Chapter 8
Landslide Susceptibility Mapping, Vulnerability and Risk Assessment for Development of Early Warning Systems in India

Sudesh Kumar Wadhawan

Abstract Landslide or the landmass movement is a geomorphic hill slope physical process of mass-wasting resulting in downslope rolling of large mass of debris, regolith and soil under influence of gravity. It is caused by a combination of particular geo-factors that are region or territory specific. Landslides are generally triggered and activated by substantial precipitation and/or earthquake tremors and other anthropogenic interventions such as over the top cutting of slant for development of mountainous roads/streets and other excavations for civil structures, etc. The relatively young entire Himalayan hilly tract, mountainous steep slopes in sub-Himalayan landscape of North-east India, Western Ghats, the Nilgiris in Tamil Nadu and Konkan ranges are susceptible to landslides or debris flow.

In order to formulate strategies to minimize societal impacts of landslides, a systematic approach would entail preparation of Landslide Susceptibility Maps linked to landslide incidence inventory and making them available to the concerned stakeholders for necessary preparatory and mitigation measures. Geological Survey of India (GSI) being the nodal agency for landslides studies in India formally launched on February 05, 2014 the National Landslide Susceptibility Mapping (NLSM) programme which has been a geoscientific exercise on 1:50,000 scale on GIS platform in making both quantitative or qualitative estimates of spatial distribution of landslides which either exists or has the potential to occur in a given area. GSI has formulated a set of standard operating procedures that emphasize on geoparametric data collection (as per standard and devised formats) for landslide inventory. These data sets are synthesized with relevant spatially-distributed causative thematic maps into susceptibility zonation which represents geospatial information indicating intensity and propensity of landslides. Such baseline data will ultimately lead to the collation and evaluation of landslide hazard and risk and mitigation plans. It will also help in disaster preparedness of the country and to indicate areas critical for landslide monitoring and developing early warning system

S. K. Wadhawan (✉)
Geological Survey of India, Jaipur, India

(EWS). It is aimed to demarcate and facilitate prioritization of areas for further detailed studies (Meso- and Micro-scales) and help in Regional Land Use Planning and provide the scientific basis for framing the Land Use Zoning Regulations. Several lessons were learnt from Uttarakhand disaster of June 2013 in India that compelled re-evaluation of the existing methodology of conducting geosurveys of macro scale landslide susceptibility maps. Additional geofactors that also need to be considered include: effect of toe erosion by higher order streams; effect of long run-outs of the debris flows and drainage morphometry; nature and size of clastic components, etc.

It is intended to elaborate here a synthesis of various approaches and constraints on continuing research on such country-wide programmes on landslides related geohazards characterization and its implications on evolving EWS for the societal preparedness and resilience for mitigating impending disasters. However, any method of predicting landslide susceptibility needs validation which sometimes may be difficult in areas having no land sliding history. Besides, EWS need also to highlight mitigation efforts/remedial measures through geotechnical and engineering solutions as suited to Indian conditions on case to case basis, delineation of safe escape routes in the event of a landslide/debris flow/flash floods, and for optimum utilization of available resources.

8.1 Introduction

Landmass movement or the landslide is a geomorphic hill slope physical process of mass-wasting resulting in downslope rolling of large mass of debris, regolith and soil owing to influence of gravity. It is caused by a combination of particular geo factors that are region or territory specific (e.g., geomorphology, slant and slope aspects, geology: bed-rock and litho-structures, nature of chemically altered or physically disintegrated weathered material, land-cover and land-use and so on). Such hill slope processes are generally activated by substantial precipitation or earthquake tremors. In Indian landscape, landslide or slope failure occasions are for the most part activated by monsoonal precipitation, however cases of seismic tremor activated landfalls and avalanche are likewise normal in India, for instance, the Uttarkashi Earthquake, Chamoli Earthquake, Kashmir Earthquake, Sikkim Earthquake, and so forth, produced several landslides in recent years [1, 2]. The whole Himalayan tract, mountains slopes in sub-Himalayan landscape of North-east India, Western Ghats, the Nilgiris in Tamil Nadu and Konkan ranges are susceptible to debris flow or landslides ($\sim$0.42 million km^2; including the permafrost locales makes it around 0.49 million km^2). Other than the precipitation and earth shaking tremors, the toe disintegration by stream and unscientific or informal anthropogenic activities, for example, over the top cutting of slant for development of mountainous roads/streets and other excavations for civil structures can likewise trigger downslope movement of loose/poorly consolidated rock-mass or debris.

India is amongst the worst affected countries in the global scenario where landslides are perennial natural hazards causing irreparable losses to properties and

infrastructure. Even, fatality due to landslides is quite high in India compared to the rest of the landslide-affected nations in the world. In India, the vulnerability to landslides mainly owes to the presence of complicated geo-environmental setting, long stretch of active Fold-Thrust-Belt (FTB) in the steep mountainous tract of the Himalayas in the north, long near coastal steep mountains alongside the Arabian Sea and unsustainable anthropogenic activity in hilly regions (Fig. 8.1). More prominently, the landslide-prone terrains in India also receive very high amount of monsoon rainfall for about 5 months (June–October) in a row every year besides severe storms, cyclones and depressions, which act as a vital triggering factor for landslides. Moreover, the vast extra-peninsular tract in India which hosts mainly the landslide-prone areas of the country (0.42 million km^2) is also equally prone to earthquakes of moderate to high/very high magnitudes, which also act as another potential triggering factor. Therefore, the risk to landslides of all types remain to be quite substantial in India.
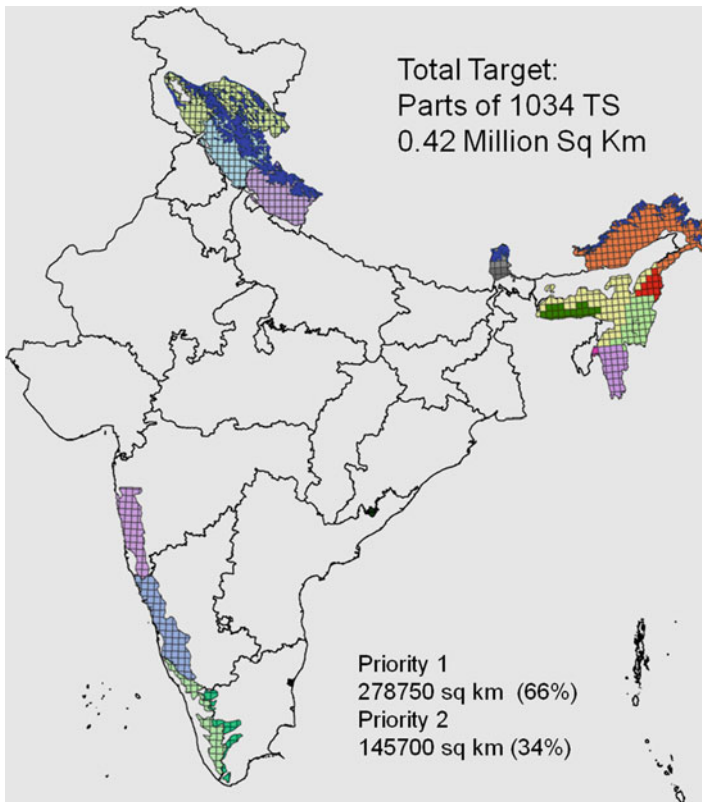

Fig. 8.1 Landslide-prone terrains in India (Source: GSI portal <http://www.portal.gsi.gov.in>, [32])

It is evaluated that landmass movements have caused more harm to properties than some other unstable topographical risk [3–5]. The reasons ascribed to this include: over exploitation of characteristic natural assets, extensive deforestation, change in atmospheric conditions, increment in slope-dwelling populace and uncontrolled strip mining thereby bringing about a higher vulnerability of surface soil to creep/flow under gravity and higher instability of the occupied human settlements [6–9]. As indicated by the National Disaster Management Act (2005) [64], the Landslide Disaster Management Plan should give utmost weightage on readiness and mitigation as opposed to adopting more consumptive temporary courses of action for rescue, help and recovery measures. In this manner, the onus of successful overseeing landslide related risks turn into a challenging undertaking because preventing or minimizing losses owing to an inevitable and consequential geomorphic phenomenon like landslide needs proper geo-scientific appraisal and studies which need to be an integral part of any legitimate geo-scientific examination and studies which ought to be the fundamental piece of any detailed point by point disaster management plan or the debacle administration design leading to an advancement of early cautioning framework or Early Warning System [10, 11].

In order to formulate strategies to minimize societal impacts of landslides, a systematic approach would entail preparation of Landslide Susceptibility Maps linked to landslide incident inventory and making them available to the concerned stake holders for necessary preparatory and mitigation measures. National Landslide Susceptibility Mapping (NLSM) is an exercise in making quantitative or qualitative estimate of spatial distribution of landslides which either exists or has the potential to occur in a given area [12]. Although such exercise is intended to provide potentially most vulnerable areas where landslide is expected to occur, yet it has not been feasible to predict time frame or magnitude of the event.

