THE SECOND WORLD LANDSLIDE FORUM

From Landslide Inventories to Landslide Risk Assessment; An Attempt to Support Methodological Development in India

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Abstract

India is now housing 17 % of the world's population. Landslides are an increasing concern in India due to the rapid population expansion in hilly and mountainous terrain. Landslides affect vast areas within India, in particular in the Himalayan chain in the North and Eastern part of the country and the Western Ghats in the Southwest. The Geological Survey of India (GSI) has been designated as agency responsible for landslide inventory, susceptibility and hazard assessment. Until recently their landslide susceptibility assessment was based on a heuristic approach using fixed weights or ranking of geofactors, following guidelines of the Bureau of Indian Standards (BIS). However, this method is disputed as it doesn't provide accurate results.

This paper gives an overview of recent research on how the existing methods for landslide inventory, susceptibility and hazard assessment in India could be improved, and how these could be used in (semi)quantitative risk assessment. Due to the unavailability of airphotos in large parts of India, satellite remote sensing data has become the standard data input for landslide inventory mapping. The National Remote Sensing Center (NRSC) has developed an approach using semi-automatic image analysis algorithms that combine spectral, shape, texture, morphometric and contextual information derived from high resolution satellite data and DTMs for the preparation of new as well as historical landslide inventories. Also the use of existing information in the form of maintenance records, and other information to generate event-based landslide inventories is presented. Event-based landslide inventories are used to estimate the temporal probability, landslide density and landslide size distribution.

Landslide susceptibility methods can be subdivided in heuristic, statistical and deterministic methods. Examples are given on the use of these methods for different scales of analysis. For medium scales a method is presented to analyze the spatial association between landslides and causal factors, including those related to structural geology, to select the most appropriate spatial factors for different landslide types, and integrate them using a combination of heuristic and multivariate methods. For transportation corridors a method is

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presented for quantitative hazard and risk assessment based on a nearly complete landslide database. Deterministic methods using several dynamic slope-hydrology and slope stability models have been applied to evaluate the relation between landuse changes and slope stability.

The susceptibility maps can be combined with the landslide databases to convert them into hazard maps which are subsequently used in (semi) quantitative risk assessment at different scales of analysis.

Keywords

Landslides • India • Landslide inventory • Susceptibility • Hazard • Risk assessment

Introduction

Landslides are significant hazards that can be disastrous to human life and property. Recent global landslide assessment studies (Petley et al. 2005; Nadim and Kjekstad 2009; OFDA/CRED 2010) reveal that the countries with the highest risk to landslides are mostly in the developing world.

About 15 % of India (~0.49 million km^2) including the mountain areas of the Himalayas, the Meghalaya plateau, and the Western Ghats are landslide-prone (NDMA 2009). During the monsoon, those areas witness frequent landslide events triggered by rainfall. Many landslide-prone areas also belong to the maximum earthquake-prone areas in India (BIS 1998), where earthquakes of Modified Mercalli intensity VIII to IX can occur, and thus, are also susceptible to earthquake-triggered landslides as well.

To mitigate the effects of such disasters, the Government of India has enacted the National Disaster Management Act in 2005. This act aims at adopting proactive and multidisciplinary approaches towards achieving disaster awareness and mitigation. The policy stresses that investments in disaster-preparedness and mitigation are much more cost-effective than expenditures on relief and rehabilitation (NDMA 2009). In this regard, predictive maps of landslide hazard, preferably at medium scales (1:25,000 to 1:50,000) are vital geo-information products that administrators/planners can use in formulating regional mitigation plans for landslide disasters. The aim of using medium-scale landslide hazard maps is to draft proper land-use zoning regulations in landslide-prone areas to alleviate, if not prevent potential loss of human life and damage to property.

Landslide research in India has always been hampered by the lack of data. In the border zones of the country, including the entire Himalayan range the use of topographical maps and airphotos has been restricted for security purposes. Thus the generation of landslide inventory maps has always been a major problem. However, due to the availability of India's own system of Earth Observation satellites, high-resolution remote sensing data (e.g. Cartosat) has become the standard input data for landslide inventory mapping, and for the generation of Digital Elevation Models used in landslide studies.

Up to now there are very few examples in India of landslide hazard maps (Sarkar and Kanungo 2005; Bhandari 2006; Sharda 2008), although a substantial part of the country's most landslide-prone area is now covered by medium-scale qualitative landslide susceptibility maps (BMTPC 2003). The Bureau of Indian Standards has formulated guidelines, among others, for landslide susceptibility zonation on a medium scale (1:50,000) (BIS 1998), using an expert-based indirect weighting approach (Anbalagan 1992). The method uses fixed weights or ranking of geofactors without directly or indirectly considering the landslide inventory data. There have been discussions on the improvement of this method, and the inclusion of landslide inventories combined with GIS-based statistical analysis as an alternative for medium scale susceptibility assessment (Sharda 2008; NDMA 2009).

In 2006 a joint research agreement was made between the Geological Survey of India (GSI), the National Remote Sensing Centre (NRSC; Department of Space, Government of India) and the Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, The Netherlands. The agreement focused on the development of training courses and the implementation of joint research projects. The Geological Survey of India (GSI) has been designated as the nodal agency for landslides by the Indian government. The National Remote Sensing Center (NRSC) under the Indian Space Research Organisation (ISRO) is in charge of rapid damage assessment using the suite of India's own satellites, and in the use of satellite data for inventory mapping and susceptibility assessment. The research collaboration included two Ph.D. researchers from GSI and one from NRSC. Later also other organizations were involved in the research. Another Ph.D. researcher from the Centre for Earth Science Studies (CESS), in Thiruvananthapuram, Kerala, was integrated in the project, as well as one from the Indian Institute of Remote Sensing (IIRS), which is the training center of the Indian Space Organization. The research collaboration also involved a number of European institutions, such as the Faculty of Geosciences of Utrecht University (The Netherlands), the National Research Council of Italy (CNR-IRPI, Perugia), the University of Vienna, and the German Geological Survey (BGR, Hannover).

The main objective of the research project was to develop and test methods for landslide inventory mapping, susceptibility-, hazard and risk assessment that are applicable in India, considering the variability and complexities of the landslide-prone terrains, and considering the data availability. Methods were developed for different scales of analysis. The methods focused on techniques for generating landslide inventories, the application of appropriate susceptibility models (heuristic, statistical, physically based), the characterization of landslide hazard in terms of temporal, spatial and size probability, and the use of this information in landslide risk analysis.

Study Areas

It was decided to develop and test the methodology in four different areas in India, each one linked with a Ph.D. research. Figure 1 shows the location of the four study areas.

Each of the four studies had its own main research focus, as can be seen from Table 1.

In the following sections the main results from these four studies will be presented.

Case Study A: Landslide Inventory Using Object Oriented Image Analysis

Landslide inventories that span a substantial period of time are one of the key requirements for landslide studies (Van Westen et al. 2008). Image interpretation still is the main method for generating these. Several research attempts have been made to automate and speed up the process of landslide interpretation as major trigering events might cause hundreds or even thousands of landslides. Since pixel-based methods have not produced sufficiently accurate results for detection and classification of landslides, object-oriented analysis (OOA) which imitates the human interpretation process in identification of landslides, has emerged as a good alternative due to its inherent ability to incorporate additional information layers such as digital terrain models (DTMs) and thematic maps in the analysis. Furthermore, as landslides are geomorphic processes, their characterisation in different types mostly relies on contextual criteria, which can best be described by objects obtained from segmenting the digital image into spatially cohesive regions/objects rather than pixel values. Martha et al. (2011b) developed semi-automatic image analysis algorithms that combine spectral, shape, texture, morphometric and contextual information derived from high resolution satellite data and DTMs for the preparation of landslide inventories. The main innovative aspect of the research lies in the selection of landslide diagnostic parameters and their use in the comprehensive characterisation of different types of landslides, a concept which is addressed for the first time for detection of landslides in an object-based environment.

DTM accuracy is an important factor since its morphometric derivatives, such as terrain curvature, slope, and flow direction, contribute to the successful detection and classification of landslides. Cartosat-1 along-track stereoscopic data, which are provided with RPCs for block triangulation, were used to create a DTM with 10 m grid size (Martha et al. 2010a). Conversion of a DSM to a DTM was carried out for calculating landslide volume and terrain morphometric parameters, by subtracting vegetation height from the DSM. The landslide volume extracted from pre- and post-landslide DTMs (Fig. 2) without control points matched well with volume extracted from the DTMs with control points, indicating that a field survey for control points is not a strict requirement (Martha et al. 2010b). It also showed that landslide volume information can be derived only with RPCs, if both pre- and post-image pairs can be brought into the same relative reference framework.

