Framework for implementation of a landslide early warning forecast model in developing countries

Challenges and lessons from SHEAR

Mirianna Budimir, Alessandro Mondini, Mauro Rossi, Christian Arnhardt, and Joanne Robbins

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Considerations for development of territorial rainfall-induced landslide forecasting in developing countries, based on experiences from the SHEAR programme.

Summary

The Science for Humanitarian Emergencies and Resilience (SHEAR) programme supports world-leading research to enhance the quality, availability and use of risk and forecast information.

Forecasting rainfall-induced landslides is a difficult yet important task that can provide time to take action to save lives, reduce economic losses and help to mitigate the impacts of landslides.

The type, quality and accessibility of data directly constrain the choice of approach used for the landslide forecasting and its skill. However, in many landslide-prone countries, limited resources, and lack of investment lead to limited data availability and/or insufficient quality data for informed forecasts.

This paper collates understanding from SHEAR consortium members on key considerations for developing territorial ('regional-scale') landslide forecasts, particularly in developing country contexts.

Authors:

Mirianna Budimir (Practical Action Consulting International), Alessandro Mondini and Mauro Rossi (Consiglio Nazionale delle Ricerche), Christian Arnhardt (British Geological Survey), and Joanne Robbins (UK Met Office).

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Email address contact: *mirianna.budimir@practicalaction.org.uk*

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1 Introduction

Landslides are complex phenomena that cause significant loss of life and damage to buildings and infrastructure. Approximately 4,000 landslides have caused over 160,000 deaths and 11,000 injuries globally over the course of two decades (Haque et al., 2019). A key trigger of landslides is rainfall; this publication focuses on forecasting and early warning for rainfall-induced landslides.

Early warning systems (EWS) provide information before a hazard occurs, providing an opportunity for people to act to save lives and livelihoods, thus reducing the impact of the hazard event. The United Nations (UN) and World Meteorological Organisation (WMO) outlined four main components of EWS, with four overarching considerations (Figure 1).

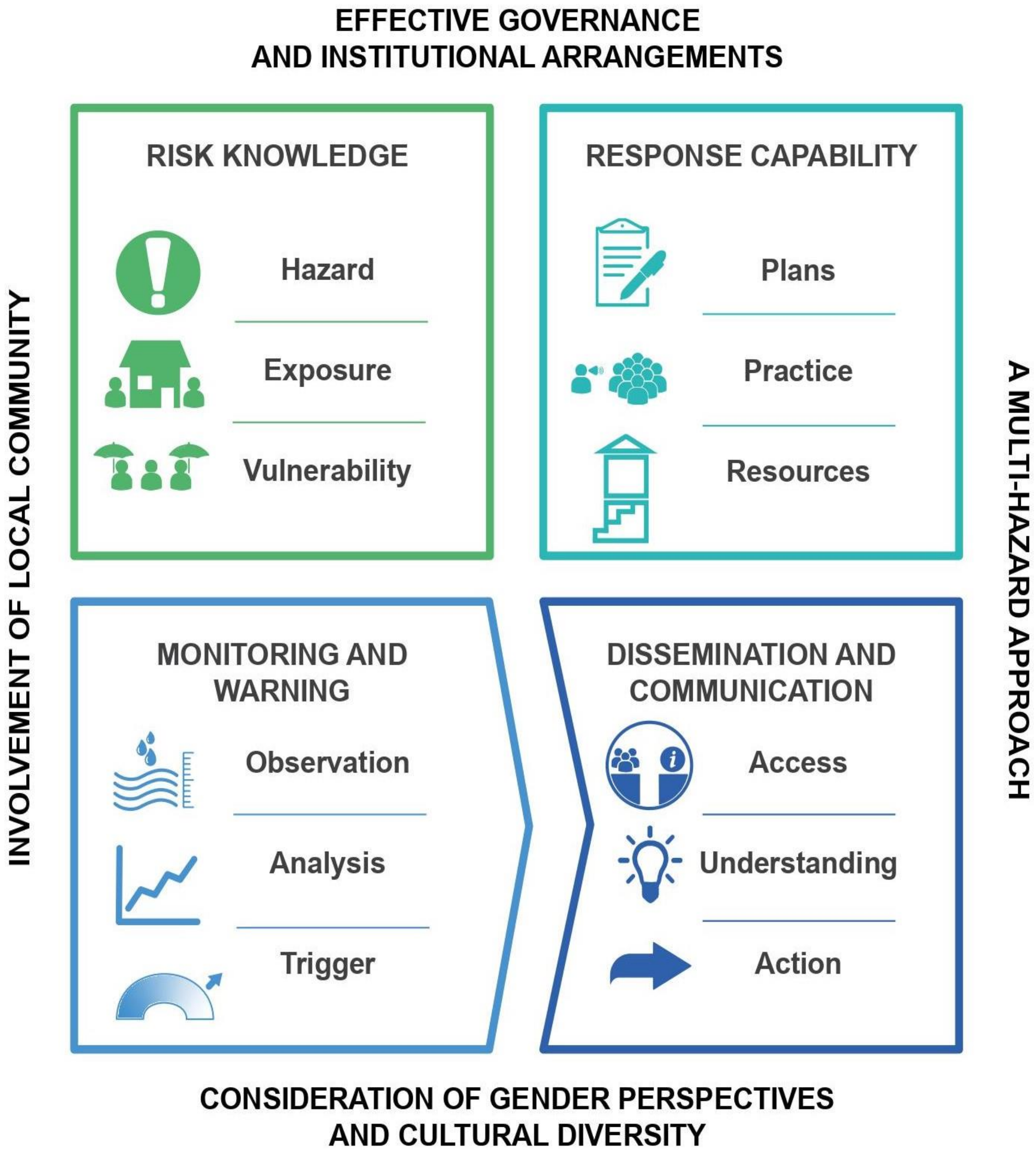

***Figure 1**. Components of an effective early warning system (Practical Action, 2021; based on WMO, 2017)*

Landslide early warning systems (LEWS) vary based on the geographical areas they cover. Systems addressing a single landslide on a specific slope are referred to as local or slope-scale LEWS, whereas systems dealing with the possible occurrence of multiple landslides over a wider geographical area are referred to as territorial or regional LEWS.