According to the National Disaster Management Act 2005, the Union Government (National Disaster Management Authority, NDMA) [13] is tasked with fortifying country's readiness to prevent any perilous hazard including slope failures rather than additional focusing on cost prohibitive remediation amelioration and alleviation and recovery processes. In this manner the assignment of multi-scale landslide zonation is an imperative geo-data device designed to assist the organizers and heads to limit such misfortunes resulting from such landslide vulnerability. To achieve this objective, the nodal Ministry of Mines and its appended Department – the Geological Survey of India (GSI) had propelled NLSM (National Landslide Susceptibility Mapping) Program to complete nation-wide standard scale (1:50,000) landslide susceptibility mapping of the large mass wasting prone territories of India in an arranged way which are probably going to be finished by 2020. GSI had started working on NLSM programme with effect from 1st April 2014 after it was formally launched in New Delhi on February 05, 2014 by the Hon'ble Minister of Mines, Govt. of India. The NLSM project in Priority-1 target areas (total target – 0.282 million km^2) will cover 62% of target by end March 2017 (1,76,000 km^2). One can view the output maps of Uttarakhand at:- http://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx

Another major concern is the maintenance of the transportation corridors or the so called "Life Line" in hill areas. Frequent landslides along transportation lines not

only result in the direct loss to properties but also indirect loss by blocking the road and rail and communication links [14, 15]. Therefore, a timely forecasting of landslides along the transportation corridors and issuance of early warning to alert the traffic is extremely important for the benefit of the society. Early warning of landslide is also important in the context of the 'residual risk'. Humans deliberately thrive in such areas and become adopted to the impending risks owing to certain inherent advantages such as running businesses, proximity to workplace, etc. Studies have shown that people residing in such areas for many generations do not want to leave their native and ancestral places in spite of having witnessed landslide disasters [16]. Under such circumstances, the only opportunity to minimize the landslide loss is to issue timely alert to the community about the impending hazard through the use of an early warning system, EWS in India. Official Nodal Agency for landslide investigations in India is the Geological Survey of India. It realized the importance of landslide forecasting in the aftermath of 2003 Varuna Parvat Landslide in Uttarakashi, Uttarakhand. Landslide forecasting and risk assessment is particularly significant in countries with emerging economies where spatial planning is not yet fully appreciated while attempting land use planning, leading to civic and infrastructural developments in vulnerable and unstable hill slopes and areas prone to landslide disasters. The recent research in risk quantification and threshold modeling for landslide initiation [16, 17] formed reasonable basis for GSI to step into a multidisciplinary science of landslide risk reduction through early warning system [11, 18].

8.2   Role of Geosciences and Engineering Geologists

Landslide, being a geomorphic phenomenon largely depends on various pre-disposing geofactors such as slope morphometry, lithology, structure, land use/cover, geohydrology, etc. and a variety of triggering factors such as rainfall, earthquake, etc. [19–22] Therefore, it is naive to consider that landslides and their spatial distribution to be a stochastic phenomenon, rather their spatial distribution is well controlled by various combinations of geofactors and their relative importance depends on different failure mechanisms [23–26], which can best be studied by application of different geoscientific tools [27]. Thus role of geosciences and application of its core knowledge in studying landslides remain the most important analytical and scientific approach to understand the causes and behaviour of landslide-related hazards [28].

The Geological Survey of India, being the premier geoscientific organization in India, is mandated to provide a gamut of necessary inputs on geological/geotechnical attributes of various slope-forming materials to meet the requirement of various modes of landslide-related studies and designing of disaster-resilient plans and protective structures for minimizing the losses caused by this particular hazard. However, being the nodal agency, the responsibilities of the GSI includes coordinating all activities related to landslide hazard mitigation and management, assisting

and providing technical support to the National Disaster Management Authority (NDMA) towards the capacity building and skill development centres such as the National Institute of Disaster Management (NIDM) and the newly-formed Technical Advisory Committee (TAC) on landslide disaster mitigation and management – the topmost advisory body of the Government of India in addressing all matters of landslides and related issues.

8.2.1 Geoscience-Based Standard Operating Procedure (SOP)

The sequence of systematic geoscientific activities in investigating and managing landslide disasters can be specified and elaborated as a Standard Operating Procedure (SOP). GSI has formulated a set of operating procedures on large mass wasting investigations in India that emphasize on systematic geo-parametric data collection and compilation (as per standard and devised format) for landslide inventory. This data is synthesized with relevant spatially-distributed causative thematic maps into susceptibility zonation which represents integrated geospatial information indicating intensity and propensity of landslides. This baseline data should ultimately lead to the collation and evaluation of landslide hazard and risk and mitigation plans.

Geoscientific studies of landslides also provide necessary inputs on geotechnical aspects to meet the requirement of disaster-resilient structures. It engages in studying and ascertaining the causes, nature of various geohazards and associated disasters with an aim to provide input parameters to work out suitable corrective measures. Technical design and execution of relevant corrective measures are the responsibility of the concerned stakeholders. Geoscientific organizations like GSI and others, render geotechnical and engineering geological inputs to the structural designer/ geotechnical engineers, who in turn design the protective structures. The possible instability of slopes and seismic status of the area on regional scale are indicated beforehand in their reports so that the stakeholders can incorporate necessary corrective measures in design of the structure required.

8.2.2 Pre-hazard Stage Investigations

Macro Scale Landslide Susceptibility Zonation on 1:50,000 are followed to classify the landslide prone terrains of the country into different tracts according to their proneness to vulnerability to mass wasting for perspective project planning. It is a multi-thematic exercise taking into account the relevant causal geofactors such as: (i) slope morphometry (slope gradient, aspect, slope shape), (ii) lithology, (iii) structure, (iv) geomorphology, (v) land use/cover, (vi) geohydrology, etc., as separate causative themes and by establishing either through an expert-driven or data-driven interrelationships with different types of landslides, adopting a number of

standard and well-established techniques [27, 29, 30]. The main objective of this susceptibility zonation is to facilitate the planners and inhabitants to understand the slope stability potential of the land parcels in an area in fragile hilly or treacherous mountainous terrains for use, further/future development and deciding on protection measures to ameliorate the slope stability conditions.

However, from the experiences of major event like that of the recent Uttarakhand disaster of June 2013, several lessons were learnt which compel re-evaluation of the existing methodology to prepare macro-scale landslide susceptibility maps. The additional geofactors that also need to be considered in light of the initiation of numerous landslides and colossal damages in Uttarakhand event are: (i) effect of toe erosion by higher order streams, (ii) effects of unplanned development of settlements on lower-level geomorphologic terraces and flat lands and proximal to trunk or higher order river/drainage systems, (iii) effect of long run- outs of the debris flows on drainage system, etc.

The existing landslide susceptibility maps exhibit zones having varying degree of susceptibility (e.g., high, low, moderate, etc.) but lack the basic information such as location of stable flat ground nearby which is to be delineated away from the river and the steep potentially failure-prone back slopes; roads/foot tracks leading to stable higher grounds that could act as safe escape routes in the event of a landslide/debris flow/flash flood, etc. It is thus relevant that after evaluating the scientific results of the landslide susceptibility maps, a user-friendly map depicting stable and unstable slopes along with all the available road/foot-tracks, rivers, higher order streams/drainages, etc. should also be prepared, marked on map and the same also to be supplied to the stakeholders and end users to facilitate them in planning disaster escape routes and relief and rehabilitation measures.

8.2.3 National Landslide Susceptibility Mapping (NLSM) Programme

National Landslide Susceptibility Mapping Programme aims to prepare seamless Landslide Inventory and Landslide Susceptibility maps in the mountainous areas of India on 1:50,000 scale which would act as the fundamental input to devise and compile maps on the macro-scale landslides geohazards and disaster prone areas of India. NLSM intends to provide Pan India macro-scale baseline information for the first time to accurately and quantitatively assess the spatial locations of landslide-prone areas in the country (Fig. 8.1). It will help in disaster preparedness of the country and will indicate areas critical for landslide monitoring and early warning. It will demarcate and facilitate prioritization of areas for further detailed studies (on Meso- and Micro-scales) and help in Regional Land Use Planning and provide the scientific basis for framing the Land Use Zoning Regulations.