A set of approaches was developed that exploit the object properties extracted using a region-growing segmentation of multispectral Resourcesat-1 LISS-IV Mx (5.8 m) image (Martha et al. 2010c). The method was tested in the Okhimath area, in Uttarakandh. An algorithm comprising 45 individual routines, such as controlled segmentation, merging and classification was developed using eCognition software, which detected 42 major and minor landslides in an 80 km^2 area. The algorithm, initially extracts landslide candidates using an NDVI threshold, and subsequently false positives were eliminated from the landslide candidates using spectral, texture, shape and contextual criteria (Fig. 3). Landslide classification was done using terrain curvature and contextual criteria, and five different types of landslides were identified. The object-based classification, when compared with a landslide inventory map prepared by stereoscopic photo-interpretation and detailed field check, resulted in a detection accuracy of 76.4 %, while 69.1 % of the landslides were correctly classified in different landslide types. The results are considered to be good, since landslides are detected in an area dominated by false positives such as rocky barren land, uncultivated agricultural terraces and river sands. The minimum landslide size detected by the method was 700 m^2.

The algorithm developed required user-defined segmentation criteria to control the object size, which was considered a drawback in applying a fast and generic method for landslide detection and classification. Therefore, an objective method to optimise segments was developed subsequently (Martha et al. 2011a). Using spatial autocorrelation and intrasegment variance, a new plateau objective function (POF) was developed, which was used to determine the segmentation criteria for multi-scale analysis, essential for the detection of landslides and elimination of false positives. Another drawback of the originally developed algorithm was the use

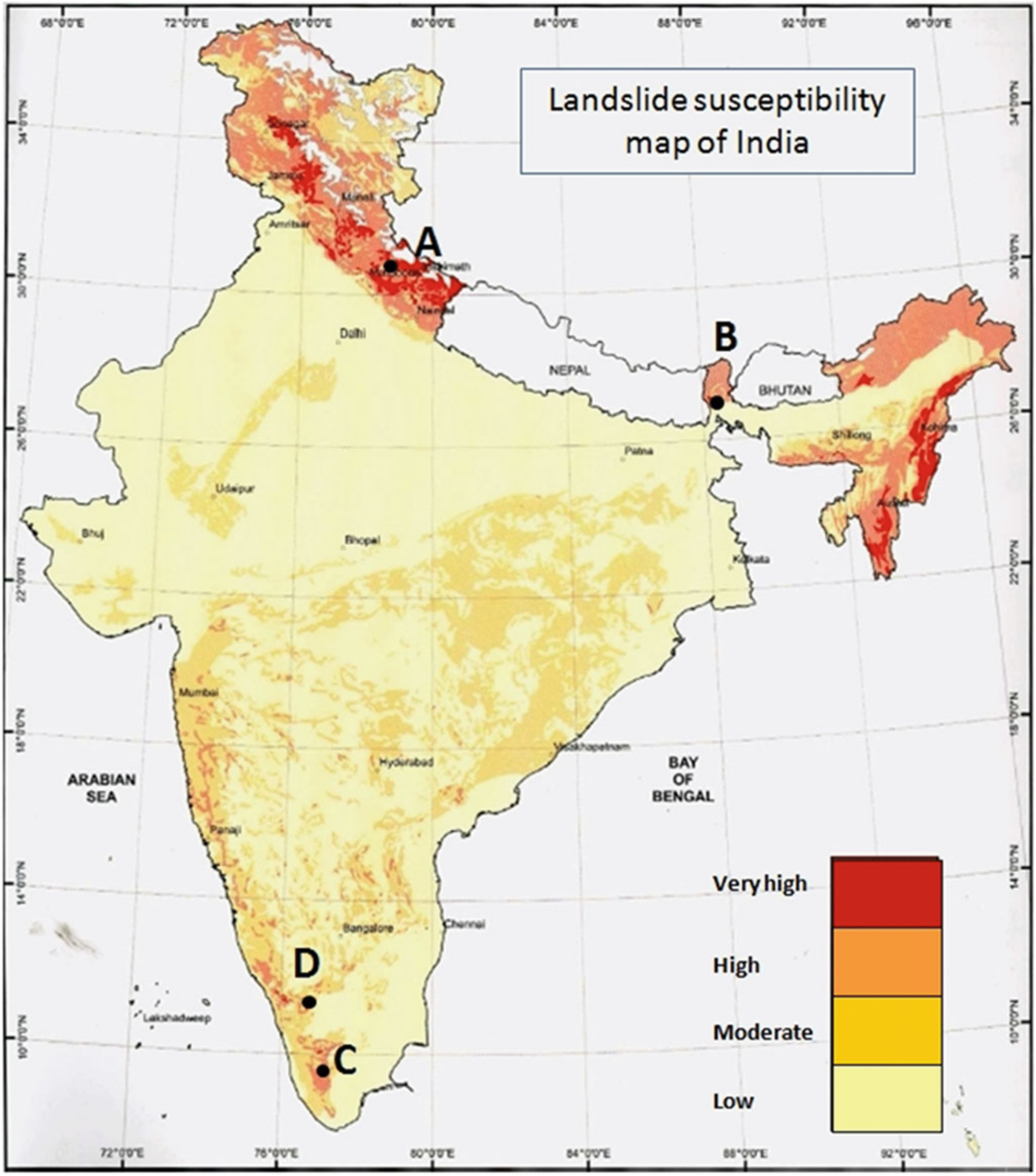

Fig. 1 National landslide susceptibility map (Rajarathnam and Ganapathy 2006) with the location of the test sites. A: Okhimath (Uttarakhand state), B: Kurseong (Darjeeling state); C: Tikovil (Kerala state), D: Nilgiri (Tamilnadu state)

of manual thresholds for the elimination of false positives from landslide candidates. This was adjusted using a K-means clustering method. The improved algorithm, comprising of four sub-modules, resulted in a detection accuracy of 76.9 % for the training area and 77.7 % accuracy for a geomorphologically distinct validation area (Fig. 4). It not only increased the accuracy of detection but also reduced the overall error of commission.

Another algorithm was used for landslide detection from archived high resolution panchromatic images, which is a

Table 1 Main research themes in the four case study areas, indicated in Fig. 1

Area	Research focus
A: Okhimath & Uttarkashi (Uttarakhand)	**Detection of landslides by object – oriented image analysis.** Generation of Digital Surface Models from Cartosat satellite images; application of NDVI-based thresholds for landslide detection; development of a rule set for removal of false polygons; semi-automatic classification of landslide types; development of a method for landslide detection from multi-temporal panchromatic images; bivariate statistical analysis; and semi-qualitative risk analysis (Martha et al. 2011b; Das et al. 2010, 2011)
D: Kurseong (Darjeeling)	**Knowledge guided empirical prediction of landslide hazard**. Landslide inventory made through multi-temporal image interpretation; event-based landslide inventories; relation with triggering rainfall; analysis of the structural control of discontinuities on rock slides; combination of heuristic and statistical methods for susceptibility assessment; temporal- spatial- and size frequency analysis; semi-quantitative risk analysis (Ghosh et al. 2011b)
C: Tikovil (Kerala)	**Physically-based dynamic modelling of the effect of land use changes on shallow landslide initiation.** Inventory made with community-based mapping; detailed soil thickness modelling; geotechnical and hydrological characterization; ground water modelling; slope stability analysis; failure probability analysis; runout modelling; prediction of future slope stability scenarios (Kuriakose et al. 2010)
D: Nilgiri (Tamilnadu)	**Landslide risk quantification along transportation corridors based on historical information.** Landslide inventory made from maintenance records for road and railroad; rainfall threshold analysis; frequency-size analysis; hazard analysis; quantitative direct and indirect risk analysis; use of risk information for disaster risk reduction (Jaiswal et al. 2011c)

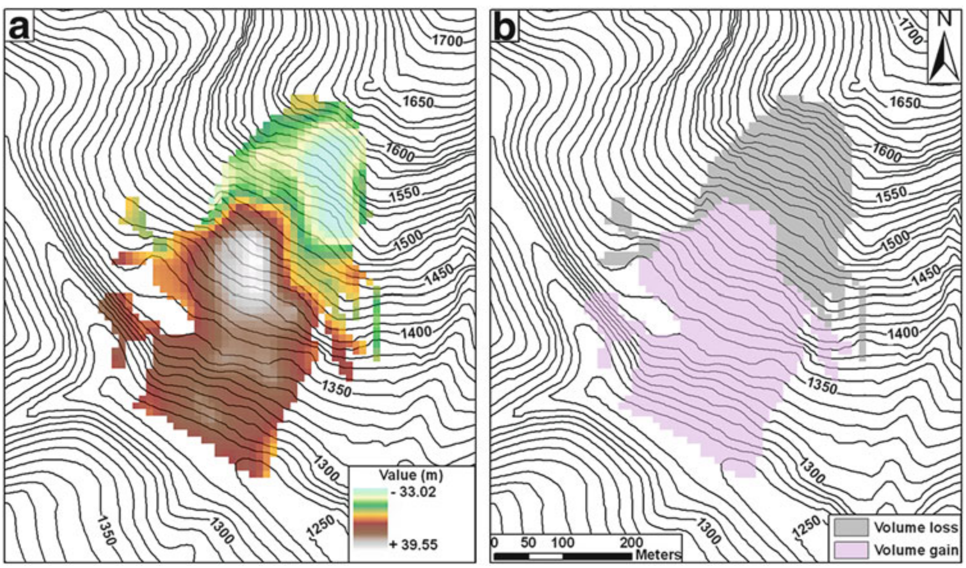

Fig. 2 Volumetric analysis of the Salna landslide based on satellite derived DTMs. (**a**) Elevation difference due to the landslide with negative values showing lowering of surface and positive values showing rising of the surface after the event, and (b) extent of the volume loss and volume gain, which corresponds to the zones of depletion and accumulation, respectively (Martha et al. 2010b)

modified version of the second one. It uses a brightness threshold instead of NDVI to extract landslide candidates (Martha et al. 2012). Local thresholds using contextual criteria showed better results than global thresholds, and allowed to identify small translational landslides within barren rocky land that are generally bright. To eliminate false positives, more texture measures, such as GLCM homogeneity and standard deviation, were used along with shape and contextual criteria. Finally, a multi-temporal annual landslide inventory for 13 years was prepared and used for the generation of a landslide susceptibility map with the help of a bivariate model (Martha et al. 2013).

