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Review of Landslide Hazard Susceptibility Models — Trends and Analysis

Anand Malik[1] and Harish Kumar[2]
[1]Department of Geography, SSN College, affiliated to University of Delhi
[2]Research Associate, Department of Geography (DSE), University of Delhitty
E-mail: anandmalik1111@gmail.com (Corresponding author)

Abstract: *Slope hazards are a significant concern in geoscience, posing serious risks to infrastructure, human settlements, and the environment. In response to the increasing need for comprehensive hazard assessment, susceptibility studies have emerged as valuable tools for understanding and predicting slope instability. Substantial number of research articles were considered and the discussions of commonalities and differences as a function of region and time, revealed significant heterogeneity of thematic data types, scales, modelling approaches, and model evaluation criteria. It was found that the range of thematic data types used for susceptibility assessment has not changed significantly with time, and that for a number of studies the geomorphological significance of the thematic data used is poorly justified. It was also found that the most common statistical methods for landslide susceptibility modelling include logistic regression, neural network analysis, data overlay, index-based and weight of evidence analyses, with an increasing preference towards machine learning methods in the recent years. This review paper examines the latest trends in slope hazard assessment and susceptibility modelling, highlighting advancements in technology and methodologies. The paper also discusses the challenges faced in creating accurate models and suggests potential directions for future research.*

Keywords: *Slope hazards, landslides, susceptibility, likelihood and landslide zonation mapping.*

Introduction

Landslide hazards denote extensive downslope movement of the surface. Such events are caused by a variety of natural reasons, including rainfall, seismic vibrations, overburdening by rock material, elimination of basal support, loosened soil structure, drainage obstruction, as well as human-induced factors. The word landslide, refers to a wide range of mass movements caused by gravity that include various forms of rock-fall, toppling, and debris-flow, including dirt, organic materials etc. (Varnes, 1984). The possibility of a landslide happening in a given region based on local topographical characteristics is referred to as landslide susceptibility (Brabb, 1984). It determines 'where' landslides are most probable to occur (Guzzetti *et al.*, 2005). This paper aims to provide a critical analysis of various landslide susceptibility and landslide hazard zonation methodologies for modelling and associated terrain zonation. The authors acknowledge that the expertise in developing and validating landslide susceptibility models and maps in a variety of physiographic and climatic situations has been the basis of this review discussion. The method adopted is universal, taking into account the major components of susceptibility modelling and associated terrain zonation techniques. For critical review, a database comprising of 215 scientific articles published in peer-reviewed international journals between January 1980 and 2020 were accessed by systematic search through Web of Science, Research Gate, JSTOR, MDPI, Springer, Elsevier and other open access Journals using a set of keywords and criteria, based on online availability.

The study expands on early studies published by several earth scientists on different elements of landslide susceptibility modelling and terrain zonation, including Anbalagan (1992), which proposed a novel quantitative technique based on primary causative components for slope instability in the Himalayas as a case study of landslide hazard zonation. Gupta and Anbalagan (1995) attempted a landslide zonation mapping in the Tehri Pratapnagar region of the Garhwal Himalayas. Average safety factors of landslide hazard zonation were calculated by Terlien *et al*., 1995). Dhakal *et al*. (2000) used GIS techniques and grid-based quantitative method to prepare a geo-hazard map of central Slovenia. This was a mathematical approach to landslide prediction, which was developed based on a number of scenarios by combining the effects of groundwater and seismic acceleration with different return periods. Carlson and Taylor (1995), as well as Lillesand and Kiefer (1999), have evaluated how satellite data can be used for landslide prediction. Woldai (1995), Hafner and Komac (1998), Komac and Ribičič (1998), Chung and Shaw (2000), Ricchetti (2000) and Hafner (2003) have highlighted on the uncertainty involved in using remote sending data for identification and interpretation of landslide incidences. Kanungo *et al*. (2006) attempted landslide susceptibility zonation in the Darjeeling Himalayas using traditional ANN black box, fluffy and mixed neural and fuzzy weighting approaches. Kundu *et al*. (2013) discussed the use of bivariate factual techniques, especially infoVal with modifications as proposed by Oztekin & Topal (2005) and Cevik & Topal (2003), for landslide vulnerability mapping in a raster-based GIS system in the Himalayan terrain. In high slope Himalayan terrain, rain is the important factor in triggering slide when increasing weight of wet saturated soil introduce lubrication and causes debris slide; especially where mining scars make the terrain unstable (Maiti, 2013). Similar occurrences of mass wasting along the valley walls are caused by super-saturated permafrost that moves down slopes and produces scree cones and rock glaciers. Himalayan flanks with altitudes around 3500–3850 m have accelerated landslides and mudslides, where the areas experience rapid permafrost degradation (Koul, 2018). Human activities like boulder mining, road construction, drainage alignment, and deforestation also play significant role in causing landslides (Mitra *et al*., 2016). Recurrent landslides, flash floods, damming of the river, snow avalanches, and glacial lake outbursts in the Himalayan region have frequently taken a heavy toll on human life and property (Chauniyal and Semwal, 2021).

