LANDSLIP KNOWLEDGE PRODUCT:
Landslide Forecasting

Introduction

Nilgiris, Tamil Nadu, India. Credit: BGS © UKRI.

ABOUT LANDSLIP

Between 2016–2021, the LANDSLIP (LANDSLIde multi-hazard risk assessment, Preparedness and early warning in South Asia: Integrating meteorology, landscape and society) project, consisting of nine partners from India, the UK and Italy, developed a prototype landslide forecasting and early warning system in two regions of India, the Nilgiris and Darjeeling.

Through LANDSLIP (www.landslip.org), experts on landslide processes, meteorological forecasting, social science, data and science-to-practice, came together and collaborated with Indian national and district authorities, and local NGOs, to help build resilience to hydrologically related landslides in vulnerable and hazard-prone areas in India.

A suite of Knowledge Products (KPs) has been developed to capture the knowledge and learning generated by LANDSLIP. The KPs have been designed to be accessible and support practitioners, policy makers and programme managers (amongst others) in the development of current and future landslide forecasting and early warning across and beyond South Asia.

CONTENTS OF KNOWLEDGE PRODUCT

This KP focuses on landslide forecasting and contains the following sections:

INTRODUCTION TO THIS KNOWLEDGE PRODUCT

A landslide forecast provides an estimation of the likelihood of landslides occurring within a specific location and time period in the future. Regional-scale landslide forecasting systems rely on landslide forecasting models. The forecasting models developed in LANDSLIP focus on forecasting rainfall-induced landslides at a regional scale.They build on historical information about landslide occurrence and their associated rainfall trigger conditions in the two pilot study areas. LANDSLIP's prototype models run daily, and attempt to forecast the likelihood of landslides occurring in these study areas, given rainfall forecasts and information based on local landslide susceptibility.

This document provides an overview of the landslide forecast models used or explored by LANDSLIP. It describes the various approaches used, their main assumptions and limitations, and highlights model calibration and evaluation phases. It concludes with a summary of recommendations for others interested in landslide risk management, data management, decision-making and communication of risk.

WHY THIS TOPIC IS IMPORTANT

Landslide forecasting is central to the operation of LANDSLIP's regional scale landslide forecasting system. Knowledge of the underpinning modeling approaches, their assumptions and limitations, is critical for anyone wishing to understand how to develop or implement a similar system.

UKRI Natural Environment Research Council

Research funding from UK NERC and FCDO under the SHEAR programme grant LANDSLIP (Landslide multi-hazard risk assessment, preparedness and early warning in South Asia integrating meteorology, landscape and society). (Grant Numbers NE/P000681/1 NE/P000649/1).

Foreign, Commonwealth & Development Office


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Examples of typical landslides found within the LANDSLIP study areas.

LANDSLIP KNOWLEDGE PRODUCT: Landslide Forecasting

Part A: LANDSLIP forecasting models

LANDSLIP SHEAR

A1 OVERVIEW

LANDSLIP integrates multiple regional forecasting approaches operating over short- and medium-time ranges. Unlike slope scale approaches, which focus on forecasting instability of single landslides or single hillslopes, regional approaches aim to forecast possible landslide occurrences over larger areas using simplified empirically derived thresholds.

Empirical thresholds are defined using historical landslide occurrence data from inventories, combined with data on past meteorological and climatological conditions.

When operational, the LANDSLIP landslide forecast model will use weather forecasts provided by the Indian National Centre for Medium Range Weather Forecasting (NCMRWF).

Modelled landslide forecasts, for both the short and medium-range, are available to the Geological Survey of India (GSI) through a decision support dashboard.

A2 MEDIUM-RANGE LANDSLIDE FORECASTS

The medium-range forecast is based on an assessment of the most likely large-scale weather patterns and how these relate to landslide risk in Darjeeling and Nilgiris, based on historical assessment of daily observed weather patterns, rainfall accumulations and a landslide catalogue.

LANDSLIP research produced a set of 30 predefined daily weather patterns for India (Neal et al., 2020) which are representative of rainfall variability within different phases of the Indian climate. **Fig. A1** shows an example of two contrasting weather patterns and how their rainfall climatologies differ. These two weather patterns will represent different levels of risk when it comes to landslide occurrence at a given location.

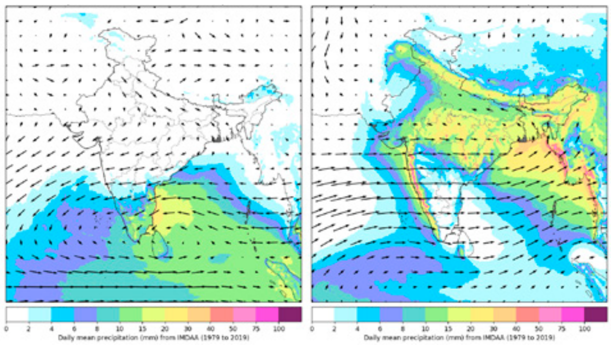

Figure A1 An example of two contrasting weather patterns showing mean wind and rainfall. Pattern 18 is a retreating monsoon type and Pattern 19 is an active monsoon type.

An historical assessment was completed to identify which weather patterns are most likely to lead to landslide occurrence. Over 100 landslide events were investigated with the observed rainfall accumulations assessed in the 15 days leading up to each event. High-risk weather patterns were then defined as those which contribute the most rainfall leading up to each event. This assessment was repeated across all events allowing for a final list of high-risk weather patterns to be derived, which differ between regions.

Within the forecasting tool, ensemble members (multiple forecast scenarios) from the 23 member NCMRWF and 51 member European Centre for Medium-Range Weather Forecasts (ECMWF) global ensembles are objectively assigned to the closest matching weather pattern. Daily forecast probabilities for each weather pattern are then based on the number of ensemble members assigned to each type.

