LANDSLIP KNOWLEDGE PRODUCT:
Meteorological Data

Introduction

Newar Goan, Bhalukhop Kalimpong. Credit: © SaveTheHills.

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 PIECE

This KP focuses on the meteorological data requirements for the development of regional Landslide Early Warnings Systems (LEWS) and contains the following sections:

- Introduction (this page).
- Part A: Overview — Observation data.
- Part B: Overview — Forecast data.
- Part C: Short-range landslide forecasting.
- Part D: Medium-range landslide forecasting.
- Conclusion and recommendations.

INTRODUCTION TO THIS KNOWLEDGE PRODUCT

LEWS for rainfall-induced landslides require meteorological data inputs. Meteorological data for LEWS typically falls under two categories: (1) historical observation data and (2) forecast data, which can be used in forward modelling to forecast the potential occurrence of future landslides.

This KP provides an overview of the meteorological data used in LANDSLIP. Part A and Part B provide an overview of observation and forecast data, respectively, while Part C and Part D describe how these datasets have been used to develop short-range (out to 3-days ahead) and medium-range (out to 15-days ahead) landslide forecast applications respectively.

This document provides an overview of the key considerations when using meteorological data for regional LEWS development. Based on the experiences of developing the two LANDSLIP forecast products, the variability, accessibility and processing considerations of using different types of meteorological data will be described. The final section provides recommendations for others interested in using meteorological data for the development of operational LEWS.

WHY THIS TOPIC IS IMPORTANT

Meteorological data is a key requirement for the development of operational LEWS. Those developing LEWS need to be aware of meteorological data requirements. Many of the datasets that are useful for landslide forecasting and monitoring are managed by national meteorological agencies. These institutions also hold a wealth of information on the performance, upgrades, limitations and benefits of different sources of meteorological information.

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

Examples of typical landslides found within the LANDSLIP study areas.

LANDSLIP KNOWLEDGE PRODUCT: Meteorological Data

Part A: Overview — Observation data

A1 OVERVIEW

Regional Landslide Early Warning Systems (LEWS) for rainfall-induced landslides rely upon meteorological observation data. Data on rainfall events associated with past landslide events is critical for understanding the rainfall characteristics that lead to different types of landslide events and how these characteristics may vary across different geographic areas and at different times of the year. Historical analysis of landslides and meteorological data enable predictors to be identified that are used to forward model the potential for future landslide occurrences.

This section (Part A) of the Knowledge Product provides an overview of the observation data that underpins the short-range and medium-range landslide forecasts applications.

Nilgiris, Tamil Nadu, India. © SavetheHills.

A2 OBSERVATION DATA

Meteorological observations are critical for developing landslide forecasts. They can be used in two ways: (1) historical observations can be used to understand relationships between meteorological variables and landslide occurrence, to produce trigger thresholds, and (2) real-time observations can be used for very short-range forecasting, referred to as nowcasting, and situational awareness. Within LANDSLIP, research has focused on the former. The key weather variable used within the LANDSLIP project is rainfall, however it is recognised that other variables may be additionally useful as predictors for future landslide events.

Gauge Data

A favoured source of historical observation data, particularly for precipitation and temperature, are from observing sites. Where rain gauges are managed by national meteorological agencies rainfall accumulation observations are measured using predefined procedures and standards. Gauge-based observations provided by the Indian Meteorological Department (IMD) were used in the LANDSLIP project and supplemented with gauge data from Tea Garden Estates to improve the spatial density of observing sites across the two pilot areas. Low spatial coverage can reduce the ability of gauge data to capture rainfall variability. A total of 37 rain gauges were used at the Darjeeling test site and 29 at the Nilgiris test site.

Gridded Observations

The IMD also provided an India-wide gridded precipitation dataset (Pai et al., 2014) that provided daily rainfall accumulation observations at a spatial resolution of 0.25 degrees x 0.25 degrees, covering more than a 100-year period from 1901 (**Fig. A1**). Data from 6955 gauges were interpolated (process of using known data points to estimate values at unknown points) to fixed spatial grid points following quality control tests, to provide a spatially and temporally consistent dataset. These datasets are very appealing for landslide analysis because of their consistency and coverage (all of India), increasing the transferability of methods beyond the case study areas of LANDSLIP. However, the process of interpolation, the spatial availability of gauges used, and the grid resolution of the data can influence the datasets ability to accurately observe high intensity and localised rainfall events. Gridded observation data offers temporal (e.g. length of record) and spatial (e.g. grid resolution) consistency which is often not available from gauge data.