Geo-parametric data sheet for collecting information and geodata on landslide inventory and details on consequent damage is compiled and documented at national
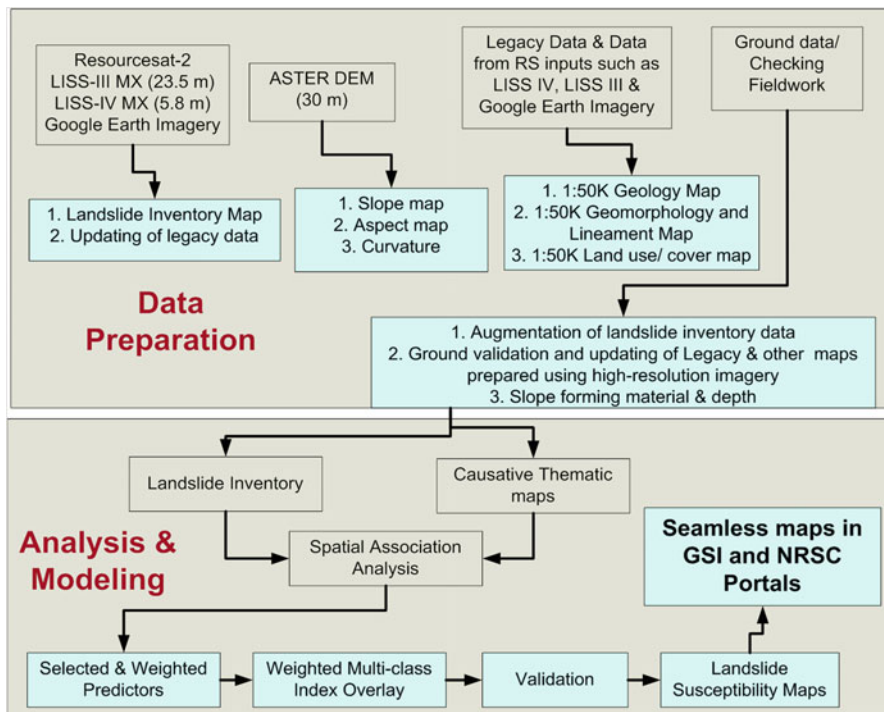
Fig. 8.2 Flow diagram is prepared to present various steps and stages of relevant data generation/compilation and synthesis (Source: GSI portal <http://www.portal.gsi.gov.in>, [12, 32])

level by GSI. A flow diagram is prepared to present various steps and stages of relevant data generation/compilation and synthesis (Fig. 8.2). As a first step, it is imperative to create and strengthen a Landslide Inventory which documents the specific spatial and temporal and other attribute of a landslide incidence on a GIS platform [12, 31, 32]. Thus a geo-referenced spatial database is created. GSI's endeavour in preparing such a national landslide database for the entire country in a GIS-based dynamic platform would be extremely beneficial in future and will also enable the Indian landslide scientists to work on predicting the temporal and magnitude component of such hazard. As a necessary logical follow-up, effective implementation of NLSM is facilitated which would lead finally to research and developement of EWS at the most vulnerable selected sites in India.

8.2.4 Web-Based Landslide Incidence Inventory Map Service

Geological Survey of India has developed a Web-Based Landslide Incidence Inventory Map Service where details of more than 1000 landslide incidences are currently

available (as on 25/04/2017). Landslide incidence compilation and uploading in such web-based interactive platform is a dynamic exercise and needs updating on a regular basis as and when a new landslide occurs. In this endeavour, GSI has already taken up systematic field surveys and research programme, the first phase of which is scheduled to be completed by March 2017. GSI primarily gathers the relevant information for this purpose from two type of sources: (i) GSI's old landslide investigation reports through compilation, and (ii) from the on-going landslide investigation programmes of GSI such as NLSM Projects which are targeted to be completed on priority by 2020, and other site specific post-monsoon field-based landslide inventory mapping programmes taken up in all the landslide-prone areas each year. To access this data, one can visit GSI Portal (www.portal.gsi.gov.in) and navigate to "Recent Landslide Occurrences in India" under "Interactive Maps" within "Interactive GIS Maps". Or, the following link can be used to access the Beta-version of the map service directly at: <http://www.portal.gsi.gov.in/gismap/landslide/index.html>.

The spatial database of landslide incidences can be seen on an Indian base map with important roads, state boundaries and important places (towns, villages) marked on it. Landslide incidences are shown as point objects. Details about various attributes (maximum 41 attributes, as given in Table 8.1) per landslide incidence are also listed [11, 12], which can be observed using "identify" button in an interactive GIS Map Service environment. The metadata showing such textural attributes can also be exported as "pdf".

Benefits likely to accrue as a result of this project include the following:-

- Can give pan-Indian geospatial scenarios about past/historic landslide occurrences or hazard
- Can evaluate the vulnerability and risk to roads, buildings and other physical features etc.
- Such type of GIS-based landslide inventory is easier to update, retrieve and also to spatially evaluate its relations with other geofactors such as slope, geology, land use, geomorphology etc.
- Acts as the most crucial and fundamental input to any landslide susceptibility, hazard and risk analyses

8.2.5 Post-Hazard Stage Investigations

8.2.5.1 Immediate Response: Reconnaissance (Level-1)

The immediate response to any natural disaster is undoubtedly evacuation, relief and rehabilitation. At this crucial stage, consultation of the available macro-scale landslide susceptibility maps by the people engaged in relief and rehabilitation work (NDRF, Army, NGO, etc.) may become helpful to plan evacuation and relief routes, etc. Embarking on a field-based scientific investigation, by GSI and related agencies,

Table 8.1 Geo-parametric sheet for collecting information on landslide inventory and damage data

No.	Field	Description
1	Landslide no.	State/district/toposheet/year/serial number
2	State	Name
3	District	Name
4	Toposheet	Survey of India number
5	Name of the slide	Maximum 20 character
6	NH/SH/locality	National highway/state highway/name of nearest village or locality (maximum 50 character)
7	Latitude	Latitude in decimal degree (using WGS 1984 datum)
8	Longitude	Long in decimal degree (using WGS 1984 datum)
9	Length	Meters
10	Width	Meters
11	Height	Meters
12	Area	m^2
13	Depth	Meters
14	Volume	m^3
15	Run-out distance	Meters
16	Type of material	Rock/soil/debris/rock-cum-debris/debris-cum-rock
17	Type of movement	Falls/topple/slide/subsidence/flows/lateral spread/creep
18	Rate of movement	Exceedingly quick, severely quick, rapid, moderate speed, gradual, very gradual, exceedingly gradual speed
19	Activity	Discernible/rejuvenated/indiscreet/temporarily quite/residually firmed-up/inactive/firmed-up in place/fully anchored
20	Distribution	Active slope process/retrogressive/spreading/expanding/restricted/creeping
21	Style	Superimposed/successive/repetitive/distinctive event
22	Failure mechanism	Shallow planar failure/deep planar failure/shallow rotational failure/deep rotational failure
23	History	Date of initiation and subsequent reactivations (date/year)
24	Geomorphology	Topography, landform, processes (maximum 100 character)
25	Geology	Lithological description, stratigraphic disposition (100 character)
26	Structure	Details of discontinuity in whole circle (e.g.: J1: 50°:150°)
27	Land use/land cover	Barren/cultivated/forest /rural/urban/anthropogenic activity/any other (maximum 50 character)
28	Hydrological condition	Dry/wet/dripping/flowing
29	Triggering factor	Rainfall in mm/daily or hourly rainfall data/earthquake (intensity in Richter scale)/lake bursting (GLOF)/anthropogenic factors like road cutting, blasting, etc. (maximum 50 character)
30	Death of persons	Numbers
31	People affected	Numbers
32	Live stock loss	Cattle death
33	Communication	Road/rail/transmission line (blocked/damaged)

<div align="right">(continued)</div>

Table 8.1 (continued)

No.	Field	Description
34	Infrastructure	Numbers of houses/building/dam/barrages damaged
35	Other land use	Agriculture/forest/barren (maximum 50 character)
36	Geo-scientific causes	Topple/planar failure/wedge failure / pore water pressure/piping/ reduction of strength on super-saturation/toe erosion by stream/gully erosion/head ward erosion, anthropogenic activities (unplanned cutting of slope, unplanned construction, loading at head region, afforestation, adverse cultivation pattern/combination of above factors/any other factors (maximum 200 character)
37	Remedial measures	(maximum 200 character)
38	Remarks, if any	Assessment remarks, if any (maximum 200 character)
39	Photographs, sketch	Photographs, sketch of plan affected by landslide – Quantity/type of cultivation and section of the slide send in jpg format
40	Summary/ abstract	(within 1000 character)
41	Pdf, soft copy	Soft copy of landslide report if data is collected/compiled from past data/maps, where feasible

immediately after any disaster may be difficult because utmost priority just after the disaster is given for relief and rehabilitation work. Moreover, inaccessibility due to damages in surface communication route hinders any immediate field inspections. Therefore, during that time, maximum stress is given for preliminary assessment by interpreting satellite based data products generated through the state of art satellite imageries and/or air surveillance, as has been carried out presently by Indian Space Research Organization (ISRO) through its National Remote Sensing Centre (NRSC), State Government officials, forest, army, etc. GSI has also earmarked trained resource personnel to be associated for any such endeavour for such rapid assessment either through remote sensing or ground truth surveys.

The field-based first-level ground appraisal is generally taken up within 15 days of the event by respective Regional HQ of GSI (where the hazard has taken place) by employing adequate number of trained personnel after due consultation with the State Government agencies, army, rescue party, etc., and as per the accessibility to the affected terrain. This reconnaissance is generally completed within 3 months after initiation of the fieldtrip along with submission of preliminary report to the concerned State Government authorities. For undertaking technical data in field per individual landslide/trouble spot, suitable geo-parametric data format is already developed (Table 8.1) which is focused on collection of all sorts of relevant information of any landslide following the international norms of classification and guidelines [3, 33–38]. It includes rapid assessment of damages, preliminary identification of landslides, its broad typology, identification of stretches of affected roads/accessibility corridors and if possible, tentative identification of probable safer slopes for temporary rehabilitation. Another main objective of this reconnaissance would be to delineate vulnerable tracts and to assess quantum of further detailed work to be taken up for the second level appraisal.