Background, definition and general concepts

Brabb (1984) defined landslide susceptibility as the geographical likelihood of a landslide occurrence based on a collection of geo-environmental parameters. In the same year, Varnes (1984) defined hazard zonation (for landslide) as — ‘the partition of the land surface into different regions and rating these areas according to the degree of existing or anticipated hazard from landslides or other mass movement on the slopes'. Putting these definitions together, Landslide Susceptibility Zonation (LSZ) may be described as the identification of landslide occurrence zones across a certain territory based on a collection of internal landslide causative elements. Susceptibility maps generated by LSZ assist in detecting landslide-prone regions and categorising them on the basis of their degree of susceptibility to landslides. This necessitates the identification of regions that are or might be affected by landslides, as well as the estimation of the recurrence of such landslides within a certain time frame. Clerici *et al*. (2006) identified three types of approaches for mapping landslide vulnerability. The first technique is the deterministic method, based on stability models and relies on the understanding of physical principles determining slope stability. This method is suited for mapping landslide hazard zones in limited regions (Montgomery and Dietrich, 1994; Dietrich *et al*., 1995; Terlien *et al*., 1995; and Okimura & Kawaltani, 1987). The second approach is the heuristic method, which is based on knowledge-based indexing which gives ranks and weights to causative components according to their expected relevance in generating a slope failure. The statistical technique based on landslide inventories is the third and final method. A landslide occurrence is designated as a 'hazard' depending on the likelihood of a landslide of a particular magnitude to occur in a given period and place. Landslide hazard forecasting techniques forecast not just 'where' a slope failure will occur, but also 'when' or 'how frequently' it will occur, and 'how huge' it will be (Guzzetti *et al*., 2005). Landslide hazard is more difficult to determine than landslide susceptibility since susceptibility is the spatial component of the hazard (Guzzetti, 2005). From this analysis it is clear that 'susceptibility' is spatial, whereas hazard is 'spatio-temporal'. Landslide susceptibility can be assigned through qualitative or quantitative approaches, as well as direct or indirect methods. Qualitative techniques are subjective, based on heuristics to determine susceptibility, and depict susceptibility levels using descriptive (qualitative) words. Quantitative approaches generate numerical estimates, or probability of landslide occurrence in every susceptibility zone (Guzzetti *et al*., 1999). All approaches and methods proposed in the literatures can be classified into five broad categories — (i) geomorphological mapping, (ii) landslide inventory analysis, (iii) heuristic or index-based approaches, (iv) process-based methods, and (v) statistical and probability-based modelling.