The final algorithm for the detection of landslides, developed by Martha et al. (2011b) is generic and requires two primary inputs (a satellite image and a DTM), and doesn't require information that should be collected in the field. The semi-automatic approach is flexible enough to address the spatial and spectral variability of landslides and false positives. The knowledge-based method shows considerable improvement over previous pixel- and object-based methods of landslide detection in terms of the location, size and type of landslide. The method has increased the potential to rapidly generate event-based landslide inventories after major triggering events, within a short

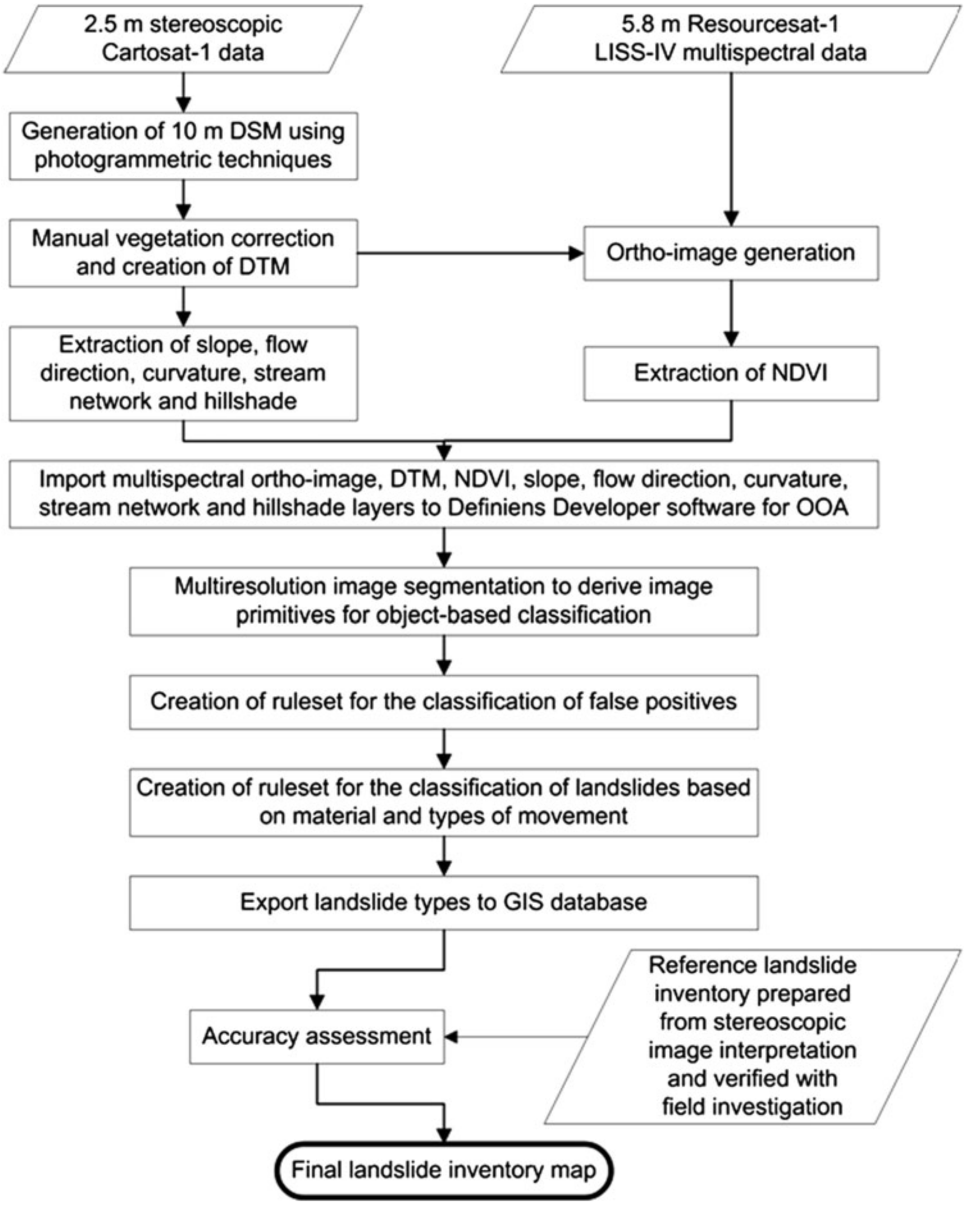

Fig. 3 Generalised methodology flowchart for semi-automatic detection of landslides using object-based methods (Martha et al. 2010c)

period of time. The method developed in this research has proven its value in several areas in the Indian Himalayas and could potentially contribute to the rapid detection of landslides in other susceptible areas.

Case Study B: Knowledge-Guided Empirical Prediction of Landslide Hazard at the Medium Scale

Estimating and mapping variations in the spatial likelihood of occurrence of landslides (susceptibility assessment) is a fundamental step towards landslide hazard prediction. Landslide susceptibility aims to identify where future landslides are likely to occur, based on the fundamental assumption that spatial factors that caused present and past landslides are likely to cause similar landslides in the future.

In Indian, the BIS guidelines (BIS 1998) recommended an indirect approach to landslide susceptibility mapping and provides a generalized heuristic system of fixed weighting or ranking of geofactors called landslide hazard evaluation factor (LHEF) rating. These LHEF ratings are applied irrespective of various terrain conditions and were determined by an expert group without directly considering the landslide inventory data. Since the spatial extents of landslide geofactors and their respective causal association with different types of landslides and failure mechanisms are variable, the fixed LHEF ratings assigned to geofactors

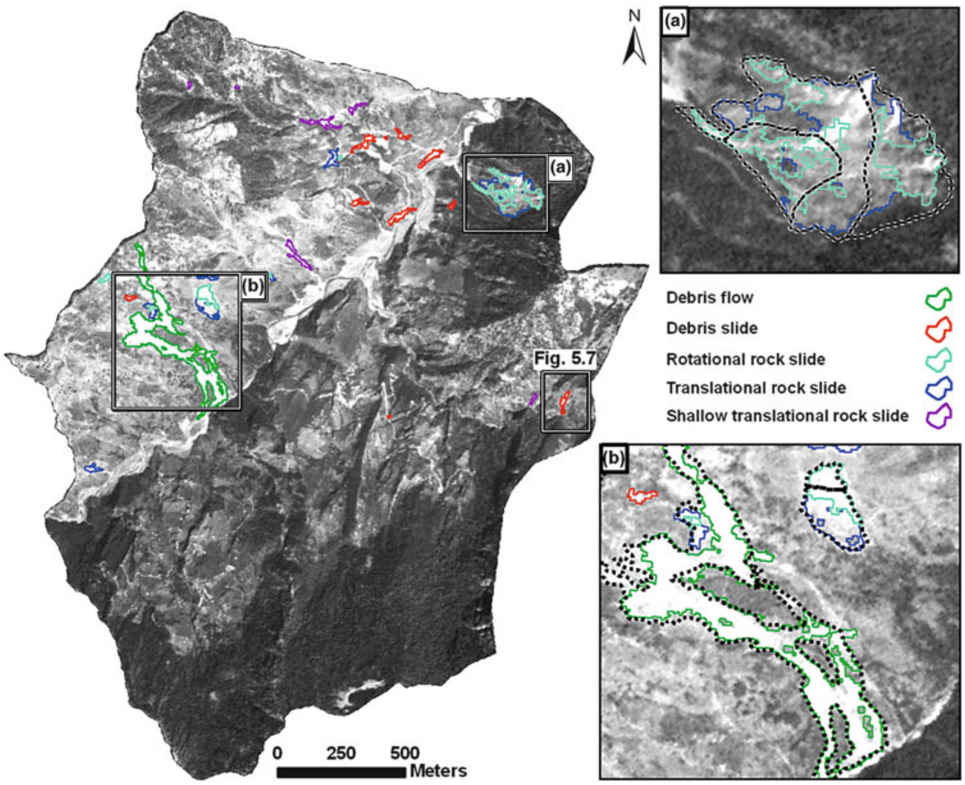

Fig. 4 Landslide types recognised using OOA in the Okhimath area. The *dotted lines* in insets (*a*) and (*b*) show the reference landslide inventory (Martha et al. 2011a)

can be inappropriate and lead to less accurate landslide prediction rates when applied to different areas. The aim of this research was to propose an effective method for medium scale landslide hazard and risk analysis suitable for the Indian geo-environment which can be readily used by the public research Institutes/Organisations engaged in landslide research in India. The proposed method considered the variability and complexities of the one of the predominant landslide-prone terrains (e.g., the Darjeeling Himalayas) and the landsliding processes prevalent there, so that the aspects of variable controls of landsliding factors can be better understood (Ghosh et al. 2009a, 2011b). This was done through:

- Generation of landslide inventory maps for different triggering events, based on the available information in the forms of landslide maps, images and archives. These maps should portray the landslide patterns and types of triggering events with a range of return periods, which can be used to analyse the temporal and magnitude probabilities (Ghosh et al. 2009b, 2012a);
- Development of an exploratory analytical technique for understanding the mutual/exclusive spatial relation between regional structures (e.g., faults/fractures) and slope aspects with rockslides of a certain type (Ghosh and Carranza 2010);
- Develop a specific method for analyzing different rock slope failure modes, by spatially incorporating the 3-D structural orientation data (Ghosh et al. 2010);
- Analyze the spatial associations between landslides of specific types and a set of causal factors, using bivariate statistical methods for selecting and weighting the appropriate spatial factors and integrate the right and weighted spatial factors into landslide susceptibility maps for each type of landslide (Ghosh et al. 2011a);
- Integrate the spatial, temporal and size probabilities of landslide events and convert the susceptibility maps into hazard maps (Ghosh et al. 2012a);

Generating Inventory Maps

The source data sets that were used in this study for landslide inventory mapping consisted of high-resolution satellite images, aerial photographs, topographic maps, old landslide inventory maps and reports of field investigations which were available for the study area in Darjeeling. The oldest data set consists of topographic maps prepared by the Survey of India (SOI) in 1969, which included the locations of prominent and active landslides of a major triggering event in 1968. The next data set consists of 1:50,000 and 1:10,000 scale black-and-white stereo-air photos from 1980, which

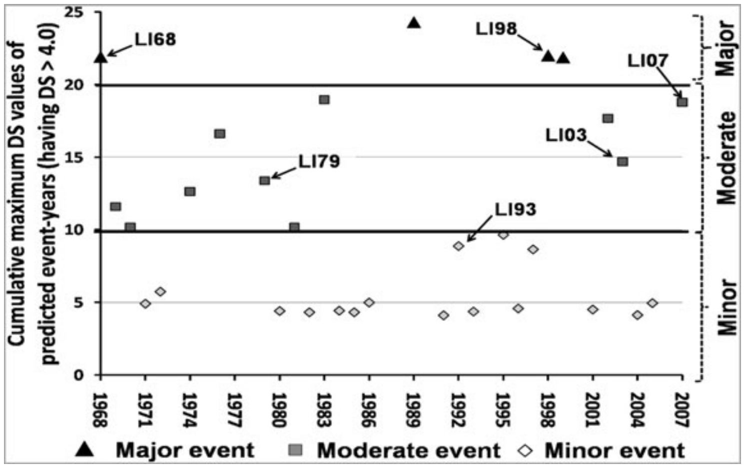

Fig. 5 Threshold cumulative discriminant scores (DS) for predicted "*minor*", "*moderate*" and "*major*" landslide events. The available six events are shown and associated with corresponding inventory numbers to depict validity of model-derived severity classifications of known landslide events

were interpreted using stereo-image interpretation. The third and fourth data sets are field-based landslide inventory map from 1993 and 1998 prepared by GSI soon after major triggering events. For the period 2002–2006, three high-resolution Indian satellite images were used as source data. The most recent data set is a detailed landslide inventory map prepared during this research through field surveys soon after a recent landslide event in 2007. For each period a landslide inventory was made, and landslides were mapped as polygons, resulting in a total of six event-based landslide inventories, which were compared to examine variations in landslide characteristics (frequency, area, density, type and activity). Unfortunately the available data was not covering all landslide triggering events in the last 50 years.

Therefore a multivariate classification technique (discriminant analysis) was used to define an empirical relationship between days with and without landslide events as response variable and daily variation in rainfall amounts as predictor variables. The frequencies of landslide events predicted via DA that were linked to triggering rainfalls were then used in a Poisson distribution model to calculate the temporal probability of similar landslide events in the future, which were classified in major, moderate and minor events (Fig. 5).

Rock Failure Type Modelling

Many of the landslides in the Himalayas are rock slides, or are in weathering soil with a clear structural control. For rock slides, since failure propagates along a near-planar surface (planar) or triggered along the intersection of two planes (wedge), the presence/absence of any planar discontinuity, its nature, extent, orientation and frequency of occurrence in relation to topography are crucial deciding geofactors. The geometric or kinematic interrelationships between the attitudes of bedding/foliation/joint planes and topography are important in deciding the mode of movement of rock slides. To determine kinematically the unfavourable discontinuity-topography/structure domains, different topographic segments were identified after establishing the geometric interrelationships of the orientations between topography and prominent discontinuity surfaces (Ghosh et al. 2010). For the calculation of the angular interrelationship, raster maps of topographic slope, topographic aspect, discontinuity dip and discontinuity dip direction were used. Dip and dip direction raster maps of prominent discontinuities were generated through interpolation of discrete dip/dip direction values of foliation planes, measured at different point locations. After this structural domains were derived by combining the above four raster maps and calculating their angular relationships. Different rock slide failure mechanisms were successfully identified spatially by studying the kinematic interrelationships between the attitudes of distributed bedding/foliation/joint planes and topography through spatial correlation. A GIS-based application was used for the spatial analysis with distributed rock structure data (Günther 2003) and areas susceptible to wedge, planar and toppling failure modes were delineated (Fig. 6). The best approach would be to parameterize all these structure domains per failure mechanism spatially and utilise them for a detailed quantitative rock slope susceptibility analysis.

Combining Heuristic and Statistical Methods

Heuristic methods for spatial prediction of landslide occurrence can either be direct or indirect. In indirect heuristic methods, individual factors are assigned specified weight values or ratings that are based on subjective criteria. The main limitations/problems of heuristic methods are related to the subjectivity involved. Although the same subjectivity could be present in selecting and mapping of the factors for data-driven methods, but the relative importance of