Typically, early forecast lead times have high probabilities for a small number of weather patterns occurring, but as the lead time increases (e.g. from day 5 onwards) the number of forecast weather patterns increases. Forecasts are updated once daily for the NCMRWF model and twice daily for the ECMWF model and are presented as stacked probability bar plots for the purpose of interpreting the likelihood of high-risk landslide weather patterns occurring (**Fig. A2**).

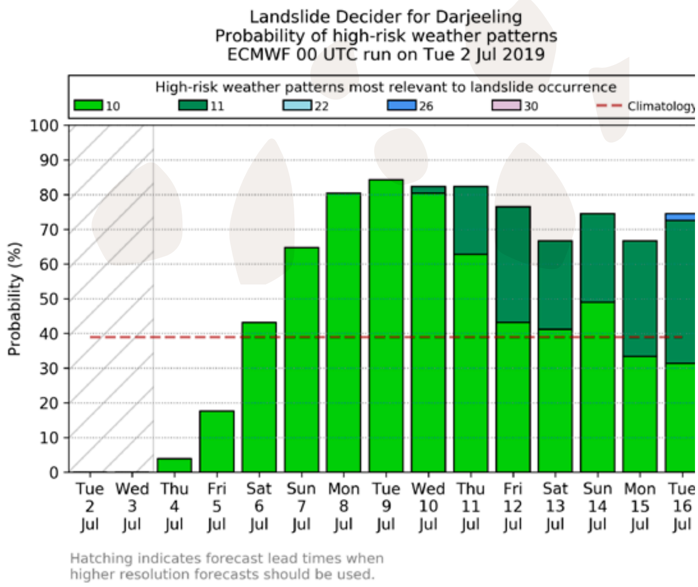

Figure A2 Probability of high landslide-risk weather patterns occurring at Darjeeling. Based on the global ECMWF ensemble initialized at 00 UTC on 2nd July 2019.

A3 SHORT-RANGE LANDSLIDE FORECASTS

LANDSLIP's short-range landslide forecast model (developed by CNR IRPI) calculates the probability of landslides occurring in a given rainfall scenario and builds on the landslide rainfall threshold concept (Rossi et al., 2012). The model, for a given forecasted combination of cumulative rainfall and rainfall duration, provides a Non Exceedance Probability (NEP) value. **Fig. A3** shows, through a graphic, how the probabilities expressed in % change for different duration and cumulative rainfall values in the NEP model.

Such a model requires calibration. This is conducted using information about the rainfall conditions that have historically been associated with landslides in the project area.

The landslide forecasting model produces daily landslide forecasts, as shown in **Fig. A4**. The model runs every day using the output of two deterministic rainfall forecast models made available by the Indian National Centre for Medium Range Weather Forecasting (NCMRWF) and calculates the NEPs corresponding to the next 24, 48 and 72 hours.

A specific forecasting algorithm, named Maximum Non Exceedance Probability (M-NEP), selects the maximum NEP values among those calculated for the different forecasting periods (**Fig. A4**), enabling GSI to identify the most critical rainfall conditions leading to landslides in the successive three days.

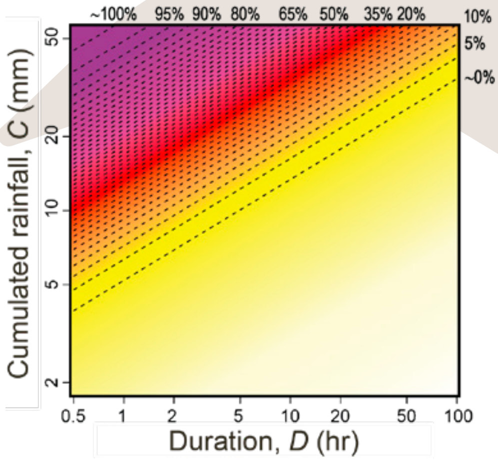

Figure A3 Graphical representation of the short-range landslide probabilistic forecast model. The model associates any *C* vs *D* rainfall condition measured or forecasted in an area, to a correspondent Non Exceedance Probability (NEP) value expressed in %.

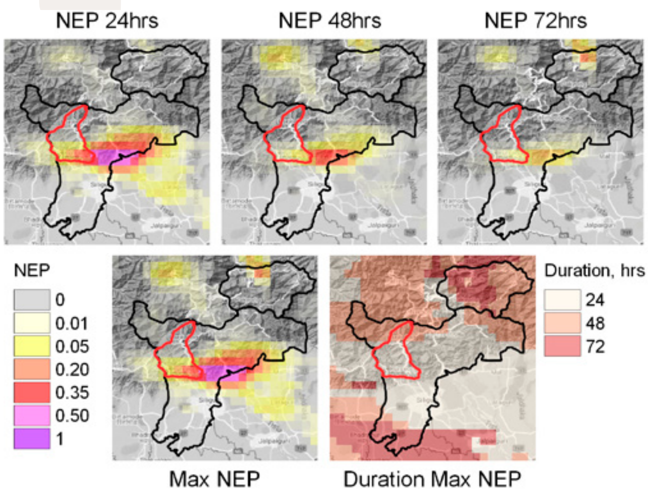

Figure A4 Example of the Maximum Non Exceedance Probability algorithm outputs in the Darjeeling area.

The short-range and medium-range forecasts inform the creation of a landslide bulletin which is distributed to key downstream users such as the District Administrator. The short range forecast NEP values, produced for each pixel in the study area, are interpreted (by GSI), along with additional ancillary data, such as the susceptibility maps, and Standard Operating Procedures (SOPs) to determine a landslide forecast warning level ('Low' through to 'Very High'). The higher NEP values in the short term forecasts correspond to an increased probability that the forecasted rainfall conditions will lead to landslides in those areas.