Reanalysis Data

A further source of gridded information is reanalysis data, which is often used in a similar way to the above mentioned observations, but are actually a blend of observations and past short-range weather forecasts which are re-run using current Numerical Weather Prediction (NWP) model configurations and data assimilation methods. They provide a consistent and typically, long record of snapshots of atmospheric conditions over time and have broad geographical coverage (e.g. global). In LANDSLIP, a range of reanalysis datasets have been used including ERA-Interim (**Fig. A2**) at 80 km grid resolution (Dee et al., 2011), now superseded by ERA5. ERA5 provides hourly estimates of a range of atmospheric variables at 30 km grid resolution, for the period 1950 to present. It should also be noted that the National Centre for Medium Range Weather Forecasting (NCMRWF) and Met Office, in collaboration with the IMD, have recently developed a regional reanalysis for the Indian Subcontinent referred to as the Indian Monsoon Data Assimilation and Analysis (IMDAA; Ashrit et al., 2020) which runs from 1979 to present and provides daily data for a range of atmospheric variables at 12 km grid resolution.

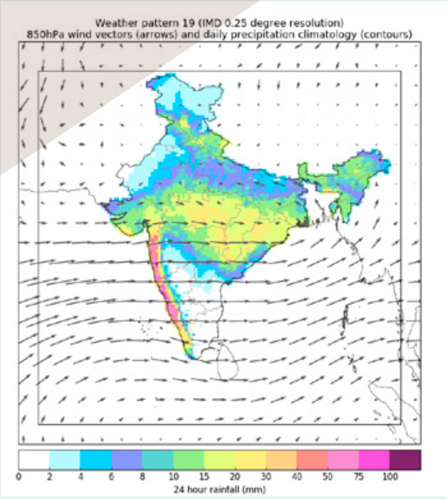

Figure A1 Mean daily rainfall under all days which experience this specific active monsoon circulation (weather pattern 19), using IMD 0.25 resolution gridded rainfall observations.

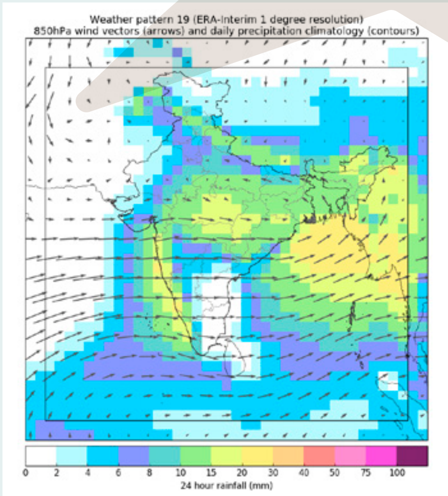

Figure A2 Mean daily rainfall under all days which experience this specific active monsoon circulation (weather pattern 19), using ERA-Interim 1.0 resolution global reanalysis data.

Satellite Data

Satellite data has not been used to develop the two forecast applications produced in LANDSLIP. However, CMORPH (Climate Prediction Centre Morphing Technique) data has been used to assess incidents of cloudbursts in India and compare meteorologically defined cloudburst events with those reported by the media.

A3 CONSIDERATIONS WHEN SELECTING OBSERVATION DATA

There are several important considerations when selecting gauge-based data for use in landslide analysis:

- 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,
- where possible 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), and
- where multiple gauge-based sources are used, it is important to consider differences in reporting procedures (i.e. manual vs automated recording; daily vs sub-daily reporting), format (e.g. written vs electronic) and availability (e.g. ad hoc vs routine).

For gridded 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 (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.

A4 REFERENCES

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LANDSLIP KNOWLEDGE PRODUCT: Meteorological Data

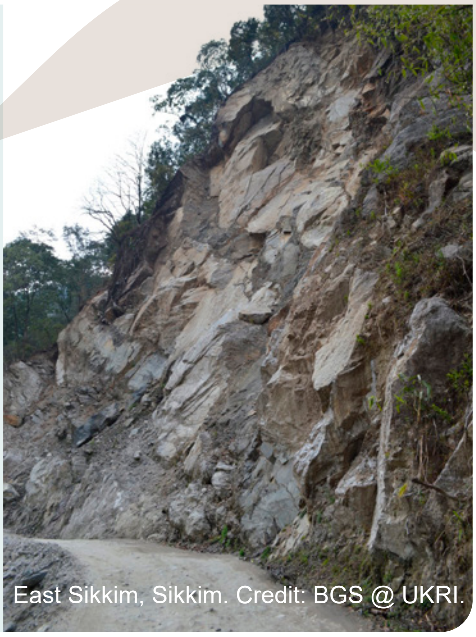
Part B: Overview — Forecast data

B1 OVERVIEW

Forecasting the likelihood of future rainfall-induced landslides requires information on what the future weather is likely to be. Numerical Weather Prediction (NWP) models use current weather observations and mathematical models to forecast the future state of the atmosphere and the associated weather in different locations.