Earlier, susceptibility classes were defined by qualitative overlaying of geological and slope-attributes to landslide inventory (Nielsen *et al*., 1979). Landslide vulnerability mapping seeks to divide a land surface into homogenous sections based on spatial distribution and temporal probability of occurrence, together with the location and displacement of the landslide deposit and prediction of future occurrences in an area (Varnes, 1984). To achieve these goals at medium scales, thematic mapping units (TMU) are created to estimate the sensitivity of a certain region to landslide occurrences, based on a given set of circumstances (Carrara *et al*., 1995, 1991; Pasuto & Soldati, 1999; Soeters & Van Westen, 1996). Several qualitative or quantitative approaches are used in the process of creating the landslide susceptibility maps (Soeters & Van Westen, 1996; Aleotti & Chowdhury, 1999). In recent years, more advanced assessment techniques such as Analytic Hierarchy Process (AHP), bivariate, multivariate, logistic regression, fuzzy logic, or artificial neural network (ANN) have been used for the assessment of landslide susceptibility. Landslide vulnerability assessment has become a serious

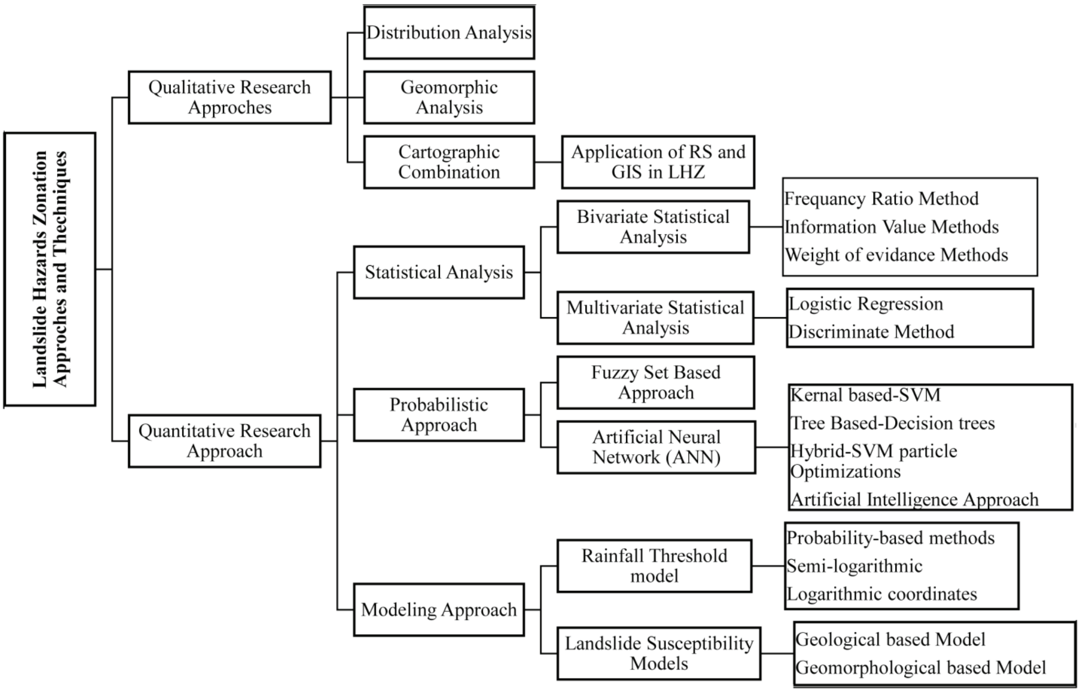

Figure 1. Classification of landslide hazard zonation approaches/ techniques based on Guzzetti *et al*., 1999 (prepare by authors).

responsibility for several groups comprising technocrats, organisers, and others, owing to a growing understanding of the economic impact of landslides (Devoli *et al*., 2007).