8.2.5.2 Response Study: Preliminary/Feasibility and Multi-thematic (Level-2)

At this level (to be initiated expectedly within three to 6 months of the disastrous event), and as per the suggestions of the first level response studies and according to the specific demands of the State Government, GSI can take up a rapid macro-scale (1:50,000/25,000) slope stability assessment (preferably GIS-enabled) of the affected area as an additional item of the investigation in that particular Field Season. The total time period of this study can range from 6 months to 1.5 years including submission of reports depending upon the extent of the affected area. Arrangements for provision of interim reports may also be kept to facilitate initiation and continuation of restoration and rehabilitation works.

8.2.5.3 Landslide Vulnerability Tracts on Macro Scale

Landslide Vulnerability Tracts on Macro Scale (1:50,000) is followed to classify the landslide prone terrains of the country into different risk prone categories according to their degree of propensity to landsliding for perspective project planning. It is a multi-thematic exercise dependant on several causal geofactors such as (i) *slope morphometry* (Slope gradient, aspect, slope shape), (ii) *lithology,* (iii) *structure,* (iv) *geomorphology,* (v) *land use/cover,* (vi) *geohydrology, etc.,* by establishing either through an expert-driven or data-driven interrelationships with different type of landslides, adopting a number of standard and well-established techniques [27, 29, 31, 39, 40, 63]. The main objective of this susceptibility zonation is to create awareness amongst the planners and inhabitants to become better equipped and prepared to cope with impending fragile and natural hilly terrain related dangers of such area and for making well informed decisions for protection, appropriate land use planning, civic development and improving resilience to address the slope stability issues.

However, based on the experiences of major event like that of the recent Uttarakhand disaster of June 2013, several lessons were learnt which compelled re-evaluation of the existing methodology to of conducting preparation of macro scale landslide susceptibility maps. Additional geofactors that also need to be considered in light of the initiation of numerous landslides and colossal damages in Uttarakhand event include: (i) effect of toe erosion by higher order streams, (ii) effects on settlements that are built on lower-level geomorphological terraces and flat lands and proximal to trunk or higher order river/drainage systems, (iii) effect of long run-outs of the debris flows and drainage morphometry, (iv) nature and size of clastic components, etc.

The landslide susceptibility maps need to exhibit zones having varying degree of susceptibility (e.g., high, low, moderate, etc.) and depict the basic information such as location of stable flat ground nearby, existing roads/foot tracks leading to stable higher grounds that could act as safe escape routes in the event of a landslide/debris flow/flash flood, etc.

Based on geoscientific evaluation a user-friendly landslide susceptibility map depicting stable and unstable slopes along with all the available infrastructure: foottracks/road, communications network, drainage lines and higher order streams, safe shelters, etc., need to be prepared to facilitate stakeholders and end-users in planning disaster escape routes and relief and rehabilitation strategies. A collaboration framework has already been finalized between NRSC and GSI regarding event-based landslide inventory mapping and landslide susceptibility/hazard zonation in the prioritized landslide vulnerable areas of India and integrated application of modern GIS based remote sensing data products and field surveys and processing. It is planned to get ready different geofactor layers on GIS stage, for example, satellite data products based interpretation and derivative information with respect to slope angles, aspects and bend, elevation and relief, landuse-landcover, site geomorphology and operative surface processes, tectonic features and structural highlights: Faults/Lineaments thrusts and discontinuities, waste support, upslope contributing range and field review surveys to synthesise geo-information in light of slope and configuration of material and its thickness, morpho-structural understanding and geoscientific reconciliation of every topical layer for relegating appropriate weightage and hazard appraisal for simulated and projected frequency-magnitude demonstrations. Notwithstanding any technique for foreseeing landslide geohazard vulnerability, it needs validation which once in a while might be troublesome in zones having no land sliding history. However, for all NLSM programs to be completed, a quantitative approval through interpolated successful achievement and related inferred forecast rate curves, following the globally acknowledged strategies proposed by Chung and Fabbri [41] and embraced by Ghosh et al. [22, 42] are firmly prescribed, which would likewise encourage grouping of crude mass movement vulnerability score maps into subjective ("High", "Moderate", "Low") landslide proneness maps, effectively justifiable and understood by all interested partners.

8.3 Vulnerability and Risk Assessment

Landslide susceptibility analysis is performed utilizing modern methods to predict sites vulnerable to disasters related to the future incidence of landslides. Such analyses reiterate that given the required combination of geofactors and hill slope process parameters, a future landslide would occur. However, this requires a prior knowledge about and reference to parametric data sets on the landslide that occurred in any area. This means that this predictive analysis would answer where, when and how large the future landslide could take place [19, 47, 48]. Therefore, it is imperative that for landslide hazard analysis, availability of historical information on past landslides is essential for desired levels of accuracy of predictions.

Landslide geohazards vulnerability (risk) analysis involves methods to fore see or estimate financial aspects of losses caused to material assets at risk (roads, buildings, telecommunications and power transmissions) or estimation of losses of

population due to any mass wasting hazard [43]. This is the consequential aim of any slope-failure geohazards investigations as it serves useful purpose to planners and insurance agencies for realistic evaluation of the inherent vulnerabilities. Nevertheless, such analysis is extremely difficult due to non-availability of either spatial and temporal information of landslide incidences in particular or magnitude-frequency data of mass wasting occurrences in general. India has been having the similar problems to grapple with, like many landslide-prone countries in the world. India has geared itself to face these challenges and launched several programmes to build its own authentic data base to rely on and work for risk evaluation for long-term mitigation measures and disaster preparedness. In order to find dependable solutions to the above and to prepare upgradable and spatially-distributed national landslide repository, the Web-based National Landslide Incidence Inventory project of GSI has been launched that will finally prepare a substantial and quantitative nation-wide landslide parametric database.

Landslide Risk Management is the ultimate assemblage and syntheses of geofactor data generated and compiled on mass movement (landslides) investigations starting from identification of a landslide-related issues, knowing its vulnerability status (predictions of spatial locations), geohazards assessment (comprehensive interpretation of spatial, temporal and magnitude aspects) and estimation of risk (loss of life and material estimation), followed by total risk evaluation and process to define and implement ground-level action towards mitigation and reduction of the forecasted dangers. Therefore, GSI's endeavour in preparing such a national landslide database for the entire country on a GIS-based dynamic platform would be extremely beneficial in future and will also enable the Indian landslide scientists to work on predicting the temporal and magnitude component of such hazard more realistically.

8.4 Development of Early Warning Systems in India

In India, landslides mainly affect the Himalayan region, Western Ghats, Nilgiris and Konkan Hill ranges [10–12, 63]. It is assessed that 30% of world's landslides occur in the geologically youthful mountain framework: the Himalayas [44]. Geoscientists consider down slope land movement events for an assortment of targets inside the system of landslide vulnerability and chance occurrences. These objectives incorporate systematic and reliable compilation of hazard incidence data base, ground surveys and susceptibility mapping, site-specific and detailed geoscientific investigation of danger prone area, hazard estimation, incidence appraisal and likely rescue and relief preparedness, and so on [27]. The ultimate aim of such studies is to help in reduction of risk to the human population, and to make life and property safe from landslide disasters. Therefore, concerted and integrated efforts need to be made to reduce the societal risk, either by reducing the probability of failure or by reducing adverse effects of consequences. Crozier [45] listed nine different approaches, grouped into three strategies, to reduce landslide risk: "land use zoning, engineering

solutions and emergency preparedness". These techniques significantly work towards either mitigation of the spatio-temporal probability of occurrence of landslide by using different remedial options or lessening the vulnerability of operative geofactors involved through enhancements of the geomorphologic built-up components or scenario by making them more safe or strong or resilient to the conceivable landslide impact as enumerated below:–

(i) In land use zoning, either building regulation or relocation of the elements at risk to hazard-free areas is often used to diminish landslide risk. However, practice has shown that relocation is not always viable as in any case, rehearse has demonstrated that migration isn't generally reasonable as individuals would prefer not to be moved unless the neighbourhood specialists/administration offer monetarily substantially greater and attractive options.

(ii) In designing engineering geological arrangements, slope adjustment works, development of waste water drainage, and so forth, are regularly used to diminish landsliding chances by limiting the likelihood of occurrence of such dangerous disaster. This procedure isn't just costly yet is reasonable for a couple of known insecure hill slope situations, as it is hard to portray the exact area of every single potential landmass movement at a catchment scale. However, technology infusion in due course will certainly make this approach cost-effective.

(iii) In crisis readiness technique or emergency preparedness strategy, chance/mishap risk lessening is accomplished through skill building, i.e., by sensitising public, expanding mindfulness and increasing awareness among the people in general and suitable training with an aim to imbibe appropriate response to the warning before or when the disaster strikes. Although studies have indicated that these three strategies, alone or in combination, are effective in mitigating landslide, yet the fact remains that since it is not possible to completely mitigate all landslide-prone slopes, the chances of 'residual' risk remains to exist.