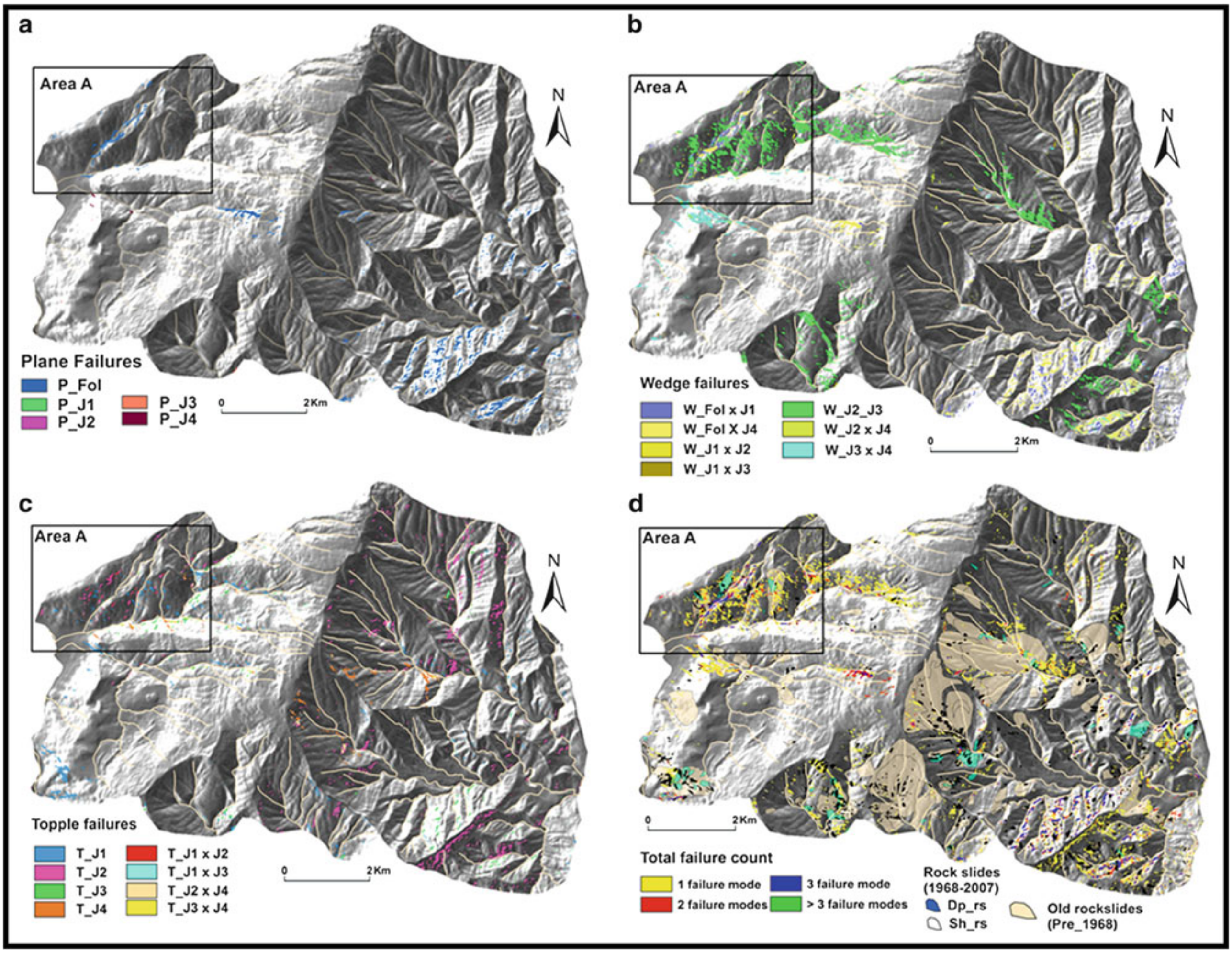

Fig. 6 Modelled unstable slopes for different types of rock slope failure (**a**) plane failure (**b**) wedge failure (**c**) topple failure (**d**) slopes where at least one failure mode is kinematically possible

the factors is determined by more objective techniques. One of the main advantages of heuristic methods is that they can allow site specific and landslide type specific evaluations of the causal factors, and avoid the generalization that is often used in data-driven ones.

Landslide susceptibility is a function of two types of spatial associations: (1) spatial associations of individual spatial factors with known landslides of a certain type; and (2) relative importance of individual spatial factors with respect to one another in relation to those known landslide occurrences. Methods of bivariate empirical analysis can model only the first type of spatial association. In contrast, multivariate methods can model those two types of spatial associations simultaneously, but often include spatial factors that do not seem to have a direct relation with the landslide process and generally do not include expert opinion. Therefore an empirical method was developed for the analysis of spatial association at a medium-scale. The data used are presented in Table 2.

For each class of a categorical factor, the Yule's coefficient was used to quantify its spatial association with known occurrence of shallow landslides. Based on calculated values of Yc for every factor, a Landslide Occurrence Favourability Score (LOFS) was calculated per factor class. Distance distribution analysis (DDA) was used for measuring the spatial association of continous variables.

For the analysis of inter-predictor weights the analytical hierarchy process (AHP) was applied. Based on the spatial association analyses and the predictor weights derived via AHP, 14 out of 21 identified spatial factors for shallow translational rockslides were used and 12 out 22 spatial factors for shallow translational debris slides. To integrate the selected predictors of each type of shallow landsliding, the weighted multi-class index overlay method was applied (Fig. 7).

The results were compared with a backward stepwise Logistic Regression analysis, which starts with all input predictors and ends with only statistically significant predictors that contribute to the prediction or classification.

Table 2 Data source, methods of preparation/mapping of spatial factors of shallow landslides. Sh_rs = shallow translational rockslides. Db_rs = shallow translational debris slides

Generic factor theme	Specific factor	Source data, scale or spatial resolution and method of mapping of factor	Landslide type: Directly related	Landslide type: Indirectly related
Topography/ morphometry	Slope aspect curvature	DEM of 10m × 10m pixel resolution; automated mapping in GIS	Sh_rs, Db_rs	–
Lithology or slope material	Rock and soil type	Field data, information from existing geological maps (1:10,000–1:50,000 scales)	Sh_rs, Db_rs	–
Depth to bedrock	Soil/overburden thickness	Estimated using field data from 400 sites and linked to lithology map	Db_rs	–
Structure	Distance to major thrusts	Compiled from 1:50,000 and 1:25,000 geological maps; interpreted from high spatial resolution satellite imagery and stereo air-photos (1:50,000 and 1:10,000); ground-truthing in the field.	Sh_rs,	Db_rs
	Distance to faults/ fractures	Interpreted from stereo-pairs of 1:10,000 and 50,000 B × W air-photos with limited ground-truthing in the field.	Sh_rs,	Db_rs
	Distance to kinematically unstable slopes	Determined using field data of rock discontinuity orientations and DEM-derived slope and aspect maps (Ghosh et al. 2012b)	Sh_rs,	Db_rs
Land-use/ land-cover	Land-use/land-cover	Interpreted from 1:10,000 and 1:50,000 B×W air-photos and multispectral IRS LISS 4 MX imagery (5.8 m spatial resolution) with limited ground-truthing in the field	Sh_rs, Db_rs	–
Old rockslides	Distance to old rockslides (pre-1968)	Mapped from stereo interpretation of 1:10,000 scale B × W stereo air-photos of 1980	Sh_rs, Db_rs	–
Hydrology	Contributing area upslope	DEM of 10 × 10m pixel resolution	Sh_rs, Db_rs	–
	Wetness index	DEM of 10 × 10m pixel resolution		
	Drainage density	DEM of 10 × 10m pixel resolution; digitized streams from 1:25,000 topographic maps		
	Distance to streams	DEM of 10 × 10m pixel resolution; digitized streams from 1:25,000 topographic maps		

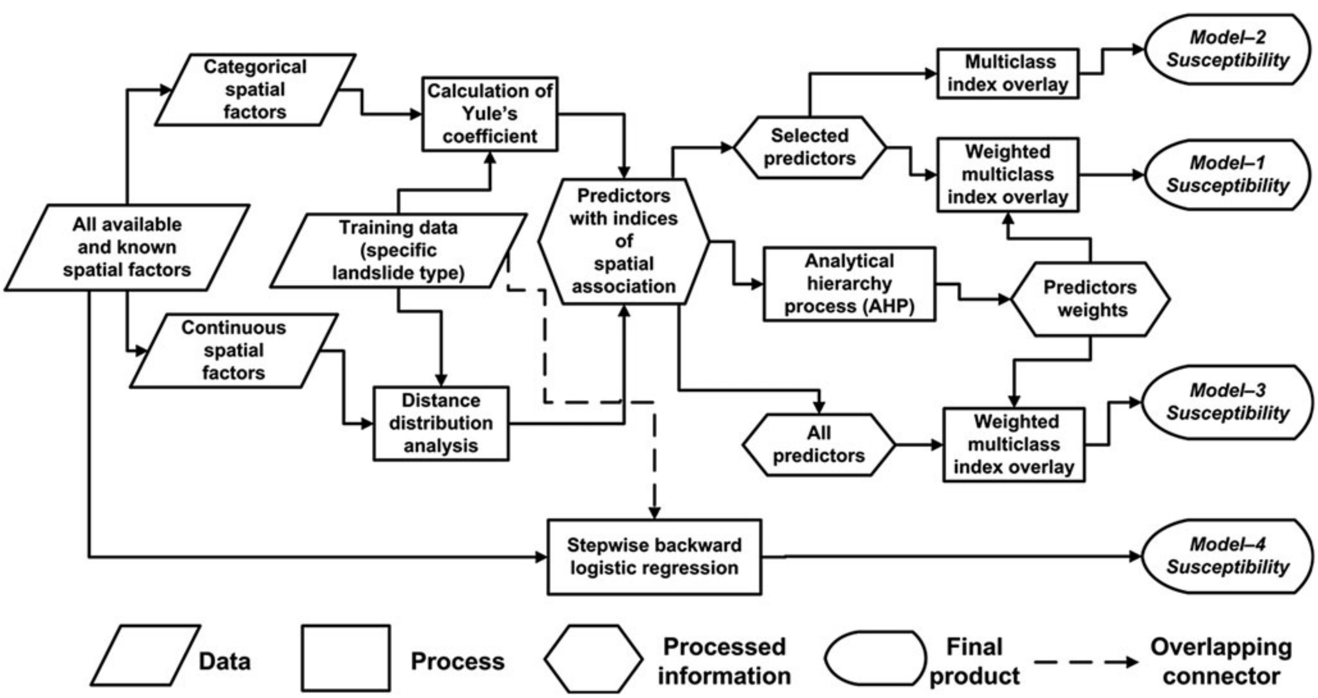

Fig. 7 Schematic flow diagram showing data, processes and steps for developing four different models of susceptibility to shallow landsliding

The resulting susceptibility map was combined with the landslide inventories for different types of triggering events (major, moderate and minor), which were used to estimate temporal and spatial probability and to convert them into a hazard map, which was subsequently used in a semi-quantitative risk assessment (Ghosh et al. 2012a).