Early works on landslide hazard zonation and susceptibility

The classification of land into homogenous zones and rating of these areas according to their degrees of actual or potential hazard caused by landslides and mass movements is referred to as landslide hazard zonation. Landslide hazard zonation maps are commonly used to show the spatial distribution of hazard classes. There are several landslide hazard zonation methods in the literature that have used various methodologies. Sarkar and Kanungo (2004) and Sarkar & Gupta (2005) experimented with different techniques to develop a regional landslide zonation map. Pachauri and Pant (1992) attempted landslide hazard mapping considering all geological attributes, while the work of Yin and Yan (1988) concentrated on statistical prediction models for slope instability on metamorphosed rocks only. Jade & Sarkar (1993), Van Westen & Lulie Getahun (2003) and Sarkar *et al*. (2008) applied GIS based spatial data analysis methods for landslide susceptibility mapping, and Carrara *et al*. (1991) integrated GIS techniques with statistical models for landslide hazard evaluation. Anbalagan (1992) adopted a landslide hazard evaluation factor (LHEF) for landslide hazard zonation in the Himalayas. Juang *et al*. (1992) mapped slope failure potential by using fuzzy sets. Chung & Fabbri (1999) and Dhakal *et al*. (2000) investigated on sampling schemes for a grid-cell based quantitative method. Kanungo *et al*. (2006) did a comparative study of conventional ANN black box, fuzzy and combined neural and fuzzy weighted procedures for landslide susceptibility zonation in

Darjeeling Himalayas. The methodologies in general differ in terms of factor selection and assigning weightage to each factor. The three broad methodological approaches for landslide hazard zonation mapping are — 1) geomorphic analysis by direct hazard mapping in the field, 2) factor overlay approach by weight assignment based on expert knowledge, and 3) statistical approach by correlating past and existing landslides with distribution of landslide influencing factors. Another difference between landslide hazard zonation techniques is the amount of danger information necessary. An appraisal of landslide potential locations can be produced across a vast terrain using regional landslide hazard zonation, which is generally done on a 1:50,000 scale. It is mostly based on information gathered from remote sensing data, topographical maps and geological maps. In general, such studies do not necessitate extensive field research. Despite such conventional methodologies, a more precise landslide susceptibility mapping based on field investigations can be successfully done for a reasonably small region. There have also been investigations including avalanche-peril assessment (Guzzetti *et al*., 1999). Landslide hazards may be assessed through — a) heuristic (Anbalagan, 1992; Saha *et al*,. 2002), b) deterministic (Terlien *et al*., 1995; Gokceoglu & Aksoy, 1996; Acharya *et al*., 2005; Dahal *et al*., 2007, 2008) and c) factual methodologies (Lee & Min, 2001; Dai *et al*., 2001; Van Westen & Lulie Getahun, 2003; Suzen and Doyuran, 2004; Saha *et al*., 2005; Kanungo *et al*., 2006; and Chauhan *et al*., 2010). In the past few decades, the concept of landslide susceptibility and risks assessment has been introduced, and many techniques for measuring and evaluating the intensity of landslides and their related processes have been developed. Any methodological approach to landslide hazard zonation (LHZ) would need identification of the factors that cause slope and rock collapse, purposeful mapping of those variables and assessment of their relative significance (Kundu *et al*., 2013).

APPLICATION OF RS AND GIS IN LHZ

Landslides are caused by complex interactions between numerous geo-environmental elements. The analysis of landslide hazard necessitates an understanding of the interaction between these parameters. Landslide hazard zonation (LHZ) maps, as described by Anbalagan (1992), are of great assistance to planners and field engineers in selecting suitable locations to implement development schemes in mountainous terrain, as well as in adopting appropriate mitigation measures in unstable hazard-prone areas. Based on the major causes of slope instability, a new quantitative technique has been developed. Balasubramani and Kumaraswamy (2013) used a quantitative technique, information value and weighted overlay, in the landslide hazard zonation of Himachal Pradesh's Giri valley. To derive the information value for a pixel, numerical data layers are stacked and weightage is assigned to the different variables. Such a quantitative technique requires a point-by-point comprehension of the physical processes, together with authentic data on the landslide events. Guzzetti *et al*. (1999) presented the mapping unit types, and the most commonly used hazard assessment methods, as well as discussed the experience of using GIS-based models of hazards and risk assessment related to slope failure in central Italy; ranging in size from tens to thousands of km^2. They also outlined the possibilities and traps of such GIS-based methodologies. In the light of the obtained results, the data quality, size of landscape unit and statistical models applied are critically reviewed. The evaluation of landslide hazards has turned into a significant task for different technocrats, planners and others, chiefly because of an expanded familiarity with the fiscal significance of landslides (Devoli *et al*., 2007). Landslide vulnerability mapping intends to isolate a land surface into homogeneous regions as demonstrated by their probability of failure brought about mass movement (Varnes, 1984). To accomplish this target at medium scales, thematic mapping units (TMU) are produced to assess the probability of landslide events in an area (Carrara *et al*,. 1991, 1995; Pasuto and Soldati, 1999; Soeters and Van Westen, 1996).