Issues are more complicated in large countries such as India where landslide-prone areas are spread over 0.42 million km^2. Using engineering solutions or carrying out risk awareness programmes for mitigating landslides for such a large area with huge geodiversity remains a challenge. In the developing countries, risk management further gets complicated due to their societal and economic considerations. Here the financial issues (socio-economic problems) are frequently so substantial and genuine that adequate consideration is not feasible to potential mass movement issues. Besides, these geohazards mostly remain confined and influence a smaller segment of the general public. Under this circumstance, endeavours are expected to enhance the practical and pragmatic methodologies of developing landslide hazard diminishing systems. One such approach is the utilization of early-cautioning frameworks or the EWS. Value-added relevance of this strategy in India in reducing human deaths and destruction was acknowledged in the recent two natural disasters: the Odisha cyclone "Phailin" where numerous lives were saved due to the timely early warning; and the Uttarakhand landslide/flood disaster of June 2013 where numerous lives were lost due to the lack of an early warning.

8.4.1 What Is an Early-Warning System?

In context of landslide, an early-cautioning framework or early-warning system (EWS) is a technology which is capable of monitoring and modelling landslide initiation and issuance of advance warning to the concerned of impending danger. In order to develop reliable EWS, the geological/geotechnical processes and mechanisms need to be understood in addition to their quantified measurements and processing for modelling and prediction. Modelling for EWS can be done manually or through the use of automated systems, such as wireless sensor networks. Warning system may be of different types, depending on the type of landslide event and resulting landslides, spatial coverage of the warning area and the communities to be warned. It can be developed for:

(a) An individual site-specific mass movement prone environment and to warn people about the movement of the delineated landslide. The warning is based on site-specific study of the landslide using movement sensors, geodetic and piezometric monitoring, etc. In India, Amrita University, Kollam has been carrying out such study since 2008 in Munnar, Kerala and some parts of eastern Himalaya [18, 63].
(b) Communities or organizations for small areas for one or more landslides. The warning is based on simple rainfall threshold values estimated for landslide initiation.
(c) Large areas and extreme weather events (such as very high rainfall prediction that could be critical for initiating landslides).

In all these three types, the most important input parameter for landslide early-warning system is the projected threshold value. For rainfall-triggered landslides, the threshold is the amount of rainfall required to initiate a ground displacement that can prograde into a mass movement capable of causing damage to life and property.

In general, a warning system for landslide has four major components:

1. **Monitoring**, understanding of geofactors and comprehensive recording which includes data collection and compilation, archival and retrieval devises, ease of accessibility and upkeep of the gadgets and machinery;
2. **Synthesis, analysis and interpretation,** leading to predictions with riders, mainly arrived at with of a set of limiting criteria and use of modern processing tools and specialist inputs, etc.
3. **Cautioning or early alert,** i.e., the rapid communication of unambiguous understandable statements and instructions alerting public for the potential disaster and
4. **Resilience and adoptability,** i.e., emergency preparedness for safety, relief and rescue operations where people are able to willingly cooperate and show collective maturity on how they must respond to the warning.

In these above four components, the role of geoscientists is restricted to the first two, i.e., the monitoring of a landslide, and analysis of the data to forecast the initiation of a landslide. The last two components, i.e., warning and response are of multidisciplinary nature and involve many stake holders such as administrators, planners, disaster response force, etc.

8.4.2 Why Is It So Important to Have Early Warning for Landslide Events?

Dissimilar to other common perils and resultant disasters, for example, woodland fire, coastal wave surges and earthquakes, landslides occur fairly consistently in hilly territories and make significant harm to life and property, both regarding immediate tragedy and consequential misfortune [4, 43, 46, 63]. Since most recent couple of decades, mass movements have been seen as a genuine and persistent risk to humankind. It is generally assessed that all inclusive, every year; landslides owing to slope failures would become more disastrous and harmful to life and properties than some other land risk [3, 5]. The reasons ascribed to this assertion are the overexploitation of natural assets, fast and extensive deforestation, change in atmospheric conditions (impacts of global warming) and steady growth in slope dwelling populace and uncontrolled anthropogenic excavations along these inherently perilous terrains thus bringing about destabilization of slope and enhanced proclivity of surface soil to creep and erode to damage the human settlements and add to insecurity of the uncovered populace [6–8].

The situation is grimmer in India where the increase in hill tourism and population have not only resulted in inappropriately planned fast and enhanced developments of infrastructure, but also prompted encroachment in hazardous areas. This was one of the reasons attributed to huge unprecedented loss of life and property in the June 2013 Uttarakhand landslide disaster. Researchers have argued that the Uttarakhand disaster was the result of an extreme rainfall, of a 1000-year return period, and could have been averted if timely warnings were issued, similar to the 'Phailin' cyclone of Odisha. Studies have shown that people residing in such hazard prone areas for many generations are generally poor and not fully aware of such potential hazards. They do not want to leave their place of settlement in spite of having witnessed landslide disasters [14–16]. Under such circumstances, the only opportunity to minimize the landslide-related loss is to timely alert the community about the expected hazard through the use of an early-warning system. Maintenance of the transportation corridors and communications network is important pre-requisites in such naturally hazardous tracts for the benefit of society [17].

8.4.3 What Makes It So Difficult to Forecast and Warn a Landslide Event?

Development of landslide EWS essentially requires:-

 (i) Establishing criteria for parameters to be monitored and working out their threshold values,
 (ii) Acquiring/developing monitoring equipments and systems,

(iii) Coordinating satellite-based data/interferometric radar data (Synthetic Aperture Radar) with local monitoring stations, where needed,
(iv) Planning detailed monitoring programmes for high-risk areas, and
 (v) Acquiring/developing computer-aided decision-making tools, information management strategies using GIS with remote sensing and 3D modelling, etc.

Unlike floods, which have defined inundation area and earthquake, which has defined source zone and follow defined pattern of ground acceleration, landslide is more complex in terms of magnitude, source location and run-out pattern, etc. [18, 19, 47, 48]. Landslide, being an individual phenomenon, each landslide is unique in terms of its morphometry (area and volume), magnitude (intensity) and spatial location. The uniqueness of landslide phenomenon and the fact that each triggering event can result in one or many landslides in an area, make this hazard comparatively difficult to predict both in space and time.

8.4.4   Difficulties Related to Spatial Prediction of a Landslide

The success of an early warning depends on prediction of the precise location of a landslide. The state-of the art model available in spatial mapping of landslide-prone zones provides only a qualitative or probability-based quantitative susceptibility maps showing the probable initiation zones (e.g., [41, 48, 49, 50]). Such maps do not point out 'precisely' where the landslide will actually initiate given the triggering condition and how it will behave down-slope. Useful links need to be established between ground movement, rainfall and pore-water pressure. The need for R&D on these issues was discussed at length during the recently concluded regional workshops on landslide disaster management in Shimla (for NW Himalaya), Shillong (for NE Himalayan region) and Wellington (for Western Ghats and south India), India [55–57]. However, the uncertainty in the absolute spatial prediction of a landslide makes early warning difficult to implement [21]. Further, absence of geoscientific data on the size of the landslide, its run-out distance, its inundation zone makes warning difficult. It has been observed that most of the landslide-related loss is not merely to vulnerable assets around locations on catchment source of landslide; rather it is more to establishments and contained elements located on the run-out zone [11, 63].

8.4.5   Difficulties Related to Temporal Prediction of a Landslide

The most important component of an early warning is the prediction of the precise time of a landslide. Till date, only a hand full of research has been carried out where temporal component of landslide initiation has been modelled for a large area (e.g.,

[17, 48, 51, 52, 60]). In this aspect, almost all research focuses on identified vulnerability with associated likelihood estimation on of occurrence of hill slope process leading to land mass movement. Uncertainty related to probability estimation is one of the hurdles in the temporal forecasting of a landslide.

8.4.6 Challenges Related to Communication of Landslide Warning

Advancement of a reasonable cautioning dialect and directions that are appropriate to the hazard prone areas and its populace are fundamental for the fruitful execution of an early-cautioning framework on ground (EWS). Although relevant Rules and guiding instructions are framed on local dialect and articulations mechanisms for various levels of caution are accessible (e.g., [16, 53, 64]), yet the issue is the means by which to educate and involve individuals or group about the approaching threat. Since, landslide distribution is localized and affects only a few individual or a certain segment of the society, communicating the warning, which are developed and issued from a place, located far away, to the concerned remains a challenge particularly in India. With hill area spreading over 0.42 million km^2 and dispersed settlements located at distant places accessible through track routes, communicating warning message within a short span has been a major challenge in real time ground alerts and execution of an early-cautioning framework.

8.4.7 Difficulties Related to Data Dissemination and Awareness

One important component of early-warning system is the availability of updated maps such as safe shelter map, alternate route map, susceptibility map, etc. In India, safe shelter and alternate route maps for landslide hazard are often not prepared or not available. These maps need to be prepared for individual settlement. People concerned should be aware of such maps and their physical representation on ground for timely response to the warning. In India, though susceptibility maps are available for important settlements, but they need to be updated periodically with respect to the changing land use condition. Another important aspect that makes early warning ineffective is the lack of public awareness. The mindfulness, prompting crisis readiness, means the capacity and skill levels of a group to put vigorously the set up action plans and methodology for vulnerability moderation [45]. This technique has a tendency to lessen the hazard by expanding awareness among the general population with a plan to convenient and suitable reaction to the notice when the perilous fiasco strikes. Albeit, Geological Survey of India, National Disaster Management Authority together with National Institute of Disaster Management and the

State Disaster Management Centres complete standard group based debacle administration (disaster management) program at a state/region level, yet at the same time more deliberate exertion is required to reach to individual and dispersed hilly settlements through the State Government, NGO and other stake-holders.