Rainfall-induced landslide forecasts consist of the spatial and/or temporal prediction of the likelihood or probability of slope failure occurring. Forecasting is a key part of LEWS, falling under the monitoring and warning component in Figure 1.

Territorial LEWS can provide forecast information with longer lead times for more people compared to local or site-specific LEWS and they can be scaled up to cover a whole country. Such territorial forecasts, when integrated into operational LEWS, can help save lives and livelihoods.

Rainfall-induced landslides are likely to increase in frequency and magnitude as climate change increases rainfall variability (IPCC, 2022). In developing countries, where landslides have high human, social, and economic costs, disaster risk managers and local government authorities are increasingly facing pressure to forecast landslides to support early warning and early action, as well as reduce losses caused by landslides, particularly in the face of a rapidly changing climate.

Landslides are heterogeneous processes and forecasting them is challenging and complex; challenges exist even in settings where a high quantity and quality of data exists. However, there are additional challenges when developing landslide forecasts related to systemic issues within developing country settings, such as:

- low levels of investment,
- limited resources,
- high staff turnover,
- a focus on response due to recurring disaster events, and
- project-based funding cycles.

These underlying issues lead to challenges that can affect the quality of data available specifically for landslide forecasting purposes, including issues related to quantity, content, accessibility, and systematised collection. However, there are examples of territorial LEWSs operating or in prototype phase in some developing countries (Guzzetti et al., 2020).

Photo courtesy of SaveTheHills

The Science for Humanitarian Emergencies and Resilience (SHEAR) programme supports improved disaster resilience and humanitarian response by advancing monitoring, assessment and prediction of natural hazards and risks across sub-Saharan Africa and South Asia. Consortium members from across the SHEAR programme have been working with stakeholders to co-produce demand-led, people-centred science and solutions to improve risk assessment, preparedness, early action and resilience to natural hazards. As part of the SHEAR programme, the LANDSLIP project developed a prototype regional landslide forecasting system for rainfall-induced landslides in two pilot locations in India, in close collaboration with research partners, local organisations, and the Geological Survey of India (GSI).

Forecasting rainfall-induced landslides is a difficult yet important task that can provide time to act to help to mitigate the impacts of landslides by saving lives and reducing social and economic losses. This publication will explore some of the challenges faced by SHEAR programme members related to obtaining data for rainfall-induced landslide forecasting in developing country settings and offer a framework for supporting the development of an appropriate approach to forecasting landslides in these types of low-data environments.

The information presented in this paper is sourced from a range of experts from within the SHEAR programme and has been reviewed by members of the LandAware[1] network executive committee. The paper has been led by members from Consiglio Nazionale delle Ricerche, the British Geological Survey, the UK Met Office, and Practical Action Consulting International from the LANDSLIP project. The content of this publication has been greatly informed by discussions within LANDSLIP reflecting on project experiences through workshops within the consortium and across the SHEAR programme.

This paper is not intended to be used as a best-practice guide, but rather as a starting point for developing an approach to territorial rainfall-induced landslide forecasting in developing countries. It collates understanding from key expert experience of conducting similar activities to establishing landslide forecasting in similar settings. The focus here is on learning from these processes and the considerations emerging from them, rather than on prescriptive advice.

This is an evolving topic area that will likely become increasingly needed and relevant as future climate change increases the risk from landslides. The authors hope that this paper will springboard discussions within the wider landslide forecasting and early warning community and encourage it to share experiences from similar perspectives, so that advice based on a wider evidence base can be delivered in the future.

[1] LandAware is a multi-disciplinary, knowledge-based, non-profit network of global individuals who are interested in cooperating for addressing and promoting issues related to Landslide Early Warning Systems. Members include global experts.

2 Key challenges

Reliable, good quality, and spatially and temporally representative landslide and weather data are fundamental to informed territorial rainfall-induced landslide forecasting. It has usually been assumed, for most landslide forecast models developed in the past, that conditions (including environment and rainfall) where landslides have happened previously are indicators of where landslides are likely to occur again. It is therefore important to have detailed information about when, where, why, and how landslides have occurred before to predict the future likelihood of similar events. It is also important to have weather data that appropriately represents the conditions on the ground, such as location, quantity of rainfall, and the length of time it has been raining before a landslide occurs.

2.1 Challenges in developing countries

Challenges that can directly affect data type and quality for landslide forecasting purposes, particularly in developing countries, include:

- **Low levels of investment,** preventing long-term policy development and implementation, including lack of funds to invest in improved monitoring and data management strategies.
  - There are often numerous development-related challenges in such contexts, which can be linked to increased risk of conflict and political instability, in turn resulting in decreasing and/or disrupted investment and development initiatives.
  - This often leads to government departments with a disaster management mandate operating without sufficient personnel, training, skillsets, and time resources.
  - Limited investment, reliance on external funding sources, and recurring disaster cycles also lead to a culture of emergency response rather than implementation of longer-term preparedness and resilience building activities.
  - Changing from response-focused activities to preparedness and forecasting activities will also require significant investments, change in institutional culture, capacities, training, and a different set of skills and expertise within teams.

- **High levels of staff turnover,** necessitated by the need to have skills in different areas, result in difficulties institutionalising capacities and retaining knowledge and expertise longer-term.

- **Disaster event cycles continually erode development gains** for disaster-specific government offices, and for broader institutional development.

- **Project-based initiatives** to improve or change data collection or forecasting approaches rely on external funding agencies. Methods, approaches, systems, and data types therefore focus on the requirements of the funder and may not be sustainable or useful for longer-term or bigger-picture institutional needs.

As a result of these underlying issues, the data available for landslide forecasting in developing country contexts can often be insufficient to develop skilful models.

2.1.1 Insufficient spatially and temporally representative data.

For landslide and rainfall data, it is important that observations be spatially and temporally representative of the region or period relevant to the forecasting application being developed. The issues outlined in Section 2.1 often lead to an incomplete landslide inventory or a poor rainfall observation dataset, directly affecting the ability to produce informed landslide forecasts.

All observation data have inaccuracies and biases, but an understanding of what is available and what limitations exist is needed when which forecasting approach to use (Figure 2). This includes understanding issues related to:

- **Lack of resources** to collect landslide observation data immediately after occurrence across remote and difficult-to-access areas, and/or to install and maintain a dense network of rainfall gauges.