Case Study C: Physically Based Landslide Hazard Assessment

The third case study focused on the application of deterministic modelling at local scale, and to use it to evaluate the effect of environmental changes on landslide activity. The case study area is in the highland region forming the western slopes of the Western Ghats of Kerala state, which is increasingly affected by shallow landslides and debris flows. High intensity rainfall, and the presence of perched water tables resulting in high pore-water pressure conditions are considered as the principal trigger of these landslides. The spatio-temporal probabilities of shallow landslide initiation in this area are dependent on the land use which in turn determines the mechanical and hydrological effects of vegetation on slope stability. The application of physically-based spatially distributed modelling was the most suitable approach to verify this hypothesis as it has the capability to not only estimate the spatio-temporal probabilities of shallow landslide initiation, but also quantitatively assess the influence of changes in environmental conditions on slope stability, for example those of land use changes.

Four shallow landslide initiation models were applied, namely SHALSTAB, SINMAP, TRIGRS and STARWARS + PROBSTAB (Kuriakose et al. 2010). The STARWARS (Storage and Redistribution of Water on Agricultural and Revegetated Slopes) + PROBSTAB (Probability of Stability) model, which is a coupled hydrology and stability model that uses a first order second moment approach for quantifying the probability of failure, was identified as the most suitable for this research. A pilot study conducted in the upper Tikoy river basin (55 km^2) revealed that it was necessary to accurately measure and spatially parameterize root reinforcement, soil depth, soil hydraulic conductivity and soil strength properties to derive reliable results from the model (Kuriakose et al. 2008). It was also evident that a detailed characterization of rainfall patterns and corresponding slope hydrological responses such as transient ground water level and discharge was necessary to calibrate and validate the STARWARS (the hydrology model) while a detailed landslide inventory was needed for the calibration and validation of PROBSTAB (the slope stability model).

To acquire hydrological data with a high temporal resolution, 13 automated open stand pipe piezometers, one discharge station (stage gauge) and one weather station were deployed in the Aruvikkal catchment from May 2007 onwards. A partially complete landslide inventory was prepared based on governmental reports, news paper clips, field work and community-based approaches. Time series analysis conducted on the rainfall and the corresponding hydrological responses revealed that the slope hydrology of the catchment exhibits very rapid response to rainfall; the discharge of the catchment will respond within 1 h. The average time necessary for a significant response of the perched water level to rainfall was 6 h while during the peak rainy season this lag may reduce to less than 1 h. It was also observed that continuous and high intensity rainfall of about 4 h may cause a steep rise in the perched water table up to critical levels in regolith filled bed rock depressions and the persistence of this level for ~10 h may lead to shallow landslides in the catchment. Thus to capture the hydrological responses that lead to shallow landslide initiation in the catchment, the hydrology model should be able to predict these responses with a temporal accuracy of at least 6 h which necessitates the model time step to be of at least 1 h in resolution.

All soil mechanical properties necessary was measured and spatially parameterized. Block regression kriging with altitude, aspect, slope, distance from streams, compound terrain index, curvature and land use as predictors was identified as the 'best' predictor of soil depth in such anthropogenic landscapes (Kuriakose et al. 2009b). Depending on the dominant plant species in each land use unit and the soil depth the corresponding root reinforcement applicable was derived from measured root tensile strength, pull out strength, root diameter and root density data. Nine species of plants were tested of which Teak (Tectona grandis) trees offered the highest amounts of net root reinforcement (Kuriakose and Van Beek 2011). The STARWARS model was calibrated and validated against the observational data of 2007–2008 period. The PROBSTAB was calibrated and validated against the landslide inventory of 2001 and 1993 respectively, for which the corresponding daily rainfall data available from a nearby tea estate was disaggregated to hourly using stochastic methods (Kuriakose et al. 2009a).

In order to evaluate the effects of long term and short term land use changes on slope stability in the region, historic (1913–2008) land use maps, soil depth maps and root reinforcement maps were derived. In addition the land use maps and corresponding root reinforcement maps of two future scenarios (2016 and 2058) were also derived. Although, these future land use scenarios represent only one of the many possible realizations, the interest in them lies in the fact that they show a possible scenario of reforestation, and hence conservation of the area. These data sets were used to simulate the corresponding slope stability and probability of failure conditions based on the 1985 rainfall time series (disaggregated to hourly) which included the most extreme

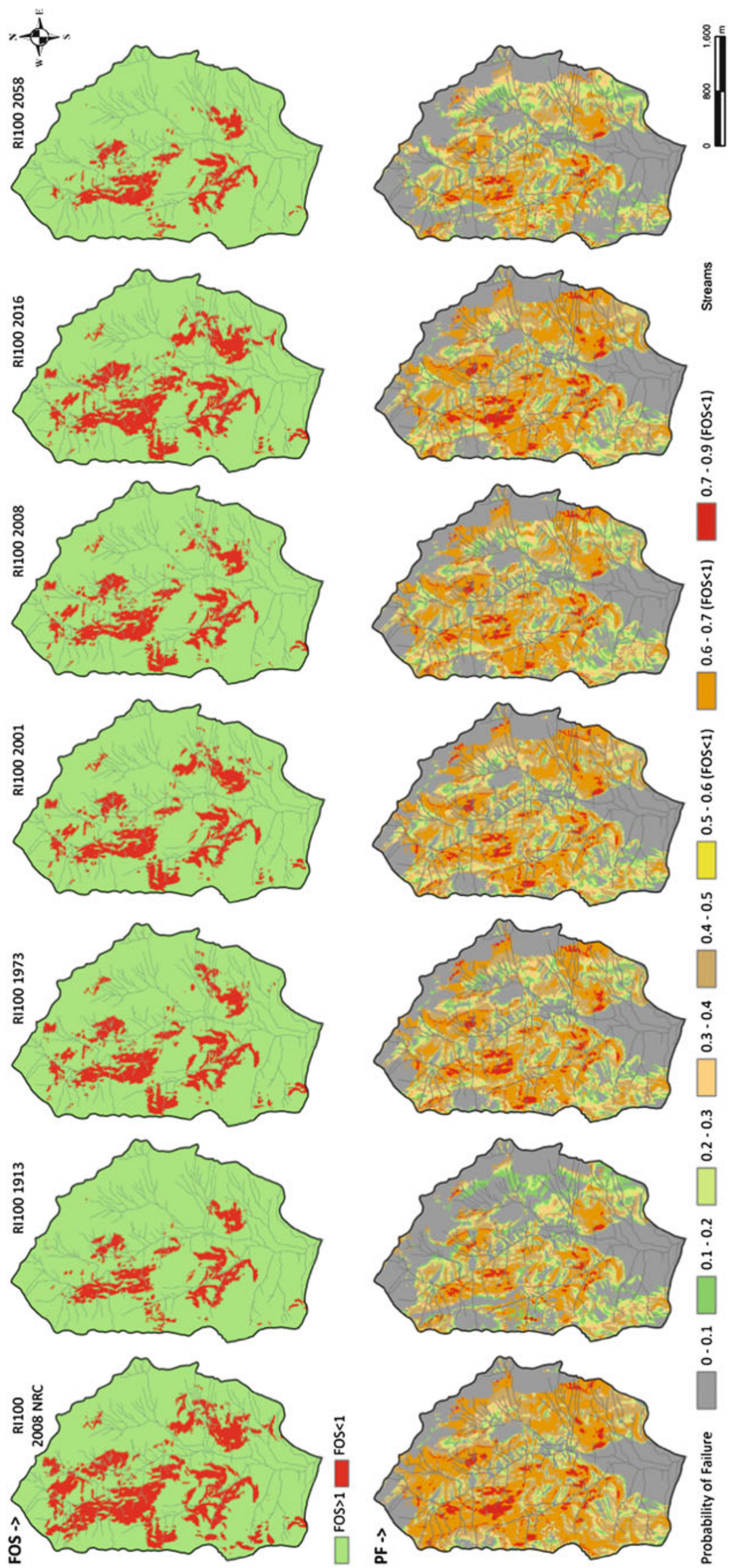

Fig. 8 Area with FOS < 1 and the probability of failure corresponding to the land use scenarios of 1913, 1973, 2001, 2008, 2016, 2058 and the no-root cohesion condition (Kuriakose et al. 2010)