The warning level is used in the landslide bulletin to reflect the potential for landslides to occur in the next 48 hours. The bulletin also includes a text summary of the medium range forecast.

A4 REFERENCES

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Rossi M., Peruccacci S., Brunetti MT., Marchesini I., Luciani S., Ardizzone F, et al. 2012. SANF: a national warning system for rainfall-induced landslides in Italy. In: Eberhardt E, et al. (eds) Landslides and engineered slopes: protecting society through improved understanding. Taylor & Francis Group, London, pp 1895–1899. https://doi.org/10.13140/2.1.4857.9527.

LANDSLIP KNOWLEDGE PRODUCT:
Landslide Forecasting

Part B: Landslide susceptibility mapping

B1 OVERVIEW

Landslide susceptibility maps provide an estimate of *where* landslides are more likely to occur. They complement the forecast models that estimate *when* landslides are likely to occur.

Susceptibility maps can depict areas which are more landslide prone but do not provide an estimate of the magnitude of the potential event or the likely timescale of failures occurring. If an area is subject to a variety of landslide types then multiple different susceptibility maps may be required.

The key factors to produce and use a landslide susceptibility map are outlined in this section (Part B) of the Knowledge Product.

B2 PRODUCING A LANDSLIDE SUSCEPTIBILITY MAP

"Landslide susceptibility is the likelihood of a landslide occurring in an area on the basis of the local terrain and environmental conditions (Brabb, 1984)".

A variety of techniques for producing a landslide susceptibility map exist in the literature, from qualitative assessments to fully quantitative methods. Experts from within the consortium agreed that when determining the appropriate technique, it is necessary to consider a number of factors:

- The size of study area will influence the approach. Is your study area a single slope, a catchment or national scale?
- The types of landslides occurring in the study area (e.g. rockfall, shallow rotational landslides, debris flows). Different types of landslides will have different driving and conditioning factors.
- The availability of resources can determine the approach taken for example, how much computing power and time is there to complete the work? Does the team have the required skills and knowledge?
- The data available to perform certain techniques may eliminate approaches which are data intensive or require many input parameters. A good quality, spatially representative, landslide inventory is an essential requirement of many landslide susceptibility maps.
- The complexity and variation across a study area will impact on the applicable technique.

Qualitative approaches such as heuristic assessments and geomorphological analysis can be utilised at a regional scale; neither approach is reliant on a complete landslide inventory. These techniques will rely heavily on available expertise and the results have a high level of subjectivity.

Quantitative methods, which include statistical (bivariate or multivariate) and deterministic/process based methods, are more objective, relying less on expert judgement but require a large quantity of input data and subsequent processing.

B3 THEMATIC VARIABLES

Alongside a landslide inventory it is also necessary to consider carefully the other thematic data layers that are included within the susceptibility analysis. Knowledge of the local conditioning and triggering factors is essential and only those relevant to the study area should be included.

Commonly considered thematic data in a susceptibility model include morphometric variables (slope angle (**Fig. B1**), slope aspect curvature), geological variables (Lithology, structure) and hydrological variables (distance to streams, TWI, SPI). Other locally important variables may include land cover/land use, distance to roads and precipitation.

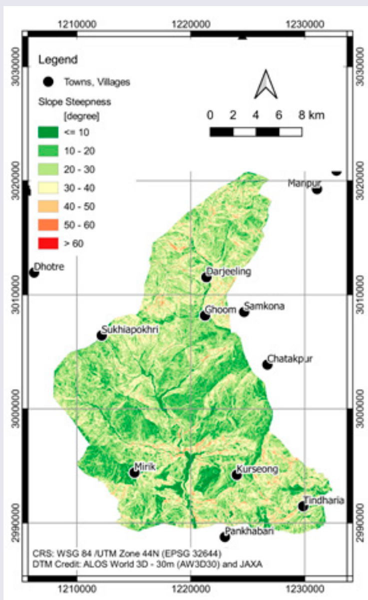

Figure B1 Example slope map.

B4 LANDSLIP: SUSCEPTIBILITY MAPS

The landslide susceptibility maps produced in conjunction with the Geological Survey of India as part of LANDSLIP show where landslides are most likely to occur based on the underlying conditioning factors. A high landslide susceptibility rating for an area does not necessarily mean a landslide has already occurred, it indicates future landslides are more likely to occur compared to lower susceptibility areas.

Different regions are often subject to multiple types of landslide processes (slides, falls, flows) and these are represented through different susceptibility maps. LANDSLIP produced susceptibility maps for each of these landslide processes. Morphometric and geological conditioning factors differed for each process and it was necessary to incorporate debris flow runout and rockfall trajectory into the modelled outputs.

B5 LANDSLIP'S DARJEELING PILOT AREA

The Darjeeling area is subject to intense monsoon rains and active seismicity which along with the steep slopes and geological conditions have resulted in a number of different landslide types impacting the region. The open source software LAND-SE (Rossi et al. 2016) was utilised to produce a map depicting the region's susceptibility to slides. LAND-SE combines the results from a number of statistical methods to produce a single landslide susceptibility map (**Fig. B2**) The output of this for the Darjeeling area highlights the increased potential for slides to occur in the steeply dissected hills and valleys formed over metamorphic rocks. Debris flow susceptibility in the region was modelled using r.randomwalk (Mergili et al., 2015). This software depicts the expected run out of the failure which can be several hundreds of meters (**Fig. B3**).