- **Dangerous environments** preventing safe landslide observation data collection during extended periods of time (e.g. monsoon seasons).

- **Location bias** in landslide and rainfall data due to lack of resources, dangerous environments, and/or remote or difficult to access areas.
    - Landslides are often reported mostly from inhabited areas or in the proximity of anthropogenic structures and infrastructures.
    - Acquisition of landslide data in remote areas is difficult and can be dangerous or restricted, which means the database will lack information on landslides away from easily accessible areas.
    - Collection of representative spatial rainfall data across variable topographies and large areas is typically lacking in developing countries due to insufficient resources to install and maintain a spatially dense network of weather stations, which can result in data not representing the spatial variabilities of rainfall accurately.

- **Insufficient temporal representation.**
    - Landslide events need to be accurately linked to specific rainfall conditions to understand the relationship between these conditions and the slope failure(s).
    - In developing countries, the best temporal resolution available for rainfall data is often daily, and the rain gauges are often not automatic, which is not the

    - optimum framework for forecasting for early warning (both in the phase of model calibration and in the operational application).
    - Real-time forecasting capabilities will depend on how frequently rainfall data is collected and whether this data is relayed in real-time to a central system.
    - Satellite-based rainfall estimates can partially solve this issue, however, not all satellite products have the same high temporal and spatial resolutions and accessing the data can be prohibitively costly.

- **Missed landslide events.**
    - Due to dangerous environmental conditions, such as monsoon rains that last for sustained periods of time, landslide event data are often not collected immediately after the landslide events occur.
    - There is difficulty recording landslides 'live' during significant severe weather events, especially if these conditions occur over sustained periods of time.
    - In many environments, rapid vegetation growth can obscure evidence of landslides within days, weeks, or months, resulting in landslide observation data that is missing or under-representative of actual occurrences.

2.1.2 Lack of standardised reporting.

A lack of standardised reporting can arise when multiple stakeholders collect different types of landslide and weather data for different purposes:

- **Response focused data.**
    - In many developing countries, disaster risk management practices are focused on response activities due to low investment and resources.
    - Landslide data collection objectives are often conducted for post-event records and distribution of aid, or for insurance purposes.
    - Moving from a post-event to a pre-event focus requires significant investment to change data type, content, and methodologies to support data use and management that are relevant to model design and testing.

- **Non-digital data:** in many situations, data are stored in analogue, or in separate digital databases, which can affect real-time forecasting capabilities.

- **Barriers to sharing data.**
    - Weather related data is often collected and held by national meteorological services.
    - Landslide data can be collected and held by different departments (e.g. disaster risk management or geological services).
    - Private weather stations (e.g. owned by tea plantations, schools, or non-governmental organisations (NGOs)) can also provide additional sources, but quality checks are needed.
    - Landslide forecasting requires cross-departmental and -organisational collaboration and data sharing, and standardisation of data, which can take time to officially mandate and invest in.

2.1.3 Lack of training or relevant backgrounds

Data collectors can lack training or relevant backgrounds, particularly where efforts to increase data collection rely on non-experts. Without sufficient data quality controls, this can result in issues in the content or quality of data collected such as:

- **Types of landslides recorded:** there are many different types of landslides, and it is important that inventories record the type correctly; without sufficient expertise, records can miss out on some types of landslides that are harder to identify (e.g. deep-seated landslides, rock-falls).

- **Information on landslide characteristics:** landslide features may not be clearly identified (e.g. distinguishing between source, runout, and deposition areas; determining whether a given landslide was one or several that were merged).

- **Cause or trigger of landslide:** reporting of minor slips or landslides in urban areas (with clear anthropogenic causes such as building work) can bias the data sources for model development and validation.
  - It is very difficult to discern the cause or trigger of a landslide without expert knowledge.
  - Rapid urbanisation in developing countries alongside a lack of building regulations or enforcement can result in significant anthropogenically caused landslides that can skew the data if they are not distinguished from rainfall-induced landslides.

- **Misidentification:** some of the landslides mapped by non-experts can be features caused by other processes, such as tree failures, or collapsed construction works, and misidentifying them as rainfall-induced landslides can introduce errors into the database.

2.2 Addressing the challenges

A more nuanced and considered approach is needed to develop forecast methodologies in developing countries to reflect and account for these challenges. This requires sufficient funding and systemic change for any long-term LEWS to operate. Whilst project-based initiatives will not change the status quo, they can aim to work sensitively, and together with local stakeholders towards a sustainable progress.

The framework in Section 3 proposes an alternative to some common practices that tend to export pre-existing models and packages without preliminary feasibility studies, resulting in failed or unsustainable approaches to landslide forecasting in developing countries.

This framework is based on experiential learning from the SHEAR programme about key considerations for developing a forecasting methodology which will be appropriate for any context but have particular value a developing country context where the implications and consequences of wasted or misused resources, or of inappropriate or ineffective forecasting approaches, will be more severe than in contexts where populations, services, and infrastructure are less vulnerable.

3 Framework

Figure 2 below outlines a framework for supporting the development of an appropriate approach to forecasting landslides in developing countries.