A variety of NWP models have been used and investigated to provide inputs to the short- and medium-range landslide forecast applications developed under LANDSLIP, for the case study areas in Darjeeling, West Bengal and Nilgiris, Tamil Nadu.

This section (Part B) of the Knowledge Product provides an overview of the forecast data used and discusses some of the key considerations for selecting and using these data for Landslide Early Warning System (LEWS) development. Part C and Part D will provide greater detail on the methods used to implement these datasets within each of the landslide forecast applications workflows.



East Sikkim, Sikkim. Credit: BGS @ UKRI.

B2 FORECAST DATA

The LANDSLIP project uses four NWP models to develop applications that forecast the potential occurrence of future landslides. Details for each are provided below:

1. Hourly rainfall accumulations are provided from the NCMRWF's global deterministic model at 12 km resolution, out to T+75 (3 days ahead). The model updates once per day, with data provided in a standard format (Grib2). Although the model is global, the NCMRWF provide data clipped to cover sub-domains that include the two case study regions of interest in LANDSLIP (**Fig. B1**). Sub-domains larger than the case study areas were used to provide additional context to the rainfall forecasts (i.e. direction and speed that rainfall is moving), while minimising processing outside of LANDSLIP's area of interest.
2. Hourly rainfall accumulations are also provided from the NCMRWF's regional deterministic model at 4 km resolution, out to T+75 (3 days ahead). The model updates once per day, using the same format and covering the same sub-domains as the global forecast data.

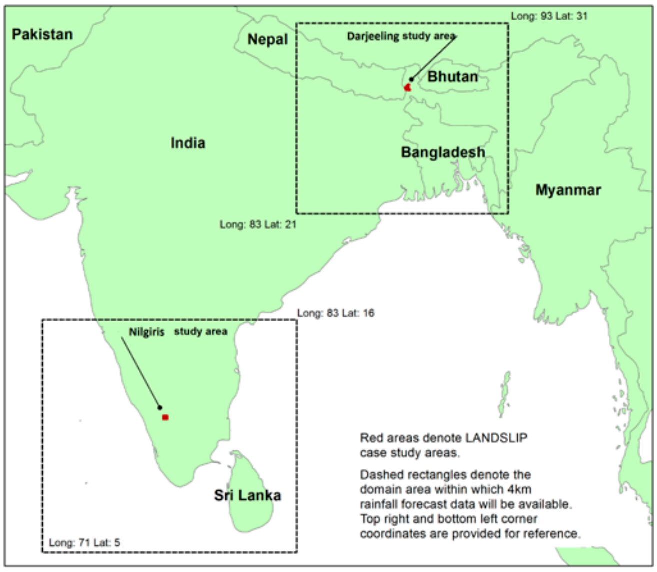


Figure B1 The dashed rectangles illustrate the coverage of NCMRWF global and regional deterministic rainfall forecasts provided for use in the LANDSLIP project. Red areas denote the LANDSLIP case study areas. Map made with free Natural Earth data @ naturalearthdata.com.

3. The NCMRWF are also using their 23-member global ensemble model to drive the medium-range weather pattern forecasting application for landslides. This model provides forecasts of U and V component winds at 12 km resolution, out to 10 days ahead. The model updates once per day and provides a weather pattern forecast for India as a whole.
4. The Met Office have used forecasts from the European Centre for Medium-Range Weather Forecasting (ECMWF) 51-member global ensemble prediction system to provide forecasts of U and V component winds at 18 km resolution, out to 15 days ahead and updates twice per day.

B3 CONSIDERATIONS WHEN USING FORECAST DATA

Availability, coverage and resolution

Different NWP models may offer different options for landslide forecasting. The choice of model is frequently determined based on availability (i.e. which models are available for the weather variable of interest) and coverage (i.e. which models cover the geographic area of interest). It is also important to consider which weather variable might be most applicable for the landslide model being designed (e.g. rainfall accumulation over a set period (hourly; daily) or rainfall intensity (maximum; mean) on or over the hour). Example rainfall forecasts are shown in **Fig. B2**.

Consideration of the spatial resolution of the NWP model, and the influence this might have, is also critical because this will have implications for landslide forecast accuracy (skill). In LANDSLIP, 12 km and 4 km deterministic rainfall forecasts have been used in the development of the short-range landslide forecast application, with rainfall accumulations provided at hourly timesteps. Different model resolutions enable different meteorological features (e.g. thunderstorms, fronts, tropical cyclones and depressions) to be resolved and it is important to consider this where these models are being used as inputs to landslide models. Forecast verification of NWP models, often conducted by national meteorological agencies, can support decisions on which models might perform best when applied to landslide forecasting.