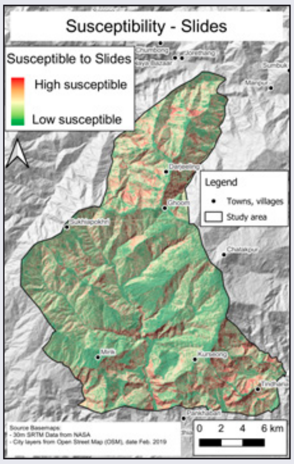

Figure B2 Slide susceptibility, Darjeeling.

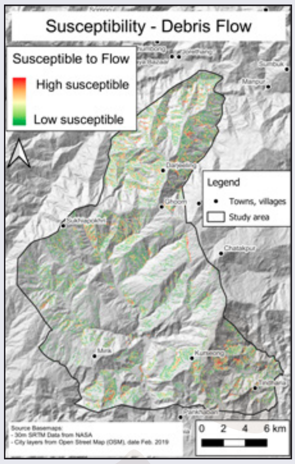

Figure B3 Debris flow susceptibility, Darjeeling.

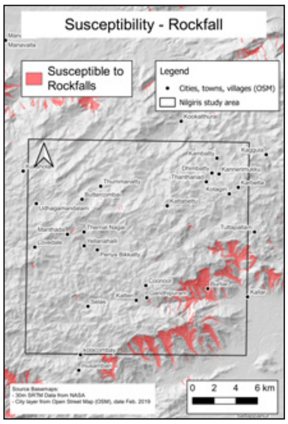

Figure B4 Rockfall susceptibility, Nilgiris.

B6 LANDSLIP'S NILGIRIS PILOT AREA

In the Nilgiris, landslides (particularly debris/earth slides or flows) are most common during the retreating monsoon season (October-December).

Debris flow susceptibility was modelled using the conceptual model r.randomwalk and the results highlight the steep scarp slopes that separate the plateau from plains below as particularly susceptible to debris flows. A number of these types of failures have been reported along the National Highway 67 (NH67), the route which traverses the susceptible region.

Alongside models for debris flows and slides the physically based model STONE (Guzzetti et al. 2002) was used to assess rockfall susceptibility and to identify where rocks may land if they were to become detached from a rock face. **Fig. B4** shows the resultant areas where rockfall is likely to occur and the trajectory of the detached material, which in the study area is predominantly focused on the scarp slopes of the plateau.

B7 REFERENCES

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LANDSLIP KNOWLEDGE PRODUCT:
Landslide Forecasting

Part C: Developing landslide rainfall thresholds

C1 OVERVIEW

Landslide forecasts quantify the likelihood of landslide occurrence in a given area at a given time for a given rainfall scenario.

LANDSLIP's prototype landslide forecasting model calculates Non-Exceedance Probabilities (NEPs) for landslide occurrence using empirical rainfall thresholds.

Empirical thresholds rely on statistical approaches based on historical landslide catalogues and rainfall series, and define the lower bound of known rainfall conditions that have resulted in landslides (**Fig. C1**). Defining accurate thresholds for small geographical areas requires robust information about the temporal and geographical location of rainfall-induced landslides as well as reliable rainfall measurements obtained from dense rainfall gauge networks.

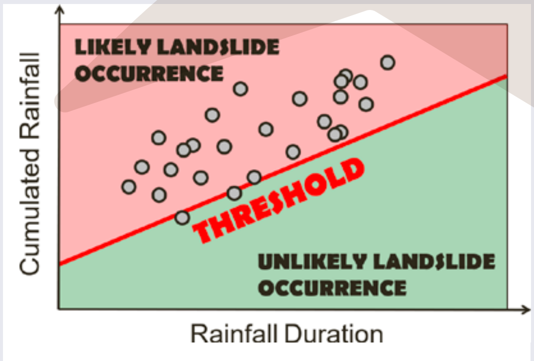

Figure C1 Threshold scheme for cumulative rainfall vs rainfall duration.

C2 DETERMINING THRESHOLDS

Cumulated rainfall event duration (*ED*) thresholds were defined adopting the frequentist method (Brunetti et al., 2010 and Peruccacci et al., 2012). Essential parameters for the creation of these thresholds include *E* the cumulated (total) rainfall (in mm) and *D* the rainfall duration (in hours). A bootstrap statistical technique is used to account for uncertainty in the threshold calculation.

C3 METHODOLOGY

The R, open source algorithm, CTRL-T (Melillo et al. 2018) was used to determine the rainfall conditions responsible for triggering landslides. CTRL-T exploits continuous rainfall measurements, and landslide occurrence information, to: (i) reconstruct rainfall events; (ii) automatically select representative rain gauges; (iii) identify multiple (D, E) rainfall conditions responsible for failure; (iv) attribute a probability to each rainfall condition; and (v) calculate rainfall thresholds at different NEP, and their associated uncertainties. For example, the 5% NEP threshold curve should leave 5% of the empirical (*D,E*) pairs below the curve.

Fig. C2 illustrates the logical framework of CTRL-T. Input data includes: setting parameters; rainfall data; rain gauge locations; landslide locations; landslide occurrence times. The algorithm is divided into three main logical blocks. 'BLOCK 1' executes the reconstruction of the rainfall events. 'BLOCK 2' selects the rainfall events that have resulted in landslides and determines the rainfall duration *D* and the cumulated event rainfall *E* responsible for the landslides. 'BLOCK 3' calculates rainfall thresholds at different NEPs.

Single rainfall events are reconstructed separating two consecutive events by considering a dry period of two days. Rainfall conditions are then reconstructed from data recorded by rain gauges located in a circular buffer with a parametrised radius from each landslide. Rainfall measurements are obtained from regional rain gauge networks. The selection of the rain gauge, depends on the number of available time series, the data quality and the location of the rain gauge, given that these characteristics are crucial to model the spatial and temporal variation of the precipitations. Using this method and the CTRL-T tool, objective and reproducible thresholds at different NEPs can be calculated for different pilot areas.