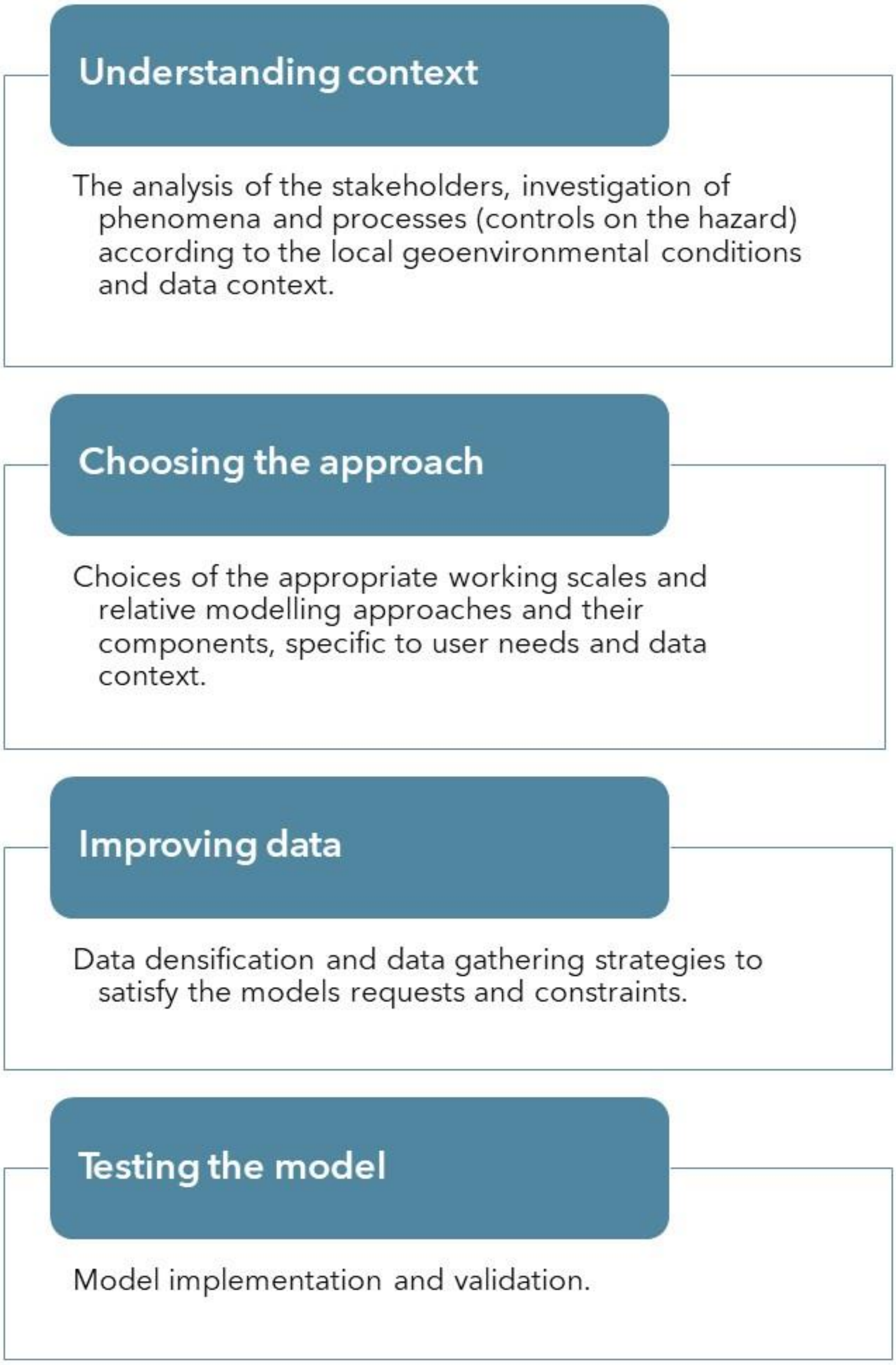

Figure 2. *Framework for supporting the development of an appropriate approach to forecasting landslides in developing countries.*

3.1 Understanding context

Landslides occur all over the world and every context is different. For any new intervention, it is necessary to understand local environments, dynamics, and needs before utilising existing solutions or creating new ones. For landslide forecasting, it is necessary to understand what data is currently available, the existing characteristics of any landslide hazards, and the needs and capacities of local stakeholders. This enables developers to be able to choose or design an appropriate and sustainable forecasting approach.

Three key areas to understand context are:

- Stakeholder mapping and engagement (Section 3.1.1).
- Understanding landslide hazards and their triggering mechanisms (Section 3.1.2).
- Understanding the available data and technical resources (Section 3.1.3).

3.1.1 Stakeholder mapping and engagement

Stakeholder mapping and engagement is a key component of understanding the local context and the needs, barriers, and limitations of stakeholders. This understanding can directly inform forecasting approaches, such as lead times and spatial and/or temporal resolution of forecast products. It will also help inform which approaches might be sustainable in the longer-term, beyond project funding, by understanding the roles, responsibilities, capacities, and resources of mandated institutions, and the flows of information and decision-making between them.

Forecasting is one part of a holistic LEWS. Researchers and developers will therefore need to engage with stakeholders who are engaged in all components from the beginning of the development process for any potential operational system to be effective. Directly engaging with stakeholders also facilitates the process of identifying existing data and obtaining the necessary permissions to access and use it.

Key questions

- Who are the key stakeholders?
  - What are their roles and responsibilities?
  - What are their strengths and limitations?
  - What are the relationships and power dynamics between stakeholders?
- What data do they collect and is it accessible?
- Are there existing EWS (landslide or other) being used or trialled in the area?
- What has already been done to identify exposure, vulnerability, and hazards related to landslides?
  - Are there any new or ongoing initiatives to be aware of?
- What are the different aims and needs of stakeholder groups?
  - Does a LEWS help them?

Considerations

Include a range of stakeholders, such as:

- Government institutions:
  - Disaster management authorities.
  - Geological or landslide-focused institutions.
  - Science-focused departments.
  - Road and/or rail authorities.
  - Meteorological or hazard-related institutions.

- Civil society stakeholders:
    - Particularly community-based organisations and networks, both formal and informal.
    - International Non-Government Organisations with good community relationships and experience in dealing with landslide risk and events.
- Local community members - there may be opportunities in the future to engage them in citizen-science data collection.
- Other initiatives, projects or organisations working on landslides, such as local self-help groups and associations involved in economic or agricultural activities.

Map relationships (both negative and positive) between stakeholders, identifying any potential sources of conflict or uneven power-dynamics.

Approaches
Ways to gather this information include:

- Desk-based mapping and documentation of relevant stakeholders.
- Approaching local stakeholders (beginning with government officials) for initial consultations and to request permissions and contact details to continue consultations with other stakeholders (e.g. NGOs, civil society).
- Snowball and introductory sampling, where existing contacts provide referrals for further information, to reach out to all stakeholders relevant to the study area.

Multiple meetings may be required. In-person engagement is preferable for building trust and developing stronger relationships that can be built on for future collaboration, and an understanding and appreciation of existing norms, such as formalities, around introductions and relationships is essential. Partnering with intermediary representatives that already have existing relationships with key stakeholders can be beneficial in bridging or supporting new relationships.