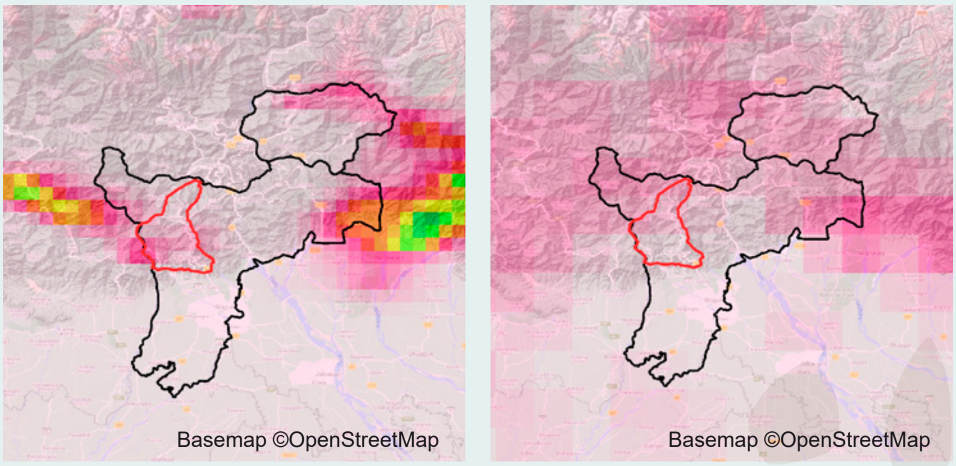


Figure B2 Examples of rainfall forecasts from (left) the NCMRWF global NWP model configuration at a resolution of 0.125° (~12 km) and (right) the NCMRWF regional NWP model configuration at a resolution of 0.004° (~4 km), dated 22/02/2020.Darker colours indicate higher rainfall intensity.

Deterministic and probabilistic forecast data

Both deterministic and probabilistic NWP models have been used in LANDSLIP. Deterministic models provide a single forecast of future weather at each forecast lead time and can provide a high degree of detail as they can be run at high resolution. However, they do not provide information on uncertainty or any indication of the range of possible future scenarios. Ensemble models can be used to provide probabilities of future weather occurring which can be particularly useful in areas where forecasting is challenging and uncertainties are high (e.g. mountainous regions), and where there is a desire to communicate future risks associated with hazardous weather and landslide events.

Processing requirements

Within LANDSLIP, weather forecast data are inputs which undergo further processing to provide a landslide forecast. The landslide forecasts are then used to produce a daily forecast bulletin covering a two-day period. For forecasts to be useful and usable they need to be produced and disseminated to users in a timely manner to enable any necessary actions to be taken. Usability is therefore directly related to the temporal availability of the forecast data, the maximum lead time of the forecast (i.e. what is the maximum extent into the future that the forecast is available for) and the time it takes to conduct processing and production tasks. Different types of NWP model may have different processing times and requirements and this needs to be considered prior to use in an operational setting.

LANDSLIP KNOWLEDGE PRODUCT: Meteorological Data

Part C: Short-range landslide forecasting

LANDSLIP SHEAR

C1 OVERVIEW

LANDSLIP has developed a short-range landslide forecasting application. This has been accomplished using meteorological observation data and meteorological forecasts and applied to the Darjeeling and Nilgiris case study areas.

Short-range refers to the forecast lead time of the model (i.e. how far into the future the forecast is available for). In LANDSLIP, short-range refers to forecasts out to three days ahead from the date the Numerical Weather Prediction (NWP) model was run.

This section (Part C) of the Knowledge Product provides a description of how meteorological datasets were used to create the short-range landslide forecasting application.

Ooty, Nilgiris: © Keystone.

C2 RAINFALL-LANDSLIDE MODEL

To forecast the likelihood of landslide occurrences under different rainfall conditions, an understanding of the rainfall-landslide relationship is required. In LANDSLIP, this is achieved by reviewing rainfall and landslide events in the recent past within the different geographical settings.

Rain gauges provide the historical rainfall information for this analysis. Some gauges are owned and managed by the Indian Meteorological Department (IMD) while others are managed by Tea Garden Estate owners. This has implications for how rainfall data is collected (e.g. automated vs manual recording) and its accuracy.

Before observations can be used, some important preparatory steps need to be undertaken.

- Each rain gauge has a different record length. It is, therefore, necessary to review the available rainfall records from each gauge and compare it to the period of available landslide data. In Darjeeling 684 landslides were recorded between 04/10/1968 and 06/07/2015, while in Nilgiris 392 landslides were recorded between 15/12/1987 and 31/12/2017. Only rain gauges with observations covering these periods in the two case study areas are used.
- It is important to review how missing data (i.e. when the gauge is not functioning or where data was not recorded) and true observations of no rainfall are recorded (e.g. zero might be used interchangeably). This might differ between gauges. In LANDSLIP, rainfall time series for each gauge were compared and gauges with large gaps in their record were not used in the analysis.
- Rain gauges showing significant differences in rainfall distributions or spurious results (e.g. exceptionally large rainfall accumulations) were reviewed to determine whether there was an obvious error in the recording that could be resolved.