LANDSLIDE AND SLOPE STABILITY

A landslide occurs when the slope's stability shifts from stable to unpredictable. Landslides are mostly aggravated by human activities such as deforestation, development, and construction, which destabilise the already vulnerable slope (Murali *et al*., 2016). A quantitative slope stability study was critical in determining landslide hazard. The goal of this examination was to establish whether the slope was stable or not. Uncontrolled excavation procedures and the use of 'standard' structures have resulted in a slew of perilous man-made slope angles. Some unstable slopes pose a significant risk to the surrounding structures and communities. As a result, geographical and geotechnical examinations are required to distinguish the hazard and risk of slope instability and to recommend prompt action when necessary. Fellenius, (1936) presented the ‘Ordinary’ or ‘Swedish’ cutting scheme. In the mid-1950s, Janbu (1954) and Bishop (1955) invented propellers. In the 1960s, electronic computing made it possible to manage the iterative procedures inherent in the strategy all the more quickly, which prompted increasingly thorough formulations, for example, those established by Morgenstern and Price, (1965) and Spencer, (1967).

BIVARIATE STATISTICAL ANALYSIS

The bivariate statistical analysis for landslide hazard zonation examines each data layer of causal component to the present landslide distribution (Kanungo *et al*., 2009). Weights are assigned to landslide causative factors based on landslide density. The Frequency Analysis method, Information Value Model (IVM), Weights of Evidence Model, Weighted Overlay Model, and others are key bivariate statistical approaches used in LHZ mapping.

LANDSLIDE INVENTORY

Landslide inventory is the most significant aspect in LHZ mapping, as it contains information about existing landslides in a region and is valuable for assessing and validating the landslide hazard map. A landslide inventory map contains data on the spatial distribution of mass movements as well as their current level of activity (Parise 2002). There is no standard method for creating a landslide inventory map. Multiple inventory maps are created with landslides represented as point, scarp, and seed-cell. A landslide inventory map of a region is the basic data source for understanding the circumstances and processes that influenced past landslide events and their evidences, which are the most essential aspect in predicting future landslides (Yilmaz *et al*., 2012). Landslide inventory maps derived from historic records, field investigation, interviews, interpretation of satellite image and aerial photographs are required to understand the frequency of the phenomena, the types of movement, the volumes involved and the damage that has been caused. But such detailed information are frequently lacking.

RAINFALL THRESHOLD FOR LANDSLIDE

Rainfall is the most prevalent cause of landslides. However, the actual process of slope failure is complex and involves a variety of elements that impact the hydrologic behaviour of the slope, the shear stress acting on the slope, and the mechanical resistance along the possible slip surface. However, the link between rainfall and landslide is indirect and often comprises a process cascade in which rainfall is followed by infiltration into the soil, which raises the pore-water pressure, which is responsible for the decrease in the shear strength of the slope materials (Terlien, 1998; Glade and Crozier, 2005). Rainfall is a well-known driver of landslides, and researchers have long sought to calculate the quantity of precipitation required to cause slope collapse — an issue of scientific and societal relevance. Rainfall-induced landslides are produced by a buildup of water pressure in the ground (Campbell, 1975). Groundwater conditions that cause slope collapses are linked to rainfall through infiltration, soil properties, antecedent soil moisture and rainfall history (Wieczorek, 1996). Over the last few decades, the association between landslides and rainfall has been provisionally established by assessing rainfall thresholds, i.e. rainfall parameters (cumulated rainfall, intensity) that, when achieved or surpassed, might cause a landslide occurrence (Reichenbach *et al*., 1998; Guzzetti *et al*., 2007).