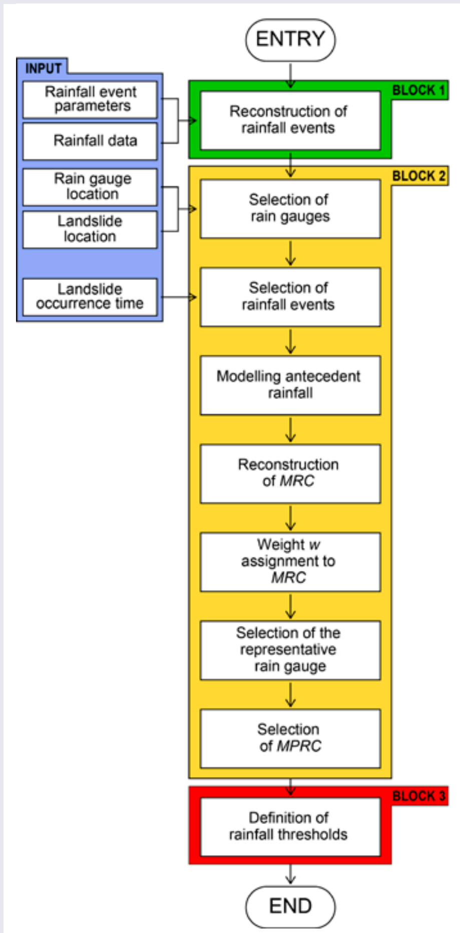

Figure C2 Logical framework of the algorithm in CTRL-T.

C4 THE DARJEELING PILOT AREA

For the Darjeeling pilot area, daily rainfall data recorded by 37 rain gauges from 01/01/1959 to 31/12/2017 and information on the occurrence of 684 landslides from 04/10/1968 to 06/07/2015 are used (**Fig. C3**).

Fig. C4 shows, in logarithmic coordinates, the distribution of the (*D,E*) rainfall conditions that have caused landslides in Darjeeling (84 blue dots), and the rainfall threshold at 5% NEP with the related equation. Landslides were associated with rainfall events ranging from 1 to 8 days.

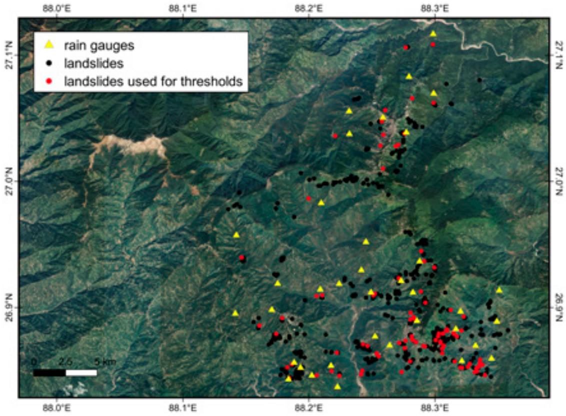

Figure C3 Map of landslides and rain gauges in Darjeeling. Satellite imagery from Google Earth.

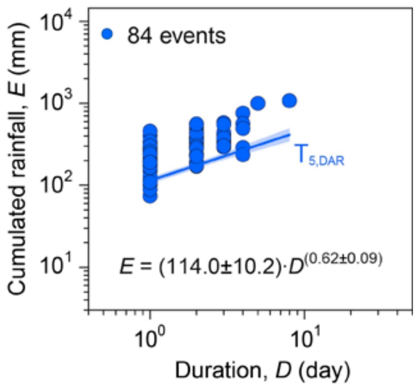

Figure C4 *ED* rainfall conditions that have produced landslides in Darjeeling pilot area (84 blue dots). Blue curve is 5% power law threshold for Darjeeling (T5,DAR). The shaded area shows the uncertainty associated with the threshold curve. Data are in logarithmic coordinates.

C5 THE NILGIRIS PILOT AREA

For the Nilgiris pilot area, daily rainfall data recorded by 29 rain gauges from 01/01/1987 to 31/07/2017 and information on the occurrence of 392 landslides from 15/12/1987 to 31/12/2017 are used (**Fig. C5**).

Fig. C6 shows, in logarithmic coordinates, the distribution of the (D,E) rainfall conditions that have caused landslides in Nilgiris (116 green dots), and the rainfall threshold at 5% NEP with the related equation. The rainfall duration associated to the landslide ranged from 1 to 6 days.

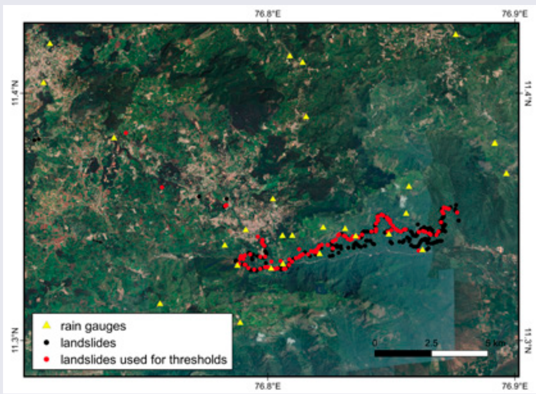

Figure C5 Map of landslides and rain gauges in Nilgiris. Satellite imagery from Google Earth.