After preparatory review of the observation data, 37 rain gauges covering the period 01/01/1959 to 31/12/2017 have been used to provide the historical rainfall record for the Darjeeling area. In Nilgiris, 29 rain gauges covering the period 01/01/1987 to 31/07/2017 have been used. Daily rainfall time series are used to identify rainfall events related to each landslide. These events are separated from one another by periods of no rainfall and is one reason why the preparatory assessment of the gauge data is so important.

The rainfall-landslide model assumes that there is a direct relationship between rainfall and landslide occurrence (**Fig. C1**). This assumption applies only to shallow landslides or to runoff supported landslides (e.g. debris or earth flows) and it does not hold for deep-seated landslides (where the trigger is due to long term infiltration processes). The model output provides the probability of a given rainfall condition (i.e. the cumulative rainfall over a certain time period) to trigger landslides.

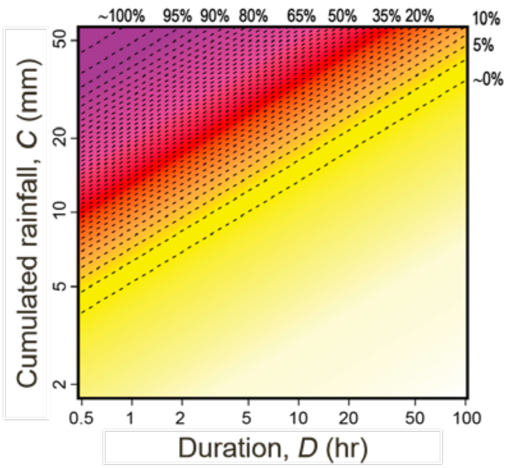


Figure C1 Graphical illustration of the rainfall-landslide forecast model. Darker colours indicate increasing rainfall intensity.

C3 SHORT-RANGE RAINFALL FORECAST

Short range weather (rainfall) forecasts are generated daily by the National Centre for Medium Range Weather Forecasting (NCMRWF) at 00UTC and provide deterministic forecasts of hourly rainfall accumulations out to 75 hours in the future. Two different NWP models are used; a global configuration with a resolution of 0.125 degree (~12 km) and a regional configuration providing forecasts at higher resolution (0.004 degree or ~4 km). The deterministic nature of the forecasts means that there is a single forecast of rainfall accumulation for each forecast time step (lead time).

The short-range NWP models provide gridded rainfall forecasts representing the spatial distribution and intensity of rainfall at each hourly time step of the model. The NCMRWF provide forecasts from both model configurations for two sub-domains of India centered on the LANDSLIP case study areas (Darjeeling, West Bengal and Nilgiris, Tamil Nadu). This is provided via an FTP site.

The rainfall-landslide model described in the previous section has been developed using daily rainfall observation data and therefore, thresholds for different rainfall scenarios (accumulation and duration) associated with past landslide events can only be forward modelled (forecast) using daily rainfall information. It is, therefore, necessary to aggregate hourly forecast time steps to produce daily rainfall accumulation forecasts that can be used to determine the non-exceedance probability of a given rainfall condition triggering landslides. The daily reference period will consistently aggregate 24 forecast time steps to produce a daily accumulation. However, the start and end point for the 'day' can vary depending on when forecasts are available and when information is likely to be disseminated. For example, in LANDSLIP the bulletin is issued at 14:30 IST and therefore we aggregate forecast time steps starting from 0900 UTC (T+9 hrs) and ending at 0900 UTC the next day (T+32 hrs) to produce a daily rainfall accumulation forecast representing Day 1. This can help maximise the usefulness of the forecasts that are provided to users.

C4 NOTIFICATIONS INTERFACE

Using the rainfall-landslide probabilistic model and the short-term rainfall forecasts, the Geological Survey of India (GSI) are able to estimate the likelihood of landslides occurring based on rainfall forecasts for each forecast grid cell across the case study areas, for different periods in the future (e.g. next 24 or 48 hours). The outputs are gridded maps showing likely landslide occurrence as a percentage per cell. Since there are multiple rainfall forecasts available (global and regional) and multiple forecasting periods (e.g. 24 hour and 48 hour), multiple landslide forecasts are available for each study site. **Fig. C2**. shows two of the landslide forecasts generated by the system for Darjeeling district using data from the different NWP models.

