capacity development activities have been organized for the proper and authenticated communication (**Figure 9**). These trainings were targeted to the municipality's officials and LEWS Users' Committee formed at the local level representing entire communities and including elderly people, Person with Disability (PWD), Women, Dalit and marginalized group. These trainings have been very beneficial to the target group in terms of data collection and dissemination.

Figure 9: Capacity Building for Communication and Dissemination

3.4 Response Capacity Development

"Response Capacity Development" stands as a crucial component within the Landslide Early Warning System (LEWS), implemented at both the Community and Municipality Levels. At the municipality level, enhancing response capacity entails the collection and dissemination of landslide and rainfall-related data, as well as the coordination of district and central-level organizations during extreme events.

The community has also been oriented about the response mechanism, understanding the indications of the landslides (**Figure 10**). The members from the user committee were oriented to take care of the instruments and safeguard it from any possible interventions or disturbances. Further, the participants from the community were oriented about the community level monitoring of landslides that included the early signs of possible landslides, Do's and Don'ts before, during and after the landslides. The landslide monitoring through the Moving-peg method was also disseminated to the community.

Figure 10: Community people participating in the moving peg method and debriefing safeguarding measures and monitoring procedures for LEWS

As outlined in the Standard Operating Procedures (SOP), the municipality issues advisory notices to communities and stakeholders based on various scenarios of rainfall forecasts (**Table 1**). These notices aim to provide communities with sufficient time for preparedness and response. Longer-duration notices, spanning 2 to 5 days, afford communities ample time to identify safe evacuation centers and routes, take stock of essential items, prepare "Go Bags," and safeguard lives, including livestock.

It's noteworthy that the municipality must stay updated with the rainfall forecasts from the Department of Hydrology and Meteorology (DHM) and other reliable sources designated by the DHM. DHM forecasts are often subject to frequent updates, necessitating close monitoring and timely updates by the municipality.

Table 1: Forecast Type and Corresponding Advisory Notice Time

SN	Forecast Type	Advisory Notice Time
1	15-Day Forecast	5 Day
2	7-Day Forecast	3 Day
3	5-Day Forecast	2 Day
4	3-Day Forecast	24 hours
5	2-Day Forecast	24 hours
6	24-hours Forecast	6 hours
7	Less than 24-hours Forecast	Less than 6 hours

4. Future Work

Following future works are suggested for the better and more efficient LEWS.

Updated Landslide Threshold Model:
The existing landslide threshold model relies on historical data of landslide occurrences, which entails landslide dates paired with corresponding rainfall amounts. This model was initially developed using limited historical landslide data and data collected during the 2023 monsoon season after the installation of instruments for the Landslide Early Warning System (LEWS). However, to enhance its accuracy and reliability, the model requires significant refinement and updating, particularly with the inclusion of data from the monitoring stations situated at Wosimpa and Singaram Sherpa. The forthcoming data from these stations is expected to substantially enhance the model's effectiveness, leading to the development of a more robust and reliable model.

Rainfall Data Resolution:
Landslides are typically triggered by intense but brief rainfall events, as well as prolonged periods of low-intensity rainfall. However, the current model is constructed solely using daily and 5-day cumulative rainfall data, overlooking the significance of lower-day (1, 2, 3, and 4-day) cumulative rainfall in the Landslide Early Warning System (LEWS). It is imperative to develop threshold models that account for these shorter-duration rainfall accumulations. Furthermore, it's essential to incorporate intense rainfall events of short duration into the rainfall threshold model.
The utilization of high-resolution sub-hourly rainfall data collected from Wosimpa and Singa Ram Basti presents an opportunity to create additional threshold models tailored to these specific conditions. Such models will play a crucial role in enhancing the effectiveness of the Landslide Early Warning System, ultimately contributing to the protection of lives and properties within Bhimeshwor Municipality.

Landslide Risk Assessment and Knowledge:
Landslide risk is a dynamic phenomenon influenced by both natural processes and human activities, leading to changes in various associated parameters over time. As such, it is essential to continuously enhance and update landslide risk assessments. Regular assessments are necessary to ensure that the community, municipality, and other stakeholders remain informed about the evolving landslide risks. Additionally, periodic re-evaluations and capacity-building efforts are crucial to equip these stakeholders with the necessary knowledge and skills to effectively respond to landslide hazards.

1 2009 UNISDR Terminology on Disaster Risk Reduction
2 MoHA, 2019, Nepal Disaster Report
3 Chu, M., Patton, A., Roering, J., Siebert, C., Selker, J., Walter, C. and Udell, C. (2021). SitkaNet: A low-cost, distributed sensor network for landslide monitoring and study. Hardware X.
4 Sehler, R., Li, J., Reager, JT and Ye, Hengchun (2019). Investigating Relationship Between Soil Moisture and Precipitation Globally Using Remote Sensing Observations. Universities Council on Water Resources.
5 BIPAD-Portal (https://bipadportal.gov.np/)

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2. This study is made possible by the support of the American People through the United States Agency for International Development (USAID). The contents of the Bhimeshwor-Alert System are the sole responsibility of IHRR and do not necessarily reflect the views of USAID or the United States Government.

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