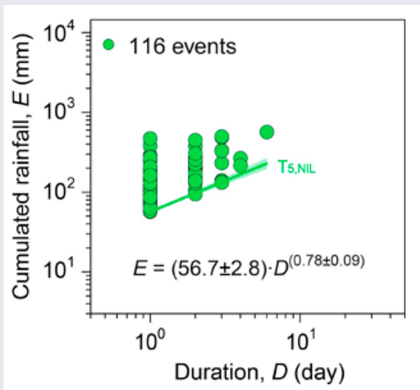

Figure C6 *ED* rainfall conditions that have produced landslides in Nilgiris Pilot area (116 green dots). Green curve is 5% power law threshold for Nilgiris (T5,NIL). The shaded area shows the uncertainty associated with the threshold curve. Data are in logarithmic coordinates.

C6 REFERENCES

Brunetti, M.T., Peruccacci, S., Rossi, M., Luciani, S., Valigi, D. and Guzzetti, F. 2010. Rainfall thresholds for the possible occurrence of landslides in Italy. *Nat. Hazards Earth Syst. Sci*. 10:447–458. https:\\doi:10.5194/nhess-10-447-2010.

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LANDSLIP KNOWLEDGE PRODUCT:
Landslide Forecasting

Part D: Water-balance model for landslide trigger thesholds

D1 OVERVIEW

Forecasting rainfall-induced landslides is a challenging task owing to the complexities and uncertainties surrounding trigger (e.g. precipitation, groundwater) and conditioning factors (e.g. geology, soil types, geomorphology, landuse). Understanding the mechanisms which lead to slope failures can help lead to better management of landslide hazards. A conceptual Water Balance Model (WBM) provides an alternative to more complex, hydrological models that can be used to develop landslide trigger thresholds. A WBM can be particularly useful when developing a LEWS in a data-limited region.

This section (Part D) of the Knowledge Product provides a high-level overview of the water balance approach based on the BGS experiences of working with water balances to forecast shallow landslides at a regional scale.

Ooty Municipality. Credit: @ Keystone.

D2 DEVELOPING TRIGGER THRESHOLDS FOR LEWS

A trigger threshold is defined as the conditions at or above which the meteorological or hydrological factors will initiate landslides. A trigger threshold can be developed using either meteorological only or hydro-meteorological variables. Several studies have shown that the initiation of shallow landslides is very much dependent on the slopes soil moisture history, which may range from one to 30 days subject to the soil type. A simplified conceptual water balance (WBM) can be used to develop a trigger threshold in combination with forecasted rainfall amount.

D3 WHAT IS A WATER BALANCE MODEL?

A WBM is a hydrological model based on the concept that the amount of water within a hydrological system is equal to the difference between the amount of water entering and the amount of water exiting the system. WBMs help estimate the amount of soil moisture in a system (**Fig. D1**).

A WBM for landslide modelling can be developed around the concept of two buckets within the soil column of a given depth, the volume of which depends on the soil type. One bucket represents the macropores; the other, the micro pores. The macropore bucket allows water to freely drain with limited storage capacity, whilst the micropore bucket can store greater amount of water (or moisture).

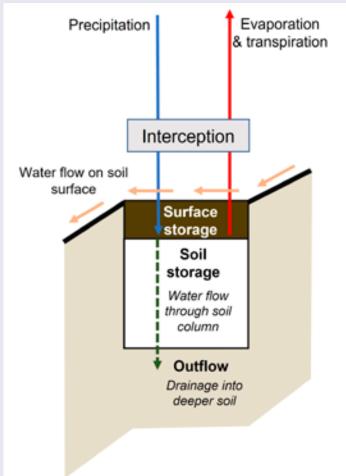

Figure D1 Illustration of conceptual hydrological model. Figure © BGS-UKRI.

D4 HOW CAN A WBM BE USED WITHIN A LANDSLIDE EARLY WARNING SYSTEM (LEWS)?

Forecasting 'when' a landslide might occur needs a good understanding of the relationship between the landslide trigger (in this example, water) and the landslide failure mechanism. Near-surface first-time shallow landslides on natural slopes can be initiated during rainfall due to different mechanisms e.g. variations in groundwater flows, perched (temporary) groundwater table, or reduction in bonding strength (owing to surface tension) between the soil particles. A WBM adopted for any of the aforementioned landslide mechanisms which affect the pilot study areas, can be used to determine the trigger threshold to estimate landslide initiation.

A conceptual WBM, based on soil moisture, for rainfall induced shallow landslides provides a simpler alternative to other, more complex, hydrological models for developing landslide trigger thresholds as they generally involve fewer parameters for calibration. This is useful when developing a LEWS in a data-limited region and can be applied to a wide area.

D4 HOW TO DEVELOP A WBM

An approach, developed by the British Geological Survey, will be used as a case study to describe how a WBM can be developed. The BGS WBM estimates soil moisture on a daily basis at a national scale. Hydrological threshold development for shallow landslides involves two key stages:

STAGE 1: Setting up a WBM

The WBM is setup using the following input datasets:

- Meteorological datasets (rainfall, temperature, and relative humidity) from rain gauge station.
- Soil types
- Saturated and partially-saturated soil properties (saturated hydraulic conductivity, soil water characteristics curve (SWCC), porosity).
- Ground-water table depth.

The water storage capacities for the two buckets are determined using the saturated and partially-saturated soil parameters. These values can to some extent be estimated using existing soil database or through lab tests. The calibrating factors, however, would need to be adjusted using expert judgement by a landslide expert with hydrological background. It is recommended that the WBM is run using at least a years' worth of meteorological data as this will decrease the sensitivity of the estimated soil moisture outputs to the assumed starting soil moisture value.