Example from LANDSLIP
Within LANDSLIP, the stakeholder mapping and engagement activities began with an initial round of **introductions** conducted in the two study sites, followed by:

- **Background study:** a desk-based review of disaster risk reduction policies and plans was conducted at the national, state and the district level for the two study sites.
  - This helped identify key stakeholders and agencies tasked with landslide-related work in the project pilot areas.
  - Local partners were crucial at this stage to support gathering of existing information.

- **Fieldwork:** fieldwork used a snowball sampling method and simultaneously engaged the local NGO and research partners and district offices. This included gradual trust building exercises such as:
  - Spending time at the district disaster offices.
  - Participant observations in drills.
  - Paying courtesy visits to district officials and authorities.
  - Visiting landslide locations and identifying their possible conditioning and triggering factors.
  - Engaging through meetings with related local organisations.
  - Detailed semi-structured interviews of all key actors who could play a role in a future LEWS.

- **Interview analysis and continued interactions:** this stage involved understanding how a LEWS might fit in the existing system, including:
  - Who is responsible and/or mandated for roles within a LEWS.
  - Who collects data.
  - How warnings and risk information could be communicated.
  - What additional training and/or changes to the institutional structure would be required to support a LEWS.

3.1.2 Understanding landslide hazards and their triggering mechanisms

It is important to understand landslide hazards and the processes that lead to their occurrence. This includes understanding the variability in failure types, pre-existing environmental conditions, and triggers for landslides in different study areas. Understanding landslide processes and types will determine which methods are used to generate landslide models and forecasting tools, which is an essential first step prior to forward modelling and forecasting.

Key questions

- What are the key landslide characteristics?
- What type(s) of landslide(s) does the location experience?
- What is triggering the landslides?
- What has been the historical impact of these landslides?

Considerations
The spatial distribution and presence of landslide conditioning factors (geology, geomorphology, climate, land use) determines the likelihood of landslides occurring in an area. These conditioning factors are key when modelling landslide susceptibility (identifying *where* a landslide is likely to occur) and differ from the triggering factors, such as rainfall, snowmelt or earthquake, that identify the main processes initiating landslide failure (identifying *when* a landslide is likely to

occur). In any location, it is vital to understand whether there are any major patterns in the triggering mechanisms (e.g. monsoons resulting in intense and long-term rainfall periods). Together, the conditioning and triggering factors determine when and where landslides might occur, as well as the type of failure that could occur.

Approaches

Ways to gather local knowledge include:

- Engaging with local stakeholders (Section 3.1.1).
- Accessing publications such as peer-reviewed journals, scientific and technical literature, and government reports.
- Conducting field visits to observe the local environment and examine previous events.

It is also important to consider any gaps in the documentation and data.

Example from LANDSLIP

Initial scoping by the LANDSLIP project found that the Nilgiris district, known as the Blue Mountains, constitutes hilly terrain in the Western Ghats. The Nilgiris district is vulnerable to multiple hazards. The three primary hazards that have been identified by the district administration are floods, landslides, and flash floods.

Nilgiris receives rainfall from both the north-east and the south-west monsoons. The south-west monsoon brings more rain to the western part of the district, while the eastern and south-eastern parts of the district get more rainfall from the north-east monsoon. The average annual rainfall is 1695 mm. The district is reportedly experiencing a trend of increasing annual rainfall in the last two decades. Based on information provided by the Geotechnical Cell of the State Government in 2017, there are over 200 village settlements prone to landslides.

Some of the worst years in recent memory in terms of heavy rainfall with resultant landslides have been during the years of 1978, 1979, 1993, 1998, 2001, 2006 and 2009, with most landslides occurring during the north-east monsoon, especially in November. The district disaster management plan includes:

- Information on vulnerability to landslides.
- A list of the roads in the district which are likely to be affected by landslides.
- Details of measures to be taken for prevention, mitigation, capacity-building, and preparedness.
- Response mechanisms and procedures in the event of a disaster.

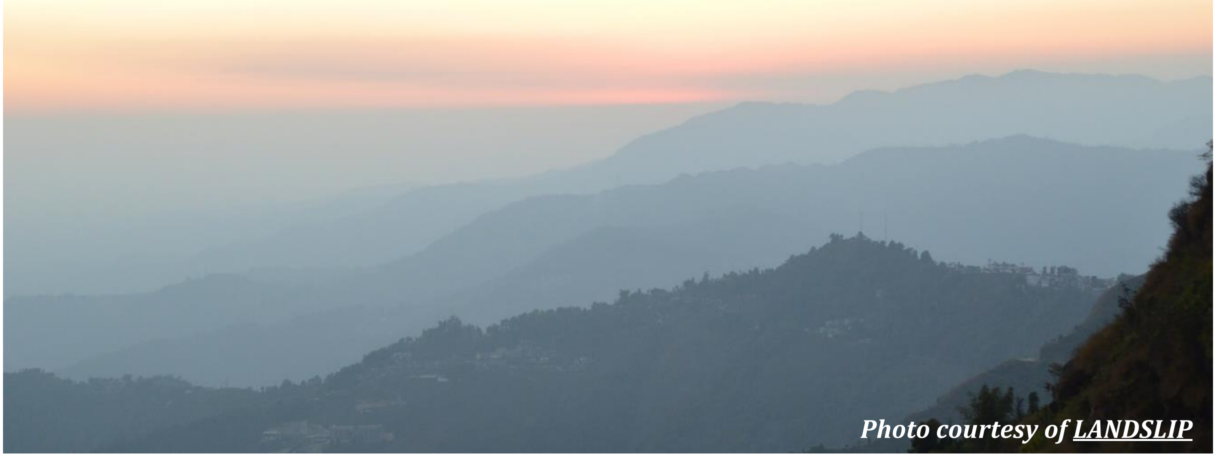
Photo courtesy of LANDSLIP

3.1.3 Understanding the available data and the technical resources

Data availability, accessibility, representativeness, quantity, and quality will all directly affect which forecast approach is most appropriate in any new context. They may also potentially indicate that significant changes in data collection methods will be needed to support alternative or improved landslide forecasting.