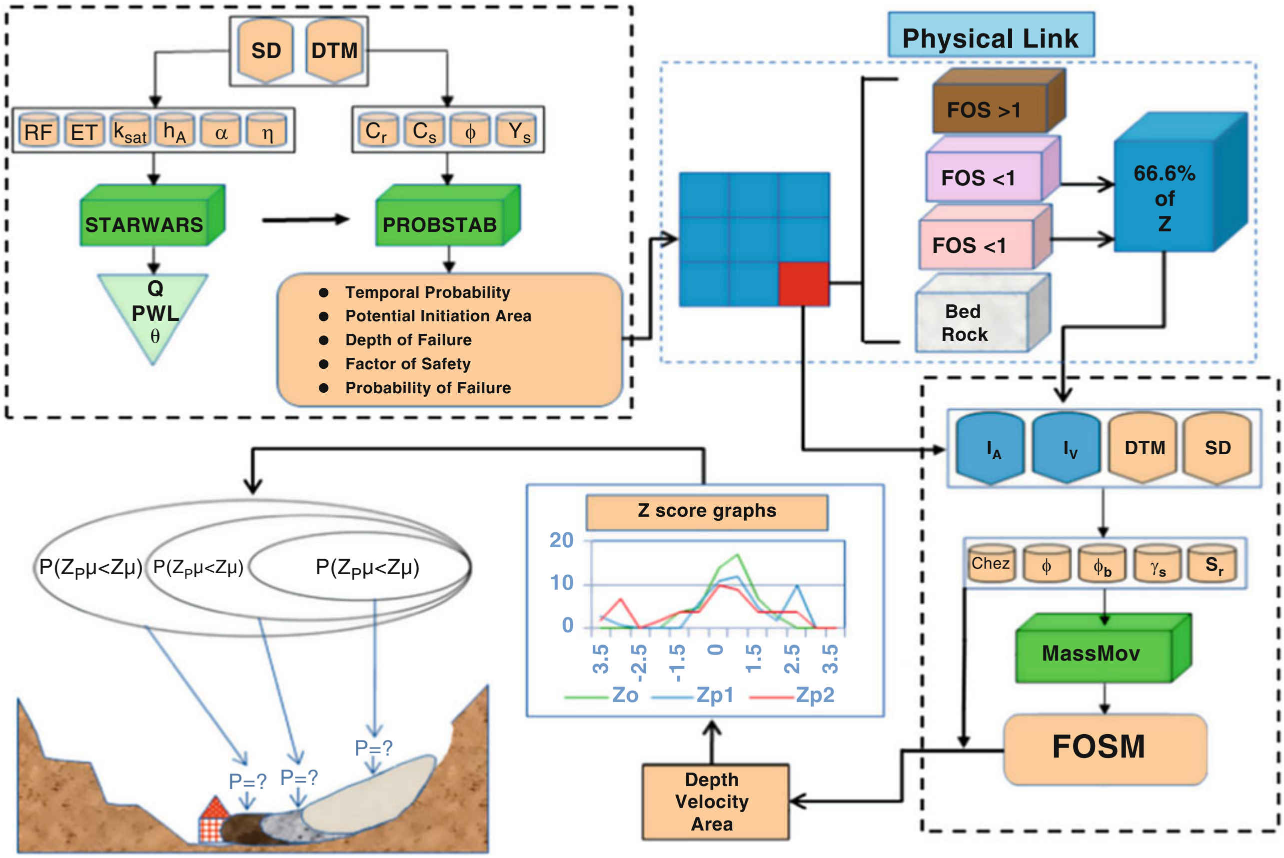

Fig. 9 Scheme for coupling the results of STARWARS + PROBSTAB with the runout model MassMov2D

daily rainfall that has caused at least one shallow landslide in the study area in the past 57 years (Fig. 8).

The land use changes from the pre-plantation (1913) scenario to present (2008) have resulted in an average increase in the potential area of failure by 43 % and the spatio-temporal probability of failure by 49 %. Despite setting up an idealistic land use scenario for the distant future (2058), the overall slope stability did not revitalize to the pre-plantation period (1913) because the root reinforcement available was relatively lower as compared to the pre-plantation period.

The simulation may imply that a policy of reforesting to promote conservation (stability) in the area might not have the intended results.

The research showed that in the study area, the transition probability of land use change (and consequently the changes in soil depth and root cohesion) outweighs the rainfall quantity in determining the spatio-temporal probability of shallow landslide occurrence. This is in contradiction with the commonly held belief that the temporal probability of shallow landslides can be quantified with only the return probability of landslide-causing extreme rainfall events. Hence, transition probabilities of land use should be assessed and incorporated in regional scale landslide hazard assessments that utilize heuristic and stochastic techniques, especially in such anthropogenically modified terrains.

The study also analyzed the coupling of the initiation model with a runout model. A tentative scheme for coupling the results of STARWARS + PROBSTAB with a runout model named MassMov 2D (Begueria et al. 2009) is presented in Fig. 9. By systematically varying the input variables based on a first order second moment approach (FOSM), one can derive the maximum, average and minimum extent of runout possible, given a certain initiation area and volume of material. Depending on the number of times that a given pixel gets affected by a debris flow, one can derive the spatial probability of being affected by a certain magnitude (depth, area or velocity) of debris flow, while the initiation model can provide the temporal probability of initiation of such a debris flow.

Case Study D: Landslide Risk Assessment Along Transportation Corridors

The fourth case study focused on quantitative landslide risk assessment along transportation corridors (a road and a railroad) in the Nilgiri area (Tamilnadu), making use of a nearly

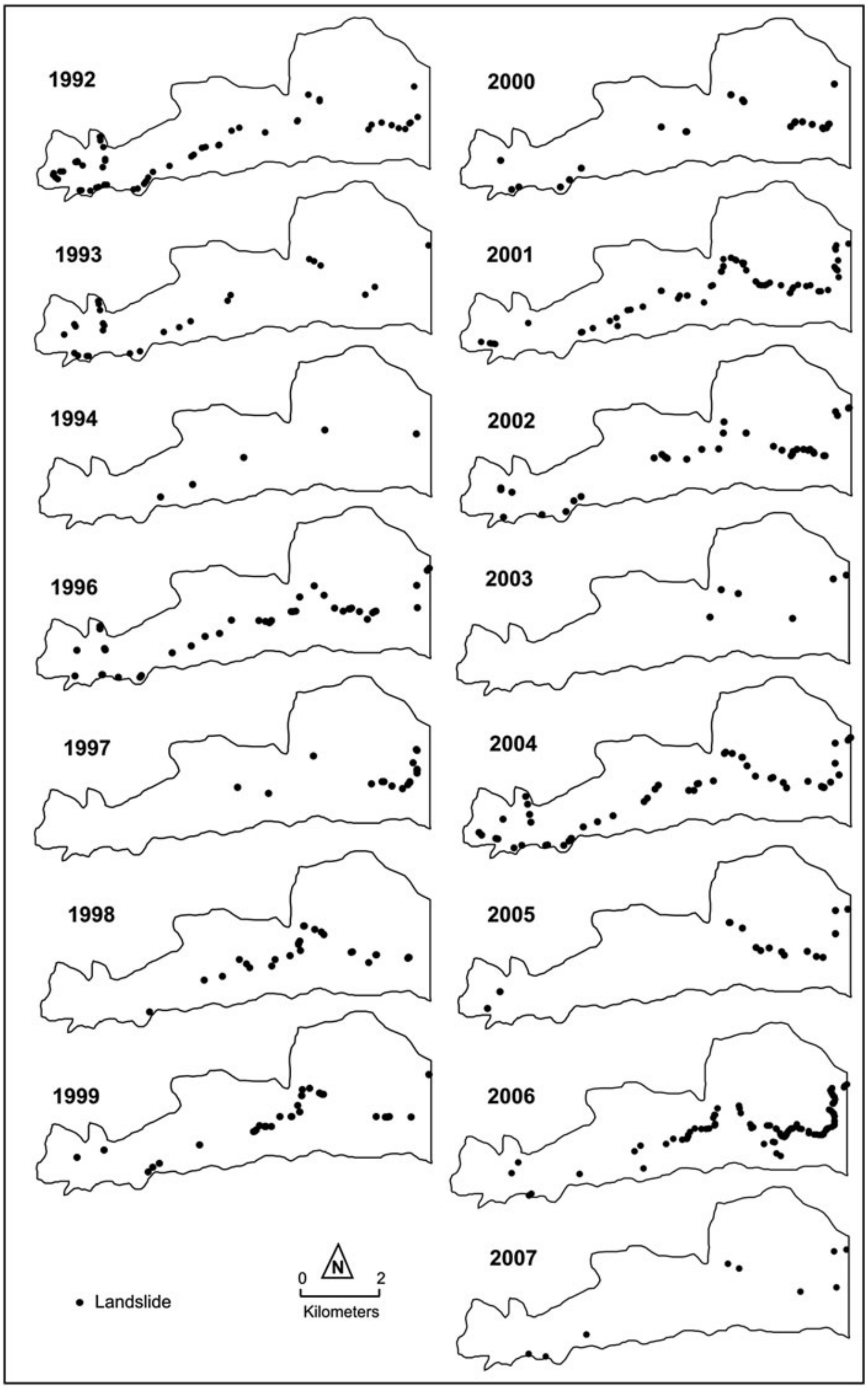

Fig. 10 Spatial distribution of landslides in different years along the railroad. Landslides are shown as *points* irrespective of their size

complete historical database of landslide occurrences over the past 24 years (Jaiswal et al. 2011c).