STAGE 2: Establishing the trigger threshold

The trigger threshold is developed using a normalised rainfall data and soil moisture (WBM output) using information of landslide occurrence dates. A landslide inventory, with initiation date and location, is essential for threshold calibration and validation. Information regarding landslide location is used to assign the appropriate soil type and the nearest rain gauge for WBM calibration. A normalised rainfall value on the date of landslide occurrence, and soil moisture one-day prior to the landslide event day is also required to establish the threshold. The results are plotted on a graph along with the next day's rainfall and soil moisture data. Empirical, statistical, or probabilistic approaches can also be used to create the threshold curves.

For an operational system, observed daily meteorological data from the rain gauge or radar (rainfall, temperature, and relative humidity) in-addition to the forecasted meteorological data will also be required.

D6 CONSIDERATIONS AND LIMITATIONS

Long-term assessment of a WBM approach and its triggering thresholds against field observations can help landslide experts better understand the performance of the model for diverse soil types in different seasons (e.g. summer, monsoon, winter). In the short-term, a sensitivity analysis of model parameters would support better management of output uncertainties.

- A preliminary evaluation of the trigger threshold should be carried out against a landslide inventory not utilised in threshold development.
- The WBM's application is limited to near-surface homogenous soil and only models water movement in one-dimension (vertical flow). Further, the trigger thresholds are valid only for first-time landslides.
- The established trigger thresholds need to be integrated with the calibrated WBM and the forecast systems.
- The WBM should be run 24-hr prior to integrating its outputs with the forecast models.
- The operationalised threshold provides a likelihood of landslide initiation corresponding to the forecast data.
- The WBM and its trigger threshold performance need to be monitored and evaluated over time.

D7 PREREQUISITES SKILLS FOR DEVELOPING A WBM

At least Master's level knowledge of hydrology and soil mechanics, and Master's level knowledge of statistics is required to develop the WBM and trigger threshold, given its complex environmental modelling methodological framework.

LANDSLIP KNOWLEDGE PRODUCT: Landslide Forecasting

Part E: Evaluating landslide forecasts

E1 OVERVIEW

One-off and routine evaluation is a critical step in forecast model design and implementation. It enables model developers to monitor and improve forecast quality and compare different models and forecast systems. Evaluation provides information on the performance and quality of the model which is essential for both users and developers.

Evaluating the performance of LANDSLIP's prototype regional landslide forecasting system requires two different forms of evaluation. The first aims to answer the question 'How good is the landslide forecast model?' in terms of accuracy, skill and reliability. This requires forecasts to be compared against corresponding observations of what actually occurred during the forecast period. The second is an evaluation of the value of the forecasts and reviews the dissemination, communication, usability and interpretability by users.

This section (Part E) of the Knowledge Product will discuss the importance of evaluating the landslide forecast model performance and discuss approaches for evaluation.

Mahakal dara. Credit: © SaveTheHills.

E2 TYPES OF EVALUATION

The prototype regional landslide forecast models developed in LANDSLIP are underpinned by rainfall forecasts. Rainfall forecasts are routinely verified against rainfall observations by National Meteorological and Hydrological Services and issuing organisations (e.g. the National Centre for Medium Range Weather Forecasting (NCMRWF)) and therefore this element of evaluation is not discussed here.

Evaluation of the Landslide Forecast models

Landslide forecast evaluation quantifies the degree of correspondence between landslide forecast models and landslide observations. The quality of landslide forecast models needs to be evaluated before they become integrated into an operational Landslide Early Warning System (LEWS). Evaluation enables model calibration (process of configuring a model) to take place to minimize errors and optimize components (e.g. trigger thresholds) to address specific performance targets determined by the developer or user. In addition to this initial evaluation, models need to be routinely evaluated so that model performance can be tracked and improved upon as needed.

The choice of appropriate evaluation metrics depends on the type and format of the landslide forecast model. Binary deterministic forecasts, often expressed as dichotomous (yes/no) forecasts of landslide occurrence, are evaluated with contingency tables and the relative binary classifications (e.g. True Positive Rate).

Probabilistic landslide forecasts require more complex metrics. It is difficult to verify a single probabilistic forecast and therefore sets of probabilistic forecasts are usually compared using sets of observations indicating whether events occurred or did not occur. Typical probabilistic metrics include reliability diagrams, the Brier Skill Score and Relative Operating Characteristic (ROC), all of which provide different insights into the accuracy of probabilistic forecasts. In LANDSLIP a range of metrics will be used to quantitatively evaluate the landslide forecast models within monsoon periods.

Evaluation of the Landslide Forecast Value

An evaluation of forecast value reviews how effectively the model is operationalised; it is vital that forecasts are disseminated in a timely fashion to allow for communication of the landslide warning and implementation of any mitigating actions. As part of any LEWS there needs to be an evaluation of how the information is received by the intended target audience and whether the information that is produced is understandable, and therefore actionable, by the target audience and in turn actionable. A robust and continuously updated Standard Operating Procedure (SOP) should capture the flow of information and be evaluated to ensure that warning issuance works under a broad range of circumstances.

E3 DATA COLLECTION FOR LANDSLIDE FORECAST EVALUATION

To assess model performance a key requirement is reliable observation data on the spatial and temporal occurrence of landslides. Such information can be collected through field mapping but increasingly new technologies are being utilised to enable the routine and robust collection of observed landslide events (e.g. citizen and data sciences methods and remote sensing).

Standard processes for observation data collection and management, sustainable over a long period, are critical and need to be defined and incorporated within the LEWS design phase. LANDSLIP has developed and adopted multiple approaches for collecting landslide occurrence data based on:

- Field surveys and investigations;
- Searching chronicles and administrative technical archives;
- Crowdsourcing data collection via mobile and web-based apps;
- Unstructured social data searching;
- Remote sensing detection and mapping (**Fig. E1**).