Key questions

- What information and data already exist?
- How is the data captured and what information is captured?
- Who owns the data?
- Is the data appropriate for landslide forecasting needs?
- Are there any gaps in the data?
- Who is maintaining and managing the data?
- How is the data being used?

Considerations

It is necessary to think in advance about the data that might be needed:

- Requirements for understanding statistical relationships.
- The minimum temporal and spatial density needed for forward modelling.
- Gaps in the data that could affect forecasting approach (quality and quantity issues).
- Data quality — is it good enough for the intended purpose?
- Does the data represent the landslide inventories — including number of landslides and types of landslide processes observed?
- Does the method of landslide data collection and/or rainfall monitoring affect sampling, thus leading to bias?

Some specific considerations for using rainfall gauge-based data for landslide analysis include:

- Datasets need to have a sufficient spatial density to enable the spatial and temporal variability of rainfall to be observed.
- The reporting period of meteorological observations needs to overlap with the reporting period of historical landslides.
- The temporal unit of the observation (e.g. daily or hourly rainfall accumulations) needs to relate to the temporal accuracy of the landslide data (e.g. landslide reported by day or hour of occurrence) where possible.
- Where multiple gauge-based sources are used, it is important to consider differences in:
    - Reporting procedures: manual or automated recording; daily or sub-daily reporting.
    - Format: written or electronic.
    - Availability: ad hoc or routine.

For gridded rainfall datasets, the considerations are similar (e.g. record length and temporal unit) but it is also important to consider the spatial resolution and whether this will enable specific meteorological features (e.g. mesoscale convective systems) relevant to landslide occurrence to be observed.

It is also important to understand the biases that may be introduced by the processing and generation of the datasets. It is recognised that some datasets (e.g. reanalysis and satellite data) may exhibit under- or over-representation of rainfall in different geographical regions and at different times of the year. It is therefore useful to have long observation records so that these biases can be assessed and considered in relation to the landslide data and planned analysis; this may mean there is a need in low data contexts to initiate data gathering efforts long-term, to provide this information in the future (see Section 3.3).

Approaches
Using stakeholder mapping to identify organisations that collect or store data, reaching out to request access and/or more information and collecting publicly available data are both recommended. This may be an iterative process (see Section 3.1.1).

Example from LANDSLIP

The LANDSLIP project found that there were many types of landslide data and other relevant data that were being collected across multiple organisations, including government, civil society, research, private sector (e.g. tea gardens, railway authorities), and media actors.

Many types of landslide observational data resided with GSI and the District Disaster Management Authority (DDMA), but there were gaps. Records of landslides were mostly collected by staff of the district administration at the village, block, and district level, and submitted to the DDMA as calamity reports for compensation. Access to these records is difficult as they can be paper based rather than digitised, and/or are not publicly available for analysis.

Landslide data lacked standardised reporting across stakeholders, with a bias in collecting observations from inhabited areas. Records of when the landslide occurred were often missing or were not specific enough for landslide forecasting purposes. Temporally accurate ground-based observation records of rainfall were often lacking (e.g. no information on how long it was raining before a specific landslide event) with a limited availability of automatic rain-gauge stations.


Photo courtesy of SaveTheHills

3.2 Choosing the approach

Once the initial information on the new location has been gathered, a review stage is needed to assess the setting and the availability of data and information before deciding what is possible in terms of forecasting.

Data needs to be scrutinised to understand where it can be matched to users' needs. In some circumstances the available data may not match users' needs exactly, which then requires negotiation to identify what can be most usefully achieved within the constraints of what is available. In all instances, the caveats associated with the data used need to be clear and the implications for modelling, forecasting, and warning need to be known. In data-sparse areas, a stepwise approach is often essential.

There are a variety of forecasting approaches that can be taken, including:

- **Geotechnical monitoring**: used to forecast the behaviour of known, single landslides or hillslope deformations within local or site-specific EWS, through the monitoring of a landslide feature or kinematic parameters (e.g. displacement and its derivatives, such as velocity and acceleration) measured directly in the field or at the site through geotechnical instruments and equipment.

- **Physically based approaches**: used to forecast landslides over larger areas (up to basin scale) using simplified, physical representations of landslide processes.
    - This requires input measures, estimates or forecasts of a triggering variable (e.g. rainfall).
    - Higher spatial accuracy is possible if knowledge and data on surface geometry, morphology and geotechnical and hydrological soil characteristics are available as result of extensive field activities.
    - The approach has limited possible usage in data-sparse regions.

- **Statistically based and empirical models**: rely on simplified relationships that link the landslide's occurrence to a triggering variable (e.g. rainfall) and are used to forecast landslides at the territorial scale.
    - This approach requires input measures, estimates or forecasts of a triggering variable (e.g. rainfall).
    - This can be effectively used in data-sparse regions but models need to be calibrated using specific landslide datasets.

- **Expert- or judgement-driven methods**: can be useful in cases where quantitative data is not sufficient to support model-based approaches.
    - Expert-elicitation methods can be used to derive thresholds.
    - In addition to technical components and modelling tools, this approach relies on a combination of different expertise to develop, plan and implement successful thresholds, including:
        - Spatial planners.
        - Engineers.
        - Historians.
        - Social scientists.
        - Natural scientists.
        - Geomorphologists.

Key questions

- Can we use models that are used elsewhere?
- Can we implement a threshold-based approach?
- Is the data in the selected location appropriate, usable, and accessible for running the model?
- Do we need to think about alternative approaches (possibly less data-driven) to suit the context?
- Do we need different forecasting models?
- Do we need new data to support the chosen forecasting approach?

Considerations

An existing model may not work in the different setting due to multiple reasons, such as:

- The existing model is inappropriate for the types of processes occurring in the location.
- The existing model lacks necessary data.
- The outputs of the existing model do not match stakeholder needs.

The process of choosing the most appropriate forecasting model is important to ensure the forecasts produced are as useful as possible and are aligned with the stakeholders' needs. It may be the case that the initial model considered is not appropriate; it is important to have the confidence to not use an inappropriate model. Improving data is an alternative and/or complementary route in cases where the data does not match the requirements of a desirable modelling approach. All the forecasting approaches need to be verified and evaluated using field observations.