8.5   A Way Forward in Landslide Warning and GSI's Initiative

GSI had realized the importance of landslide forecasting in the aftermath of 2003 Varunavat Parvat landslide in Uttarkashi, Uttarakhand. It resulted in high expenses of alleviation and recuperation or relief and recovery after landslide disasters had taken place [63]. Adequate considerations on geoscientific planning for safe and cost effective land use practices need to be followed rigorously in such hazardous territories that need to be equipped with early cautioning mechanisms on impending catastrophes. The recent research in risk quantification and threshold modelling for landslide initiation [12, 16, 17] form a potential basis for any geoscientific organisation to step into a multi-disciplinary science of landslide risk reduction through early-warning system. Geoscientific observations based on detailed field- and laboratory based studies would help to formulate strategies on hazard characterization. These include frequency, magnitude, extent, onset and consequences of past mass-wasting events.

GSI has already built-up database structure with a provision of storing as many as 41 different attributes per landslide incidences. It is currently operational and any stake-holder can access upwards of 281 such data sets in GSI Portal. The web-based landslide incidence inventory will also have spatial locations of all the landslides that are being mapped in the on-going NLSM programme of GSI which is being carried out to collate and map several landslides in different mass wasting vulnerable tracts in the country on a dynamic GIS platform. Collation and syntheses of such dynamic data sets will enable formulations on Early Warning Systems including: Landslide Hazard Warning Plans, routines participation and operating procedures, monitoring using in-situ real-time monitoring devices (e.g., geophones, inclinometers, piezometers, extensometers, etc.) and monitoring using geodetic scanners (Terrestrial Laser Scanner). Geodetic monitoring using differential GPS systems and detailed-scale field mapping of permanent surface features using Total Station, remote monitoring systems for field measurements with automated data collection by web-enabled devices are needed for comprehensive determination of both empirical and deterministic threshold modelling of triggering factors (e.g., rainfall, earthquakes, etc.) for devising an empirical system of early warning based on triggers. Development of EWS is considered to be the next higher-level step towards forecast or pre-warn the essential elements-at-risks. Therefore, the general step for developing EWS is essentially to be preceded by detailed site-specific stability and hydrologic modelling, followed by sufficiently long-term monitoring of any particular landslide.

Developing such site-specific landslide early warning system is mainly instrument-based, time-consuming and costly and requires specialized knowledge on this particular subject.

One of the important components of landslide forecasting is the establishment of rainfall threshold value for rainfall-induced landslides. In 2009, GSI made an attempt to model rainfall threshold for shallow landslides in Nilgiri Hills using landslide events up to 2006 [17, 57]. The model was found accurate in forecasting 2009 landslide events in Nilgiri Hills [54]. Making one stride ahead of the 'threshold model', GSI had published a conceptual model and operating procedure of an early cautioning framework after evaluating risk perception of affected community in Nilgiri Hills [16]. However, the efficacy of the model is yet to be tested in the field and in genuine ground circumstance. The model includes the establishment of rainfall related thresholds triggering mass movement, region specific meteorological predictions, establishing a network of rainfall gauges for real time monitoring and an automated computing system for processing and evaluation of data sets. The system is essentially based on actual precipitation dependent forecast and using satellite data products linked to a large network of rain gauges that are equipped to issue alerting messages on surpassing tripping limit – the computed threshold. Such work practiced on the Nilgiri Hills in Tamil Nadu can be a good basis for the development of an early-warning system in the country [11, 16].

Recently, GSI has initiated a joint venture with Defense Terrain Research Laboratory (DTRL), New Delhi and Amrita University, Kollam for automated instrumentation-based monitoring of landslides in Himalayan region. The objective is to develop and test an early-warning system for a single landslide. DTRL and Amrita University are already in advance stage of data collection for the pilot study sites in Uttarakhand and Munnar, Kerala, respectively. GSI is also in advance stage of collaboration with Indian Meteorological Department (IMD) for rainfall threshold modelling in a catchment scale, with an aim to develop an early-cautioning framework for multiple landmass movements covering a large area in the Himalayas. GSI's national programme on the generation of seamless landslide susceptibility map (NLSM) for the entire country on 1:50,000 scale is nearing completion [10, 31]. These maps in GIS platform will form an important input in: (i) targeting potential hazardous areas for landslide monitoring (ii) evaluation of hazard potential and (iii) development of an early-cautioning framework – the EWS.

Besides, the recently created Geohazards Research Division in GSI has also taken up a 2-year long project in collaboration with Natural Resources, Canada (NRCan) for an Interferometric Synthetic Aperture (InSAR) based landslide monitoring and early warning research programme at two active landslides in Eastern Himalayas (14th Mile-Gayabari and Chibo landslides, Darjeeling district, West Bengal). The main aim of this collaboration is to develop a suitable InSAR-based technique to monitor activity of ground movements of these two landslides. After completion of the target of this collaborative research item, a time series of ground movement at two active landslide sites and a map showing active kinematic movement of slope will be prepared which can be used in developing landslide hazard scenarios in the study area and as a suitable output for monitoring of landslides and early warning in

the Himalaya. For this particular collaborative investigation, NRCan is providing GSI the required technical advice, guidance, training and 20 scenes of RADARSAT-2 images of the study area for a period of 24 months. In addition, NRCan has also provided GSI five Trihedral Corner Reflectors for installation at site. Apart from the five Canadian-make Corner Reflectors, GSI's Geohazards Research & Management Centre Kolkata has indigenously manufactured five more Corner Reflectors at Kolkata following the similar design and installed all the ten Corner Reflectors at two landslide sites in Darjeeling Himalayas, India (five at **14th Mile** and five at **Chibo** sites). All these ten (10) Trihedral Corner Reflectors were successfully sighted by the RADARSAT satellite and the official acquisition of RADARSAT-2 image has started by NRCan since September 2016 and till March 2017, seven (07) RADARSAT-2 scenes were acquired by NRCan for further analysis in developing landslide hazard scenarios in the study area.

Owing to complex environmental conditioning and triggering processes that cause landslides, the extent and variability of their spatial and temporal scales imply that they are inherently difficult to forecast and mitigate at site, slope, catchment and regional spatial scales. However, various programmes of research across the world have mapped, catalogued and monitored landslides (e.g., field mapping, remote sensing) to better understand triggering mechanisms of landslide processes. As these processes are often triggered by local in-situ site conditions/ events (e.g., antecedent hydro-metrological conditions, land-use) it is difficult to develop forecasting and early-warning systems (EWS) that are equally-applicable and useful beyond a local site (<1 km^2) to larger area ($\approx$10 to $\approx$100 km^2) on spatial scale. There are many projects nationally and internationally that monitors landslides and landscapes in real-time through instrumental sensor networks (e.g., rain, soil moisture, slope movement; now, many of these wireless) and investigate specific triggering mechanism associated with individual or sets of landslides. These networks provide local site to slope/catchment scale EWS for landslides and help individual communities at risk (e.g., Munnar, India; Hong Kong, China, and several sites in Japan, etc.). However, these studies provide triggering thresholds and warnings that are difficult to scale-up (to catchment and regional spatial scales) and apply to other areas/regions. This knowledge gap and challenge are being addressed in a 4-year long UK-funded Project called **LANDSLIP** (**Landslide Multi-Hazard Risk Assessment, Preparedness and Early Warning in South Asia: Integrating Meteorology, Landscape and Society**) in India, which aims to integrate landscape, climatic and social dynamics by a multi-institutional international consortium, where Geological Survey of India (GSI) has agreed to be one of the nine partner organisations of the LANDSLIP by signing an agreement with the British Geological Survey (BGS), the latter being one of the main co-leads of the LANDSLIP [3, 11, 12, 18, 60].

LANDSLIP will aim to reduce impacts of hydrologically related landslide multi-hazards (in terms of fatalities, livelihoods, assets) and build skill levels and capacity to mange disaster owing to mass wasting in hazard prone terrains (often remote) and vulnerable tracts in South Asia. LANDSLIP will address this issue by using two pilot study areas in north-eastern (Darjeeling/East Sikkim) and southern (Nilgiris) India and will enhance access and response to both landslide risk assessments and robust

landslide related multi-hazard early warnings, on a slant/catchment and regional satellite data based aerial scale and diurnal to seasonal time series scale. This means that the proposed LANDSLIP project, where output of this item will be incorporated, aims at to provide simultaneous and better understanding of landslide risk for a smaller catchment area (~25 km^2) as well as for a larger regional area (~400 km^2) with the development of an early cautioning framework/mechanism of landslides for the same on differing temporal scales (~1–15 days to 1 month, etc.). In these particular study areas, 1:50,000 scale national landslide susceptibility mapping (NLSM) database are already available, which will be used as base input thematic maps for further up-scaling at 1:25,000/1:10,000 scales.

The above collaborative endeavour will ultimately prepare an improved rainfall threshold model by incorporating weather regime data, improved landslide susceptibility, hazard models at 1:25,000 and 1:10,000 scales to assess landslide risk at multiple scales. Ultimately, the final outputs of landscape and meteorological dynamics so developed will be assimilated with social dynamics (output generated by other LANDSLIP Collaborators) to achieve the final goal of LANDSLIP that is: improved understanding and risk evaluation on slope failure mass movement and advance alert mechanism.