LANDSLIDE RISK ASSESSMENT

The aim of assessing landslide risk is to establish the 'anticipated degree of loss due to a landslide and the projected number of lives lost, persons hurt, property damaged and disruption of economic and social activities' (Varnes, 1984). The ideas of landslide susceptibility and hazard assessment have been introduced in the recent decades and various methods have been developed for assessing and evaluating the intensity of landslide and its related processes. Any method and approach towards the LSH would require identification of the conditions prompting slope and rock failure, their mapping and assessment of their relative contributions (Kundu *et al*., 2013). Various investigations have been made in these lines, including evaluation of avalanche-risk zones (Guzzetti *et al*., 1999). Landslide hazards can be assessed using heuristic (Anbalagan, 1992; Saha *et al*., 2002), deterministic (Terlien *et al*., 1995; Gokceoglu and Aksoy 1996; Acharya *et al*., 2005; Dahal *et al*., 2007, 2008) and factual methodologies (Lee and Min, 2001; Dai *et al*., 2001; Van Westen & Lulie Getahun., 2003; Suzen and Doyuran, 2004; Saha *et al*., 2005; Kanungo *et al*., 2006; Dahal *et al*., 2007 and Chauhan *et al*., 2010) among others. Rautela and Lakhera (2000) analysed the landslide hazards and risk along the Giri and Tons rivers in Himachal Himalaya. The area around Sataun in the Sirmur district of Himachal Pradesh was considered for landslide vulnerability based on the experience of local inhabitants. Rai *et al*. (2014) has shown through their analysis that slope plays a very important role in gravity force which is major causes for the landslide process. This study targeted on mitigation and management of hazard due to landslide. Landslide mitigation is successful only with the detailed knowledge about the expected frequency, characteristic and magnitude of mass movement in the region. El Bchari *et al*. (2019) carried out an integrated analysis of landslide hazard in the coastal area of Safi in Moroccan Meseta. The analysis was done on the basis of satellite images using predictive models in the GIS environment. The final output for landslide hazard zonation in coastal area revealed that: the parameters of slope, geologic formation and structural weakness have strong correlation and predicts 75% of the existing instabilities.

Review of different approaches for landslide susceptibility and zonation.

The mapping of landslide hazard zones is a key instrument for disaster management in vulnerable mountain terrain. Landslides are common in hilly and mountainous area with critical slope stability. Varnes (1984) defined landslide hazard zonation as 'the process of dividing the land surface into areas and ranking these areas according to the degree of actual or potential risk from landslides or other mass movements'. Jiménez-Perálvarez *et al*. (2009) discussed the landslide-susceptibility map as a progressive zonation of areas or slopes increasingly prone to landslides. A model for the validation of the landslide-susceptibility maps is also presented, based on the determination of the degree of fit, which is calculated from the cross tabulation between a set of landslides (not included in the susceptibility analysis) and the corresponding susceptibility map. Nafuti (2010) used multiple-regression for analysing the accuracy of the proposed model for validating landslide hazard zonation. Couture (2011) explained the concept of landslide hazard as 'division of land into somewhat homogeneous areas or domain and their ranking according to the degrees of actual or potential landslide susceptibility, hazard or risk or applicability of certain landslide related parameters'. Othman *et al*. (2012) deals with the use of GIS and Multi-criteria Decision Making (MCDM) technique to map the landslide hazard zones. Pardeshi *et al*. (2013) considers landslide hazard assessment as an important step towards landslide hazard and risk management. There are several methods of Landslide Hazard Zonation (LHZ) viz. heuristic, semi quantitative, quantitative, probabilistic and multi-criteria decision-making process. Kahlon *et al*. (2014) explored the spatial and temporal dimensions of landslide in Himachal Pradesh with a focus on identifying critical zones of landslide occurrences.