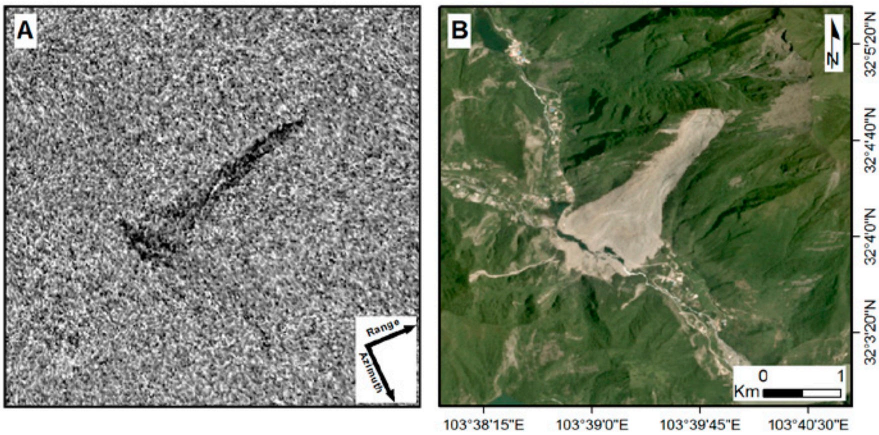

Figure E1 Example of a landslide detected from remote sensing data through to analysis of SAR amplitude changes (A) and optical images (B). Figure provided with permission of A. Mondini and adapted from *Remote Sens*. **2019**, 11(7), 760; https://doi.org/10.3390/rs11070760.

The LANDSLIP project has developed a conceptual tool to collect and use historical and real-time social media data, such as Twitter and online news articles, to gain landslide-related information. Alongside this a landslide tracker App has been developed to allow crowdsourcing of landside data and a methodological framework was developed which contextualises relevant information about landslides from Twitter and then attempts to retrieve additional information that could support pre-event detection (refer to LANDSLIP Knowledge Product 2: Landslide Data for Regional LEWS).

Not all landslide events will be in populated areas and as such these events may be less likely to be recorded in an app or on social media. To counter this issue an approach was developed utilising Synthetic Aperture Radar data to automatically detect changes in amplitude that can be related to landslides. The automation of this would allow for rapid mapping post event to increase the inventory of landslides that can be used to evaluate forecasted results.

E4 FORECAST VALUE—INCORPORATING USER FEEDBACK

Evaluation of how the forecast is received, understood and actioned is an integral pat of the process of developing a LEWS. If the forecast is not delivered in a timely fashion then the information cannot be actioned appropriately and the forecast is of limited use. Development of a SOP, considered a live document which requires updating, alongside a series of Responsible Accountable Consulted Informed (RACI) model diagrams ensures the forecast reaches its intended target, and that the lines of communication, roles and responsibility of all partners is identified at each step of the process.

During the research phase of LANDSLIP, when the forecasts were being developed and refined, a series of meetings between the District Authorities and the consortium team were held to discuss the format of the bulletin, how the data was being interpreted and actioned as well as outlining the limitations of the current forecasts. Pre- and Post-Monsoon workshops were also held with the District Authorities during the research phase, gaining important feedback on how the DC understood and interpreted the prototype bulletins. This user feedback highlighted areas for refinement of the bulletin.

LANDSLIP KNOWLEDGE PRODUCT:
Landslide Forecasting

Conclusion and recommendations

SUMMARY

LANDSLIP harnessed data from a variety of sources (weather forecasts, landslide information, susceptibility models) to produce an assessment of landslide likelihood in the short- and medium-term (up to 15 days) in the the Darjeeling and Nilgiris pilot areas. Designed to support the Geological Survey of India (GSI) prepare forecast bulletins, these prototype landslide forecast models ran each day during the summer monsoon period (June to September) in 2020 and 2021. The models drew upon weather forecasts provided by the Indian National Centre for Medium Range Weather Forecasting (NCMRWF) and were calibrated against historic data on landslide occurrence and antecedent rainfall conditions.

KEY LEARNINGS

- An effective landslide forecasting model is a fundamental component of the LANDSLIP Landslide Early Warning System (LEWS). A number of different modelling approaches can be taken to produce a landslide forecast.
- The LANDSLIP model comprises short- and medium-range forecasts on landslide occurrence (spatial and temporal) developed using past landslide events alongside meteorological and climatological conditions. Landslide susceptibility maps/zonations complement these forecasts, providing information on where landslides are most likely to occur due to the natural ground conditions.
- An interdisciplinary team, with a range of expertise that included meteorology, landslide process science, programming/data science and earth observation, was required to develop the models.

RECOMMENDATIONS

Landslide forecasting models require ongoing evaluation, assessing both forecasting and operative capabilities. This evaluation relies upon standardised and sustained landslide data collection and data management capabilities that need to be embedded and resourced in the system for the long-term.

LIMITATIONS AND OUTSTANDING CHALLENGES

- The current prototype landslide forecast models are applicable and reliable only within the project study area, where they have been calibrated. As with any regional landslide forecasting system, the forecast products cannot be used to predict the exact location or timing of a landslide at a site specific scale but rather they are used to express the likelihood of landslide occurrences over larger areas within a given time scale.
- Ongoing model evaluation and refinement is essential for model improvement. This must be supported by systematic collection and management of landslide occurrence data.

Improvements or refinements to the landslide forecast models used in LANDSLIP should be considered and could include:

- Different rainfall data inputs (e.g. measured from gauges, and/or estimation from radar networks);
- Different weather forecasts (e.g. ensemble or probabilistic forecasts);
- Incorporating other landslide forecast models into the system, such as a water balance model, and/or exploring forecasting approaches to more complex multi-hazard interactions.

FURTHER READING

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CITATION

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