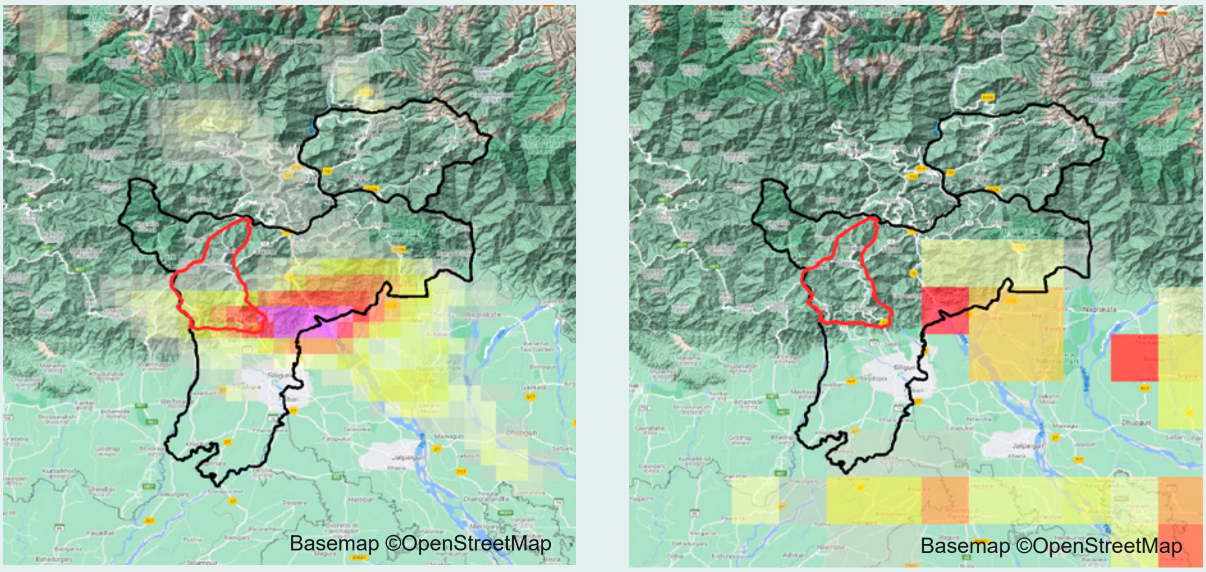


Figure C2 Examples of (left) Global landslide forecast of Darjeeling district and (right) Regional landslide forecast of Darjeeling district. Red line shows the Darjeeling study area, while black lines show Taluk boundaries. Colours denote landslide forecast probabilities. Darker colours show increasing probability.

LANDSLIP KNOWLEDGE PRODUCT:
Meteorological Data

Part D: Medium-range landslide forecasting

D1 OVERVIEW

LANDSLIP has developed a medium-range landslide forecasting application. The application uses a set of 30 predefined weather patterns for the Indian subcontinent (Neal et al., 2020) which are illustrated in **Fig. D1**. These patterns describe different atmospheric circulation types which vary daily and represent the larger-scale setup of the atmosphere which drives day-to-day variability in the weather.

This section (Part D) of the Knowledge Product describes how meteorological datasets were used to create the medium-range forecasting application.

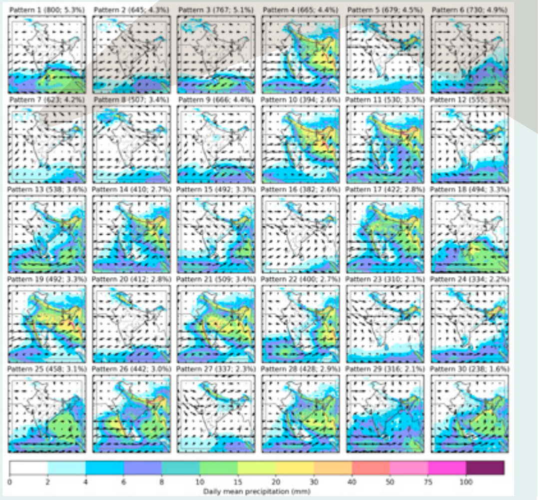


Figure D1 Set of 30 predefined weather patterns for the Indian subcontinent (Neal et al., 2020).

D2 WHAT IS A STANDARD OPERATING PROCEDURE?

To forecast future periods with a heightened susceptibility to landslide occurrence, the relationship between weather patterns, rainfall accumulations and landslides in the recent past needs to be understood. This analysis is conducted for each case study area (Darjeeling and Nilgiris) separately and uses:

1. a daily record of weather pattern (number from 1 to 30) occurrences covering the period January 1979 to December 2016,
2. gridded daily rainfall observations at 0.25° resolution (Pai et al, 2014) provided by the Indian Meteorological Department (IMD) and available from 1901 onwards,
3. and a record (date and location) of past landslide occurrences in the two case study areas. For the purposes of this analysis only landslides between 01/01/1979 and 31/12/2016 were used, coinciding with the availability of the meteorological datasets.