Approaches

- **Define similar areas:**
    - Consider scales, types of physical processes, land use, and how important these processes are in terms of impact - are they affecting people or assets of concern?
    - Prioritise areas where there are a high number of landslide incidents.

- **Choose a model:** start with a model that has worked elsewhere; there is good confidence in its skill, and the basic limitations are understood. Also consider:
    - **Processes:** do the models we are considering reflect the processes (type of landslides, spatial and temporal scales) in the new area?
        - If the existing model does not work in this area, check if there are other modelling approaches or tools that you can use that are more appropriate to local processes and data availability.

    - **Data:** do we have the right data for the models?
        - If the data is not sufficient for the modelling approach, consider alternative approaches that are less data-dependent or instigate a programme of work that helps you ensure you have good data in the long-term so that you can aspire to more data-driven or statistically based models in the future.

    - **User needs:** does the model produce outputs which usefully address the needs of the stakeholders?
        - If the outputs do not produce useful information for stakeholders, consider alternative approaches or ways of translating outputs into useful products.

Example from LANDSLIP
LANDSLIP's prototype landslide forecasting uses two models, which are run daily for the two pilot study areas.

The first model calculates non-exceedance probabilities for landslide occurrence, building on the concept of empirically derived rainfall thresholds that rely on statistical analysis of historical landslide catalogues and rainfall series. This model is used to produce short-range forecasts valid for the next 24 hours (and up to 72 hours) and takes in daily rainfall forecasts.

The second model is based on an estimation of the probability of occurrence of high landslide risk weather patterns, identified through a statistical, historical assessment of weather patterns most likely to lead to landslides. This model is used to produce medium-range forecasts valid from five to fifteen days in advance.

Photo courtesy of SaveTheHills

3.3 Improving the data

The available data may not be appropriate or sufficient for landslide forecasting purposes for reasons outlined previously. Improved data may be needed for model development (e.g. offline analysis) or for the running of routine models in forecasting mode. The requirements for each are likely to be different; forecasting purposes will require real-time data (typically automated), whereas data collected manually or via paper-based systems will be useful for model development and forecast evaluation.

New, more, or different data may need to be collected to address gaps in existing data. In data-sparse regions, this might involve developing and implementing a longer-term strategy to improve data with a specific long-term view to improve forecasting capabilities, or a short-term strategy to collect more data to improve a landslide database.

Setting up structures and methods for sustainable new data collection for landslide forecasting requires considerable forethought to ensure any new efforts are sustainable, have clear ownership, are appropriate for future needs, and bear in mind the resources and capacities of the responsible stakeholders, so that they can continue data collection.

Key questions

- What data is essential for landslide forecasting?
  - What is nice to have and what is the gold standard of data?
- Where are the gaps in the data for the current forecasting approach?
  - Are there any gaps in the data for alternative approaches or future improvements?
- What specific information points are needed for landslide forecasting?
- Who can collect and manage the data in the long-term?
- Are there sufficient funding or resources to support changes or increases in long-term data collection?
- Is the strategy futureproof?
- Are procedures or regulations in place to allow a continuous and standardised process of data collection?

Considerations

Consider who is collecting or monitoring the data, including existing roles and responsibilities for data collection, monitoring and storage. It is often easier to adapt existing structures rather than starting from scratch and this is more likely to encourage long-term use. Local capacity and knowledge can be used to support new or improved data collection (e.g. government, NGOs, civil society, private sector). Strategies that are institutionally mandated or embedded within organisations (e.g. government, education) tend to have longevity and be more sustainable.

Using non-governmental local resources may provide benefits and opportunities for scaling-up data (e.g. rapid landslide tracking after an event or citizen science approaches to rainfall monitoring) but local collectors may need compensation or incentives to continue these activities over a longer period. Strategies for dealing with uncertainty, trustworthiness of data sources or collectors, and validation of data from a variety of sources will be needed.

It is important to consider the capacity and resources of institutions that may affect or dictate the frequency of collection, transfer of information, storage, accessibility, or ownership. The timing and logistics of data collection or transfer and any reliance on external sources may be affected by issues related to accessibility, safety, capacity, and resources.

Changes to data collection or monitoring systems require time and resources. There may also be a need for advocacy, education, and outreach to effect a change in data practices. Emphasising the importance of landslide and weather data to local stakeholders throughout this process will increase the likelihood of sustainable practices.

At this stage, it is useful to not only consider immediate data needs, but also to take the time to think about longer-term and potential future needs and integrate them into implementation plans. It is better to set up a system that considers futureproofing approaches early on rather than re-invent the process again to adapt to changing needs. Of course, it may not be possible to identify all potential future needs. It is therefore important to design and develop a flexible and adaptable data collection or monitoring system.

Approaches

There are many ways to collect new data. A blended approach can allow for any redundancies and for complementarity to be built into the system. The best approach will also be dictated by the purpose of the data, for example for real-time forecasting or offline analysis.

Data collection approaches include:

- **Manual data collection**: may be time, people, and resource intensive, but can facilitate localised and, potentially, more data to be collected.

- **Paper-based formats**: may be easier to fill in while in the field, but resource intensive to transfer to digital records later and can become damaged in bad weather.

- **Electronic formats:** such as a website or an app can introduce quality control early if set up well and can either immediately send the data to a central database or store it until within range of Wi-Fi or mobile signal if collecting information in remote areas.

- **Automated monitoring systems**: may send data in real-time but may be costly to install and maintain long-term.

- **Social media**: an emerging area to crowdsource data either actively or passively.

- **Remote sensing sources**: may support remote data collection but requires specific expertise to conduct with accuracy.

Using a systematised, consistent data reporting template for multiple formats can ensure that, whichever method is used, the data provided can be joined seamlessly in central databases.

Example from LANDSLIP

The LANDSLIP project aimed to improve landslide data across two main areas: scaling up the overall number of landslide events recorded and increasing the content of those records to create a more complete record of each specific event. This was done by:

- Increasing the sources of data.
- Using a blended data approach.
- Combining existing sources of data.
- Developing consistent data requirements.
- Increasing local data collection.

Standardised data collection procedures and tools and structures for data storage and management were defined for this purpose.