Generation of Landslide Inventory from Archives

In the Nilgiri area it was possible to generate a very detailed landslide inventory based on historical data. The records include railroad and road maintenance registers, and technical reports. From 1987 maintenance data were present in an analog form recorded in a register. This register is updated soon after the occurrence of a landslide triggering event and is used for tendering contracts for (rail)road clearance. The technical reports include published and unpublished technical

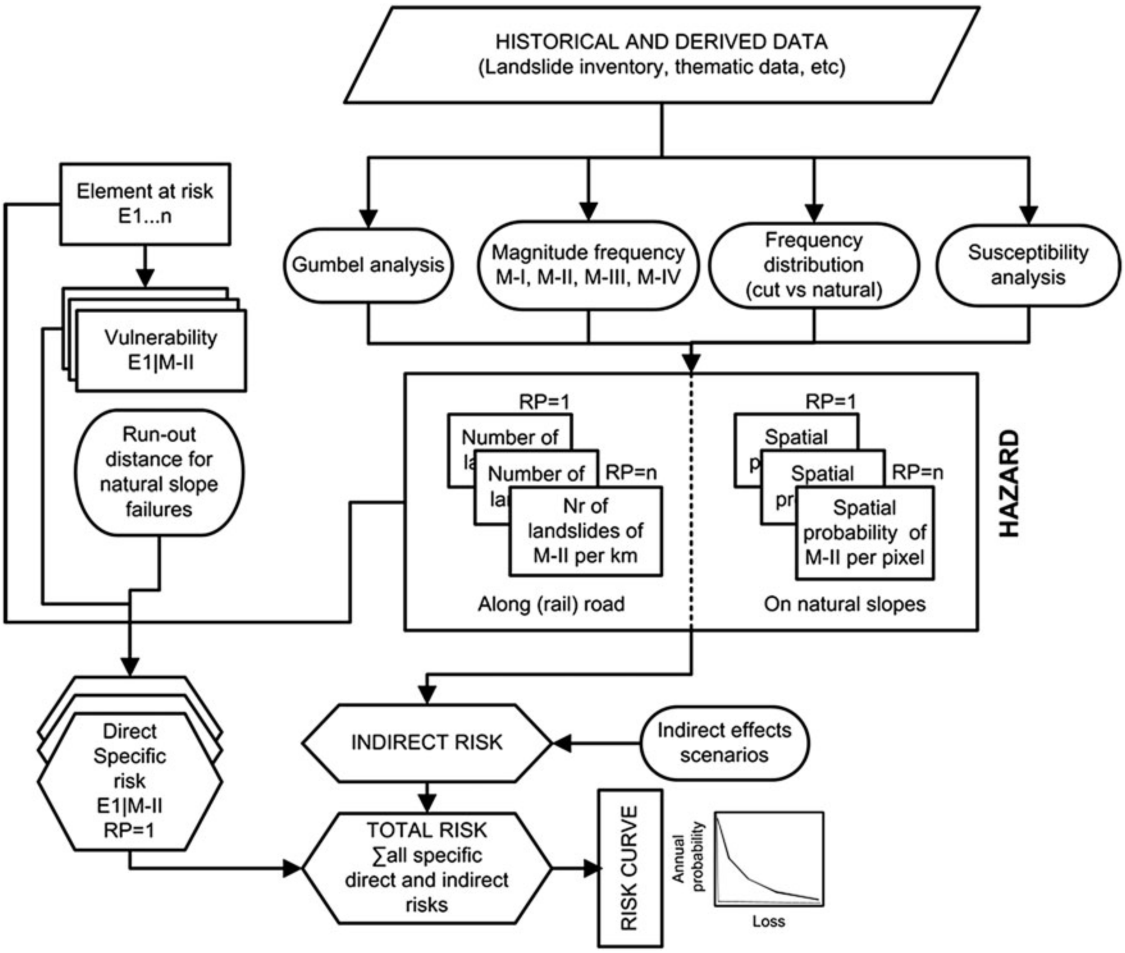

Fig. 11 Flow diagram showing the process adopted for landslide risk analysis (Jaiswal et al. 2010b)

documents of landslide investigations. The data were used to reconstruct the landslide occurrences along the road and railroad over several decades. Data on 901 landslides were compiled from the historical records covering a 21 years period from 1987 to 2007. Figure 10 displays annual landslide maps from 1992 to 2007 (Jaiswal).

The landslide dataset was used to analyze the landslide intensity for different years, by calculating the recurrence interval of the percentage of unit lengths of the road and railroad that would be interrupted during triggering events (Jaiswal and Van Westen 2009).

To quantify landslide hazard using such a complete inventory, as was the case for the Nilgiri case, two essential parameters were assessed: the probability that landslides affecting the infrastructure are of a given magnitude, and total number of landslides per kilometer affecting the infrastructure in a given return period. The landslides in the study area were grouped in five magnitude classes ranging from I (less severe) to V (catastrophic). The classification is essentially based on landslide type and volume but it also gives other characteristics such as the location of the source, damage potential and human perception about the risk

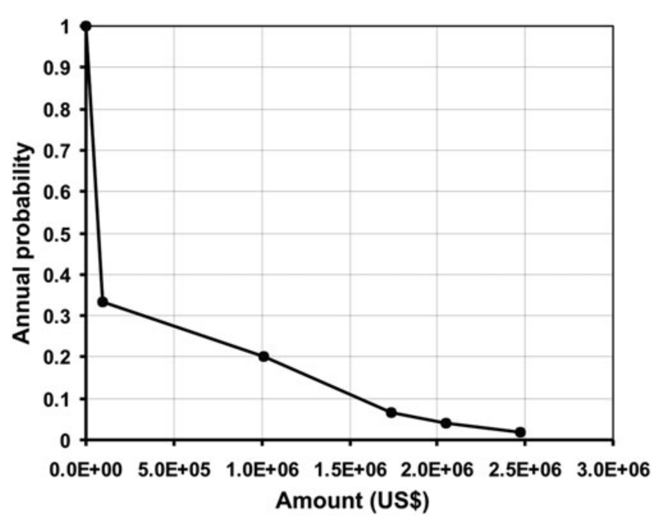

Fig. 12 Risk curve for total landslide losses in the study area (maximum risk) expressed in monetary value (US$) (Jaiswal et al. 2011a)

related to landslides. The probability that a landslide affecting the infrastructure is of a given magnitude class was estimated using magnitude-frequency relationships. Annual

Fig. 13 Participants of the symposium on landslide hazard and risk assessment in India, held in ITC on 4 and 5 July 2011

probability of landslide occurrence was estimated from the observation of the frequency of past landslide events, by determining the annual exceedance probability (AEP), using Poisson and Binomial distribution models. The estimation of landslide risk, particularly indirect risk resulting from the blockage of transportation line, requires estimation of the number of landslides reaching the infrastructure per year. The number of landslides is required to calculate the blockage period based on clearance time needed per cubic meter of debris. The relation between the annual probability of occurrence of landslides (or return period) and the number of landslides of a magnitude class per kilometer was established using a Gumbel extreme value distribution (Jaiswal et al. 2010a).

Logistic regression analysis was carried out to model the susceptible areas to landslides on natural slopes. Rainfall threshold analysis was used to estimate the temporal probability of landslides, and magnitude-frequency analysis to obtain the probability of landslide size. These data were combined in an analysis of landslide initiation hazard on cut and natural slopes (Jaiswal et al. 2010a). Landslide run-out analysis was carried for landslides on natural slopes. Landslide vulnerability was established for landslides with different magnitudes and for different elements at risk. Landslide hazard and risk estimation was done using landslide events that occurred between 1987 and 2007 and the results were validated using landslides that occurred in 2008 and 2009. As a final output direct risk was quantified for properties (alignments, vehicles, buildings, and plantations) and people (commuters and residents) and indirect risks due to the traffic interruption (Jaiswal et al. 2010b, 2011a, b) (See Fig. 11).

The results provided a quantitative estimate of total annual landslide losses, expressed in monetary value (US$) for properties (Fig. 12) and in annual probability of death for people. An F-N curve was used to express the societal risks. The results are of important societal value and will provide inputs for planning risk reduction strategies, for developing risk acceptance criteria and for financial analysis for possible damage in the study area. The methodology provides a cost-effective approach to estimate direct and indirect landslide risks. The methods can be applied elsewhere if a similar historical landslide data is made available.

The research also presented the perception of Nilgiri people to landslide risk and the use of the obtained hazard and risk information in reducing landslide risk to the society.

Conclusions

The joint research programme between GSI, NRSC and ITC, in which also other Indian organizations were involved (IIRS and CESS) resulted in five Ph.D. thesises (Kuriakose et al. 2010; Ghosh et al. 2011b; Jaiswal et al. 2011c; Martha et al. 2011b; Das et al. 2011) and over 20 publications in scientific journals. The defence of four of the researchers was integrated with a symposium on landslide hazard and risk assessment in India, which was held on 4 and 5 July 2011 (See Fig. 13) in ITC, The Netherlands. The results will also be presented in a workshop in November 2011 in Hyderabad, India, during which further steps towards the development of improved guidelines for hazard and risk assessment in India will be discussed.

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