It is important to recognise that the type, frequency, persistence and transitions between weather patterns can influence the amount of rainfall that is observed. To identify those weather patterns that are related to heavier rainfall and therefore increased likelihood of landslide occurrence, each variable is analysed for different preceding periods (3, 5, 10 and 15 days) prior to each historical landslide event.

Fig. D2 shows a time series of daily weather pattern occurrence and the corresponding rainfall accumulations for the same day preceding an observed landslide in the Darjeeling case study area. The total rainfall over each proceeding period is calculated, as well as the total rainfall associated with the occurrence of each weather pattern. The percentage contribution of each weather pattern to the total observed rainfall is then calculated (**Fig. D3**).

The above is completed for all historical landslides across both case study areas. The distributions of the weather pattern percentage contributions for all events are then compared to the climatological average percentage contribution for the specific preceding period (e.g. 15 days). Those weather patterns that show increased percentage contributions compared to climatology represent high-risk patterns that are subsequently used in the forecast application.

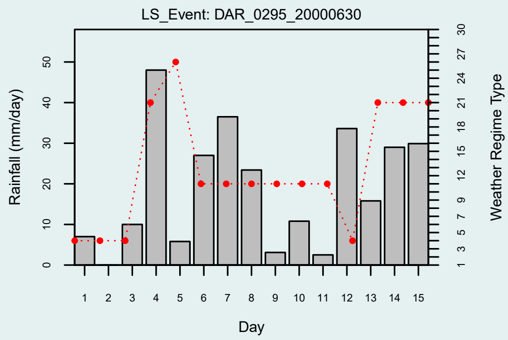


Figure D2 Weather pattern type (red dots) and rainfall accumulation (grey bars) for the 15-days preceding a landslide recorded to have occurred on 17/09/2001 in the Darjeeling case study area.

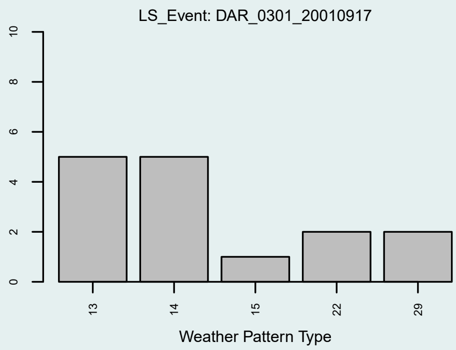


Figure D3 The percentage contribution to the total observed rainfall over the 15-day period preceding the landslide event, associated with each weather pattern observed over the same period.

D3 MEDIUM-RANGE LANDSLIDE FORECASTS

The medium-range landslide forecasting application uses forecasts from the European Centre for Medium-Range Weather Forecasting (ECMWF) 51-member global ensemble prediction system. Forecasts of U and V component winds over the entire Indian subcontinent are used. Each ensemble member is assigned to the nearest matching weather pattern type, based on the 30 predefined classifications. Daily forecast probabilities for each weather pattern are based on the number of ensemble members that are assigned to each weather pattern type. Forecasts are provided out to 15-days ahead and are updated twice daily.

To provide an efficient forecast specific to landslides, forecast probabilities for high-risk weather patterns relevant to landslides are provided for each case study area as stacked probability bar plots (**Fig. D4; Fig. D5**). The colours denote the weather pattern type, while the height of the bars denotes the total probability of high-risk weather patterns occurring on each day of the forecast. As the forecast lead time increases uncertainty grows, and therefore multiple high-risk weather patterns can be forecast to occur as seen in **Fig. D5**, where weather patterns 11, 19 and 21 are forecast from day 9 onwards. These are all considered high-risk and this enables the Geological Survey of India (GSI) to identify periods (windows) when landslide occurrence might be more or less likely, based on the weather patterns that are forecast to occur.

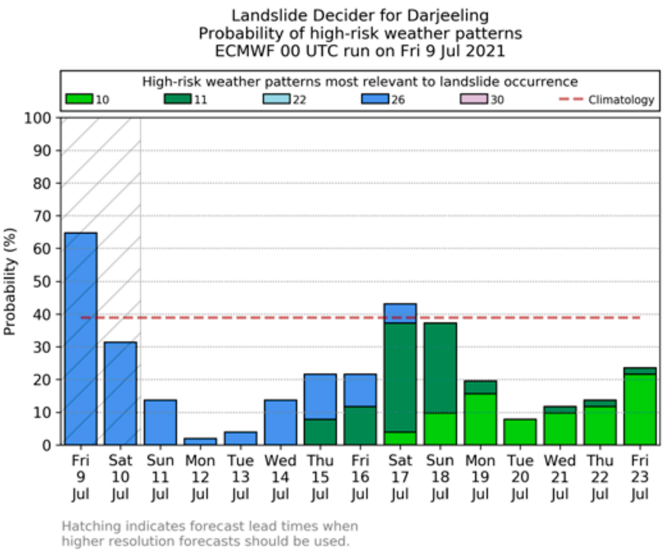


Figure D4 Forecast probability of high-risk weather patterns relevant to landslides occurring in Darjeeling based on ECMWF ensemble forecasts initialised at 00:00 UTC on Friday 9th July, 2021.