The project took a long-term and systematised approach to producing a landslide tracker methodology to support improved data collection, spending significant time considering current and potential data needs. The following information was deemed essential for each landslide event:

- Reporting date, time, and person.
- Landslide occurrence date and time, plus a confidence indicator (exact, in last day, in last week).
- Landslide location data (district, town, coordinates, landmarks, type of environment (forest, tea plantation), indication of proximity to road (plus road type, above/below/on road)).
- Landslide type (fall, slide, flow).
- Landslide size (small, medium, large).
- Landslide trigger (rainfall, earthquake, other).
- Landslide material (rock, earth, debris).
- A record of how we know each piece of information.

The project targeted two main stakeholder groups to collect new data: the government, through the District Disaster Management Authority, district administration and GSI; and non-government, through NGO field staff, volunteers, geology students and those in the local area.

A paper-based landslide tracker form and a mobile app were also developed for use by those collecting landslide data locally. Awareness-raising activities and training were carried out at different levels to support those collecting the data.

Photo courtesy of LANDSLIP

3.4 Testing the model

Once a modelling approach is chosen, it needs to be developed and reviewed to ensure it produces desirable outputs. There are multiple options for model testing, including:

- Running the model for sets of past events ('hindcasting').
- Running the model as a prototype.
- Trialling the model outputs with users.

In all instances, the model outputs need to be evaluated for accuracy, reliability, and uncertainty. Once a model is fully implemented and running routinely, it will need to be regularly re-evaluated and recalibrated with new data. This can take place over a period of several years, to guarantee model evaluation over a range of representative triggering conditions.

It is also important to recognise that forecast models are produced to support and enhance the ability of users to make timely decisions. Although a baseline level of skill (which will be metric dependent) for forecast models is needed, value can often still be provided to users even where very simple methods are applied. It is therefore important that testing involves user feedback as well as more traditional verification statistics.

Key questions

- Are the forecasts accurate (temporal, spatial, level of accuracy)?
- Does the model accurately reflect observed processes?
- Is the output from the forecast model useful (scale, timing, accuracy) for the stakeholder?
- Is this the most appropriate modelling approach for this context?

Considerations

Consider evaluating the operational systems capabilities to address how the technological forecasting chain can work in real-time. Think about using multiple evaluation metrics, to have a complete understanding of the model errors and uncertainties. Some evaluation metrics can be biased or can weight specific types of model predictions. Systematised and standardised evaluations are needed continuously; testing and evaluation should be a complementary part of the approach, accompanying it throughout its lifetime.

Approaches

- **Develop statistical and empirical relationship**: establish a statistically robust relationship between landslides occurrences and a triggering variable (e.g. rainfall).

- **Run and evaluate the model:** running the model in real time for several months allows for sufficient forecast data to be collated for future verification and case study assessment.
    - **Verification** should be completed at this stage (ideally objective verification if sufficient observations are available), otherwise a case study assessment may be needed.
    - Results can be used to **calibrate** the model where possible, which will feed into improved forecast output.

- **Feedback:** obtain feedback from stakeholders on the content and usefulness of the forecasts being produced.

- **Quantify uncertainties:** uncertainties will exist in any model, but these need to be acknowledged and examined — new data points not fitting in as expected or predicted does not mean the original model is wrong, but rather that there are uncertainties within it.

- **Adapt and update models**: based on an assessment of how well the model is behaving related to observations, adapt the model (calibrate) or change the approach based on needs and observations (an ongoing process).
    - **Calibration:** calibrate with new data that can tell you where the model might or might not need recalibration.
        - There are statistical techniques such as bootstrapping or Monte Carlo to resample the data to see uncertainties.
        - Models can change with changing land use and changing natural factors, so models will need recalibration from time to time,
    - **Alternative modelling approaches**: if the forecasts do not adequately reflect what is being observed, alternative forecast modelling approaches can be taken.
        - Consider new models — it is important to bring in models that are complementary (i.e. based on different assumptions).
        - It is not about 'different' models with the same approach but using different types of models that have very different approaches (e.g. statistical vs. parametric).
    - **Alternative visualisation approaches**: some model outputs are post-processed to aggregate information (e.g. gridded data) to a desired geographical unit (e.g. administrative boundaries) relevant to the user, with the aim of providing a more useful forecast or warning.
        - It may be necessary to adapt the visualisation and update the post-processing in cases where forecasts don't adequately reflect observations.
    - It is important to **evaluate all aspects of the forecast modelling chain** to understand where adaptations and updates might be most beneficial.

Example from LANDSLIP

The current LANDSLIP prototype landslide forecast models are applicable and reliable only within the project study areas, where they have been calibrated. GSI will continue to use the LANDSLIP approach to forecast landslides for the study sites beyond the end of the project.

Improvements or refinements by GSI to the landslide forecast models currently in use should be considered and could include:

- Making use of different rainfall data inputs (e.g. measured from gauges, estimation from radar networks).

- Using different weather forecasts (e.g. ensemble or probabilistic forecasts).

- Incorporating other landslide forecast models into the system (e.g. water balance model) or exploring forecasting approaches to more complex, multi-hazard interactions.

4 Exportability of the frameworks

As noted previously, conditions are very different from place to place. For any new landslide forecasting system to be set up, the steps in Section 3 need to be covered to choose the most appropriate forecast model for the setting. Replicating models or exporting them to a new area or region will be dependent on whether the new location has similar processes, data and stakeholder needs.

Exporting data-intensive modelling approaches (such as those used in more developed countries) in data-poor environments (such as in developing countries) without considering the framework outlined in Section 3 will likely lead to significant challenges, poor forecast skill, and unsustainable processes.

5 Evolving topic

As mentioned in Section 3, the information in this document is based on reflections from LANDSLIP team experiences. It is important to take the content of this paper as a suggested framework or starting point for considerations for developing an approach to landslide forecasting in developing countries. This is an evolving area of research and has potential application across the globe.

In the face of a rapidly changing climate and increased risk from landslides — and an associated increase in demand for LEWS in risk-prone, developing countries — this topic requires significantly more research, practice, and shared knowledge to guide better landslide forecasting in the future.

Further reading

LANDSLIP Knowledge Products
Introduction to Local Landslide Early Warning Systems
Introduction to Regional Landslide Early Warning Systems
Introduction to Landslide Early Warning Systems