8.6 Discussion and Conclusions

According to the National Disaster Management Act 2005 [64], the Union Government (National Disaster Management Authority, NDMA) [13] is occupied with reinforcing country's readiness to prevent and keep any danger at bay rather than focusing on allocating additional resources on alleviation and recovery from disaster. Similarly carrying out of multi-scale landslide hazards propensity zonation is a vital geo-data instrument to the organizers and overseers to limit such misfortunes because of such land movement risk. To fulfil this objective, the nodal Ministry of Mines and its attached Department – the Geological Survey of India embarked upon the NLSM Program to finish large scale (1:50,000) landslide susceptibility mapping of the whole mass wasting prone tracts of India in a prioritised way on GIS stage which is likely to be completed by 2020. Standard operating procedures for NLSM have been discussed and debated amongst the stake-holders during three major regional workshops on Landslide Disaster Management held in 2013–2014 respectively at Shimla, Shillong and Wellington (Nilgiris) and the Brain Storming Sessions held at GSI, Kolkata [55–57].

GSI started working on NLSM programme with effect from the Field Season 2014–2015, after it was formally launched on February 05, 2014 by the Hon'ble Minister of Mines, Govt. of India. The NLSM project aims to prepare and integrate seamless Landslide Incidence Inventory and Landslide Susceptibility Maps in the mountainous areas of India on 1:50,000 scale on GIS platform which would provide the fundamental inputs to compile the macro scale landmass movement (landslide) geohazards and spatially documented propensity scenarios of India. It will give pan India macro scale baseline information for the first time to accurately and

quantitatively assess the spatial locations of landslide prone areas in the country. It will also help in disaster preparedness of the country and to indicate areas critical for landslide monitoring and developing early warning system.

Significance of documenting down slope landcover movement and forecasting was acknowledged in India since the repercussions of Varuna Parvat Landslide tragedy in Uttarkashi, Uttarakhand in 2003. It has been envisaged to get ready different geofactors layers on GIS stage, for example, satellite data products based interpretation and derivative information with respect to slope angles, aspects and bend, elevation and relief, landuse-landcover, site geomorphology and operative surface processes, tectonic features and structural highlights: Faults/Lineaments thrusts and discontinuities, waste support, upslope contributing range and field review surveys to synthesise geo-information in light of slope and configuration of material and its thickness, morpho-structural understanding and geoscientific reconciliation of every topical layer for relegating appropriate weightage and hazard appraisal for simulated and projected frequency-magnitude demonstrations. The recent multi-disciplinary and collaborative research in risk quantification and threshold modelling for landslide initiation will pave way for landslide risk reduction through development of Early Warning System [11, 18]. Notwithstanding, any technique for foreseeing landslide geohazards vulnerability, it needs validation which once in a while might be troublesome in zones having no land sliding history.

Himalayan landscape is relatively young and slopes are steeper, hence causative factors triggering landslide will be more complex. Besides, slopes in the Himalayas are covered under a very different type of material which is mostly transported fluvio-glacial and slope-wash from younger geological formations [61–63]. Therefore, geo-scientific considerations will play greater role in the Himalayas in Uttarkhand, Himachal and Kashmir as well as in Sikkim, Darjeeling in West Bengal, Arunanchal Pradesh, Nagaland and Mizoram in addition to rainfall and meteorological parameters and will have to be factored in for evolving appropriate models for EWS. These are the topics of advanced research aimed to creating reliable high quality geo-data devices to empower the organizers/managers for delineating landuse zoning regulations for sustainable and safe development with appropriate considerations, geoscientific planning and preparedness in handling such approaching geohazards and for potential disaster management. Therefore it is reasonable to assert that EWS innovative research work and development of instrumentation will take off from the robust products and outcomes of the NLSM programme [12]. EWS need also to highlight mitigation efforts/remedial measures through geotechnical and engineering solutions as suited to Indian conditions on case to case basis for optimum utilization of available resources.

Developing early-warning system for Indian conditions is an important tool for risk reduction, both for a single site as well as for large area. Since, the majority of the landslides in the nation are precipitation activated, advancement of an early-cautioning framework based on precipitation received versus landslide incidence relations, through the use of a rainfall limiting or triggering constraint (threshold), appears to be the best and most cost-effective solution. EWS for a single landslide, threshold can provide information on the precise loci of ground displacement and its acceleration, while for a catchment area it can provide information on when and

where land sliding would occur. This in conjunction with presently prepared land sliding propensity maps (NLSM) can portray conceivably the perilous territories. In fact, in a few nations, precipitation limits have been utilized to gauge precipitation initiated land sliding, especially in the San Francisco Bay range, USA [53, 58, 59]. The capacities of early cautioning depend on the observational limit models which in turn depend on different precipitation estimations, for example, forerunner precipitation, precipitation intensity and duration, cumulative precipitation and areal spread and total pouring time, and standardized/normalised precipitation, and so on. The subtle elements of the sorts of limit models utilized everywhere throughout the world can be found in Guzzetti et al. [47, 48] and would require being adjusted to Indian condition.

Although, world over threshold-based early warning is considered to be the most reliable option, yet the lack of information on past landslide event dates and corresponding rainfall data for the desired locations make threshold definitions difficult to model. Since, landslide is a site specific phenomena and the fact that in hills rainfall vary considerably due to 'orographic effect', the use of rainfall data from distant stations with respect to the location of landslide is yet another factor inducing uncertainty to the threshold modelling [61–63].

Successful usage of any early caution framework requires critical assets and skilled man power. Such EWS methodology entails automated rain gauges, updated and refreshed landslide susceptibility maps, specialists to decipher outcomes about, logical and reliable precipitation conjectures, and so forth. In India, a large portion of these assets are not promptly accessible and subsequently the initial step is to set up the operational centralised infrastructural establishments, field based monitoring instruments and involvement of committed proficient staff for timely observing of threshold values and to provide estimated early cautioning on incidence of potential landslides. Besides, a micro early warning system can be developed at a community level, with community participation. This, however, would require organizing a regular Community Based Disaster Management Programme (CBDMP) for public awareness. Through participatory activities, trainings and dedicated information campaigns, it is conceivable to make the targeted community groups mindful of possibly dangerous territories and of potentially hazardous areas, to fortify their ability to be strongly prepared to face challenges pertaining to perilous fiascos and to build up an enlightened association of humans to shoulder the risk diminishment activities in affected areas [10, 11, 57, 63].

The launch of a national programme on Landslide Susceptibility Mapping on scale 1:50,000, as a joint venture between GSI and NRSC, on modern digital base will contribute significantly to develop national risk monitoring plans. It will be built on robust underpinning of landslide hazard studies and research and will lead to improved understanding and provide perspectives at multiple scales of vulnerability and resilience to ongoing adverse land and climate changes and impending hazards. Recognizing the importance and the need, GSI has taken important steps for adopting interdisciplinary and collaborative multi-institutional approach to generate and provide relevant, reliable geoscientific data needed for management of landslide hazard and risk, development of EWS and increase of public awareness to face the challenges.

References

 1. Champati Ray PK, Parvaiz I, Jayangonda-perumal R et al (2009) Analysis of seismicity induced landslides due to the October 8, 2005 earthquake in Kashmir Himalaya. Curr Sci 97 (3):1742–1751
 2. Ghosh S, Chakraborty I, Bhattacharya D et al (2012) Generating field-based inventory of earthquake-induced landslides in the Himalayas – an aftermath of the 18 September 2011 Sikkim earthquake. Indian J Geosci 66(1):27–38
 3. Varnes DJ (1984) IAEG commission on landslides and other mass-movements. Landslide hazard zonation: a review of principles and practice. UNESCO Press, Darantiere. 61p
 4. Schuster RL, Fleming RW (1986) Economic losses and fatalities due to landslides. Bull Assoc Eng Geol 23:11–28
 5. Petley DN, Dunning SA, Rosser NJ (2005) The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities. In: Hungr O, Fell R, Couture R, Eberhardt E (eds) Landslide risk management. Taylor and Francis, London, pp 367–374
 6. Nadim F, Kjekstad O, Peduzzi P et al (2006) Global landslides and avalanche hotspots. Landslides 3:159–173
 7. Hoyois P, Scheuren JM, Below R et al (2007) Annual disaster statistical review: numbers and trends 2006. Centre for research on the epidemiology of disasters (CRED), Brussels
 8. Sarvothaman H, Kumar AKJ (2013) Disaster management – engineering and environmental aspects. Asiatech Pub. Inc, New Delhi, pp 73–83
 9. Hemalatha T, Ramesh MV (2015) Indian landslide scenario: with special reference to landslide research methods. J Eng Geol XL(1):45–61. [Spl. Issue for Landslides: Management & Mitigation Strategies – 2015, Defence Terrain Research Laboratory, Defence Research and Development Organisation, New Delhi]
10. Wadhawan SK, Raju M, Ghosh S et al (2013) Geoscience considerations in formulation of National Landslide Disaster Management plan. Indian J Geosci 3&4:203–216
11. Wadhawan SK, Jaiswal P, Ghosh S (2013) Landslide early warning in India – prospects and constraints. Indian J Geosci 3&4:229–236
12. Wadhawan SK (2015) Implementation of landslide susceptibility mapping programme, vulnerability and risk assessment – a gateway to research and development of early warning systems in India. J Eng Geol XL(1):20–32
13. NDMA (2009) Management of landslides and snow avalanches, 2009. National Disaster Management Authority (NDMA), Government of India, New Delhi, p 144
14. Jaiswal P, van Westen CJ, Jetten V (2011) Quantitative estimation of landslide risk from rapid debris slides on natural slopes in the Nilgiri hills, India. Nat Hazards Earth Syst Sci 11:1723–1743
15. Jaiswal P, Srinivasan P, Venkataraman NV (2013) A data-guided heuristic approach for landslide susceptibility mapping along a transportation corridor in the Nilgiri Hills, Nilgiri District, Tamil Nadu. Indian J Geosci 3&4:273–288
16. Jaiswal P, van Westen CJ (2012) Use of quantitative landslide hazard and risk information for local disaster risk reduction along a transportation corridor: a case study from Nilgiri district, India. Nat Hazards. https://doi.org/10.1007/s11069-012-0404-1
17. Jaiswal P, van Westen CJ (2009) Estimating temporal probability for landslide initiation along transportation routes based on rainfall thresholds. Geomorphology 112(1–2):96–105
18. Hemalatha T, Ramesh MV (2015) Challenges in predicting landslides with space borne SAR technology. J Eng Geol XL(1):99–106