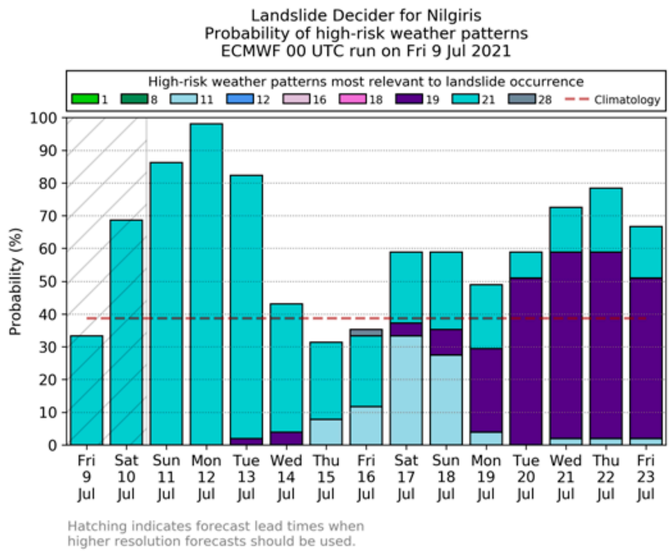


Figure D5 Forecast probability of high-risk weather patterns relevant to landslides occurring in Nilgiris based on ECMWF ensemble forecast initialised at 00:00 UTC on Friday 9th July, 2021.

D4 BENEFITS OF MEDIUM-RANGE LANDSLIDE FORECASTS

In addition to the stacked probability bar plots a table showing forecast probabilities for all weather patterns (including those not identified as high-risk) is available to GSI via a webpage. This enables a narrative around an upcoming scenario (e.g. window of heightened susceptibility) to be developed. This narrative can highlight the duration of a high-risk period or when a period of high risk might start or subside and can be written as text in the Landslide Bulletin. This type of information can be useful for preparedness and planning. The early forecast lead times overlap with the availability of the short-range landslide forecast application, which can provide additional spatial and temporal detail that can be useful for taking targeted action. Together, the short- and medium-range forecast applications optimise the available skill of the current forecasts to provide an improved assessment of the future potential risk of landslides.

D5 REFERENCES

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LANDSLIP KNOWLEDGE PRODUCT: Meteorological Data

Conclusion and recommendations

SUMMARY

Meteorological data is critical for the development of rainfall-induced landslide forecasts. This Knowledge Product has described the meteorological data that has been used in the LANDSLIP project to create the short- and medium-range landslide forecasting applications, applied to the case study areas in India.

KEY LEARNINGS

There are several considerations when selecting and using different sources of meteorological observation and forecast data which are outlined across this KP. The choice of data will have implications for the success of any historical analysis undertaken, and the accuracy (skill) of any forecast model developed.

The sample size (temporally and spatially) of observation data (for rainfall and landslides) is important to ensure relationships between variables are robust and temporal and spatial variability is represented in the analysis.

Models are always a representation of a system and will never perfectly match reality. Understanding the uncertainties both in the data used to develop the model, and the forecasting of future events is vital for effective communication.

RECOMMENDATIONS

Partnership between the Geological Survey of India and national meteorological institutions in India will support access to newly available meteorological datasets that can enhance landslide forecasting and sharing of expertise (metrics used to routinely evaluate rainfall forecasts or different triggers for different landslide types) across disciplines.

LIMITATIONS AND OUTSTANDING CHALLENGES

A limited and confined sample size of landslide observations used to identify rainfall trigger thresholds and high-risk weather patterns, means that there are likely to be circumstances where landslides have occurred under different meteorological conditions but which have not been captured in the initial analysis. The thresholds and definition of high-risk weather patterns are likely to change as more data becomes available. A reassessment of the analysis undertaken in LANDSLIP is therefore an important step in maintaining and updating the forecasting applications that have been developed.

Both the short- and medium-range forecast applications need to be evaluated against rainfall and landslide observations. These datasets need to be separate from the observations used to undertake the historical analysis and requires a long-term plan for routine data collection. Metrics for evaluation of both the rainfall forecasts and the landslide forecasts should be decided early and used over repeated evaluations to assess incremental improvement. Discussions with national meteorological institutions in India who do this regularly could prove beneficial.

The Indian Meteorological Department issue an 'All India Weather Forecast Bulletin' which is made available to similar users as those receiving the new landslide forecast bulletin. The usefulness and usability of the landslide bulletin needs to be considered in the context of other material that users receive.

FURTHER READING

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CITATION

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