19. Guzzetti F, Carrara A, Cardinali M, Reichenbach P (1999) Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology 31(1–4):181–216
20. Cardinali M, Reichenbach P, Guzzetti F et al (2002) A geomorphological approach to the estimation of landslide hazards and risks in Umbria, Central Italy. Nat Hazards Earth Syst Sci 2:57–72
21. van Westen CJ, van Asch TWJ, Soeters R (2006) Landslide hazard and risk zonation—why is it still so difficult? Bull Eng Geol Environ 65(5):167–184
22. Ghosh S, Carranza EJM, van Westen CJ et al (2011) Selecting and weighting spatial predictors for empirical modeling of landslide susceptibility in the Darjeeling Himalayas (India). Geomorphology 131(1–2):35–56
23. Baeza C, Corominas J (2001) Assessment of shallow landslide susceptibility by means of multivariate statistical techniques. Earth Surf Process Landf 26:1251–1263
24. Popescu ME (2002) Landslide casual factors and landslide remedial options. Keynote lecture. In: Proceedings of the 3rd international conference on landslide, slope stability and safety of infrastructures, Singapore, pp 61–81
25. Castellanos Abella EA, van Westen CJ (2008) Qualitative landslide susceptibility assessment by multicriteria analysis: a case study from San Antonio del Sur, Guantánamo, Cuba. Geomorphology 94(3–4):453–466
26. Lee S, Hwang J, Park I (2013) Application of data-driven evidential belief functions to landslide susceptibility mapping in Jinbu, Korea. Catena 100:15–30
27. Fell R, Corominas J, Bonnard C et al (2008) Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Eng Geol 102(3–4):85–98
28. Crozier MJ (1989) Landslides: causes, consequences and environment. Routledge, London
29. Bureau of Indian Standards, BIS (1998) Preparation of landslide hazard zonation maps in mountainous terrains – guidelines. Bureau of Indian Standards (BIS) IS 14496 (Part – 2). Government of India Press, New Delhi
30. Aleotti P, Chowdhury R (1999) Landslide hazard assessment: summary review and new perspectives. Bull Eng Geol Environ 58:21–44
31. Saibal G, Das R, Goswami B (2013) Developing GIS-based technique for application of knowledge and data driven methods of landslide susceptibility mapping. Indian J Geosci 3&4:249–272
32. Ghosh S, Raju M, Jaiswal P (2014) Need to launch the national landslide susceptibility mapping (NSLM) programme in India – a roadmap to create a national database on landslide. ISEG News Bull 10(2):3–4
33. UNESCO-WP/WLI (1990) A suggested method for reporting a landslide. Bull Int Assoc Eng Geol 41:5–12
34. UNESCO-WP/WLI, Cruden DM (1991) A suggested method for a landslide summary. Bull Int Assoc Eng Geol 43:101–110
35. UNESCO-WP/WLI (1993) Multilingual landslide glossary. Biotech Publishers Ltd, Richmond. 34 p
36. UNESCO-WP/WLI (1993) A suggested method for describing the activity of a landslide. Bull Int Assoc Eng Geol 47:53–57
37. UNESCO-WP/WLI (1994) A suggested method for reporting landslide causes. Bull Int Assoc Eng Geol 50:71–74
38. Cruden D, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (eds) Landslides investigation and mitigation, Special report 247. Transportation Research Board, National Academy of Sciences, Washington, DC, pp 36–75
39. Sarkar NK, Megotsohe C, Theophilius PK et al (2013) Debris flow characterization causes and consequences – a study from Kohima District Nagaland, India. Indian J Geosci 3&4:303–328
40. Sharma VK, Rawat PVS (2013) Post-disaster slope stability evaluation of catastrophic events in Uttarakhand. Indian J Geosci 3&4:337–346
41. Chung C-JF, Fabbri AG (1999) Probabilistic prediction models for landslide hazard mapping. Photogramm Eng Remote Sens 65(12):1389–1399

42. Ghosh S, van Westen CJ, Carranza EJM et al (2012) Generating event-based landslide maps in a data-scarce Himalayan environment for estimating temporal and magnitude probabilities. Eng Geol 128:49–62
43. Sterlacchini S, Frigerio S, Giacomelli P et al (2007) Landslide risk analysis: a multi-disciplinary methodological approach. Nat Hazards Earth Syst Sci 7:657–675
44. Government of India (2011) Disaster management in India. Ministry of Home Affairs, New Delhi. 233p
45. Crozier MJ (2005) Multiple occurrences of regional landslide events in New Zealand – hazard management issues. Landslides 2:247–256
46. Zezere JL, Oliveira SC, Garcia RAC et al (2007) Landslide risk analysis in the area North of Lisbon (Portugal) – evaluation of direct and indirect costs resulting from a motorway disruption by slope movement. Landslides 4:123–136
47. Guzzetti F, Mondini AC, Cardinali M et al (2012) Landslide inventory maps: new tools for an old problem. Earth Sci Rev 112(1–2):42–66
48. Guzzetti F, Reichenbach P, Cardinali M et al (2005) Probabilistic landslide hazard assessment at the basin scale. Geomorphology 72:272–299
49. Soeters R, van Westen CJ (1996) Economic losses and fatalities due to landslides. Bull Assoc Eng Geol 23:11–28
50. Lee S, Pradhan B (2006) Probabilistic landslide hazards and risk mapping on Penang Island, Malaysia. J Earth Syst Sci 115(6):661–672
51. Zezere JL, Reis E, Garcia R et al (2004) Integration of spatial and temporal data for definition of different landslide hazard scenarios in the area North of Lisbon (Portugal). Nat Hazards Earth Syst Sci 4:133–146
52. Harp EL, Reid ME, McKenna JP et al (2009) Mapping of hazard from rainfall-triggered landslides in developing countries: examples from Honduras and Micronesia. Eng Geol 104:295–311
53. Keefer DK, Wilson RC, Mark RK et al (1987) Real-time landslide warning during heavy rainfall. Science 238:921–925
54. Jaiswal P, van Westen CJ, Jetten V (2010) Quantitative assessment of direct and indirect landslide risk along transportation lines in southern India. Nat Hazards Earth Syst Sci 10:1253–1267
55. Geological Survey of India (2013) Proceedings of the regional workshop on landslide disaster management. 19–20 June 2013, Shimla, Himachal Pradesh, 112p
56. Geological Survey of India (2013) Proceedings of the regional workshop on landslide disaster management. 22–23 November 2013, Shillong, Meghalaya, 131p
57. Geological Survey of India, (2014) Proceedings of the regional workshop on landslide disaster management, 17–18 January 2014, Wellington, the Nilgiris, Tamil Nadu, 105p
58. Baum RL, Godt JW (2010) Early warning of rainfall induced shallow landslides and debris flows in the USA. Landslides 7(3):259–272
59. Chan R.K.S., Pang P.L.R., Pun, W.K., (2003) Recent developments in the landslip warning system in Hongkong. In: Proceedings of the 14th Southeast Asian geotechnical conference, Balkema, Lisse, The Netherlands
60. Ramesh MV, Vasudevan N (2012) The deployment of deep-earth sensor probes for detection of landslides. Landslides 9(4):457–474
61. Gabet EJ, Burbank DW, Putkonen JK et al (2004) Rainfall thresholds for landsliding in the Himalayas of Nepal. Geomorphology 63(3–4):131–143
62. Dahal RK, Hasegawa S (2008) Representative rainfall thresholds for landslides in the Nepal Himalaya. Geomorphology 100(3–4):429–443
63. Pachauri AK (2016) Disaster management of landslides in the Himalaya. J Indian Geol Congr 8 (1):27–48
64. National Disaster Management Act-2005 (2005) Ministry of Home Affairs, Government of India. New Delhi. The Gazette of India Extraordinary Part-II, Section 1[No.64]:1–29