Construction and analysis of the database

To construct the literature database, we searched peer-reviewed articles in the Web of Science, Research Gate, JSTOR and other online platforms for open access journals (formerly a Thomson Reuters™ product, now part of Clarivate™ Analytics) using a set of keywords and boolean search criteria and applying the criteria to the 'title', 'abstract', and 'keywords' of the publications. Conference proceedings, 'grey literature' (e.g. government, technical, and project reports), and dissertations were not considered to compile the database. Keywords used included 'landslide', 'rock-fall', 'debris flow', 'hazard', 'susceptibility', 'slope', 'instability', 'inventory', 'vulnerability', 'risk', 'management' etc. As the authors were interested in popular (and recent) statistical approaches for landslide susceptibility mapping, the search was narrowed down to a subset of the literature based on the citation number listed below — (i) for articles published prior to 2019, only those articles were considered with ten or more citations; (ii) for articles published between 2007 and 2008, articles with five or more citations we considered; and (iii) for articles published between 2009 and June 2016, all articles were considered, including those without any citation. This has influenced the result of the database. However, assuming that citations are a useful indicator of an article's impact, the selected technique did not exclude any 'relevant' old articles from the database.

For each of 215 articles in the literature database information was identified and populated the six categories and 30 subcategories of information listed in Table 1.

Article

In the literature database, the article data includes (B1) the name of the journal, thesis and report, (B2) the article title, (B3) the author(s), (B4) the year of publication, and

Table 1: Summary statistics for categories and sub-categories used in the literature review database of different methods of landslide susceptibility models and terrain zonation, based on articles from 1980 to 2019. In Table 1, 'counts' indicates the number of occurrences as given by the authors. Classes and clusters refer to different levels of grouping performed in the analysis, with clusters being groups of classes. Counts, classes and cluster values are specified only where applicable.

	Counts	Sub-Category	Category
A	ID	A1 Article identification Number	215
B	Articles	B1 Journal, reports, dissertations B2 Title B3 Authors B4 Publication Year B5 No of citation (July 2019)	85 1 to 8 35 > 400
C	Study area	C1 (C1a) continent, (C1b) country C2 Locations C3 Number of study area C4 Spatial extent (km2) C5 Latitude and longitude of approximate centers	7, 45 356 (including duplicate) 1 to 3 per article
D	Landslide inventory	D1 Single, multiple, no Inventory D2 Inventory Type (s) D3 Inventory years(s) D4 Mapping techniques D5 Landslide type D6 No of Landslide in the Inventory D7 Total landslide area (m2) in the inventory	309, 69, 12 63
E	Susceptibility model production	E1 List of thematic variable E2 DEM Pixel Size (m) E3 Scale of thematic variable (s) E4 Type of mapping unite(s) E5 Pixel size(m), where different from DEM pixel size E6 Model types	226 1 to 1000 126
F	Susceptibility Model Evaluation	F1 Model fit Performance Measure(s) F2 Model Fit Description and results F3 Model Validation criteria F4 Model Predication performance measure F5 model Prediction description and Results F6 Estimated Model Uncertainty	53 27
G	Susceptibility Quality	G1 Susceptibility Quality Level (SQL)	

(B5) the number of references cited since July 2019 (Table 1). Examination of the database revealed that the 215 articles were distributed in 105 recognised journals. Figure 2 shows the number of articles, the absolute number of references to those articles recorded in the Web of Science online platform and the average number of references per article for the period from January 1985 to January 2020. For this period, the inclination of the

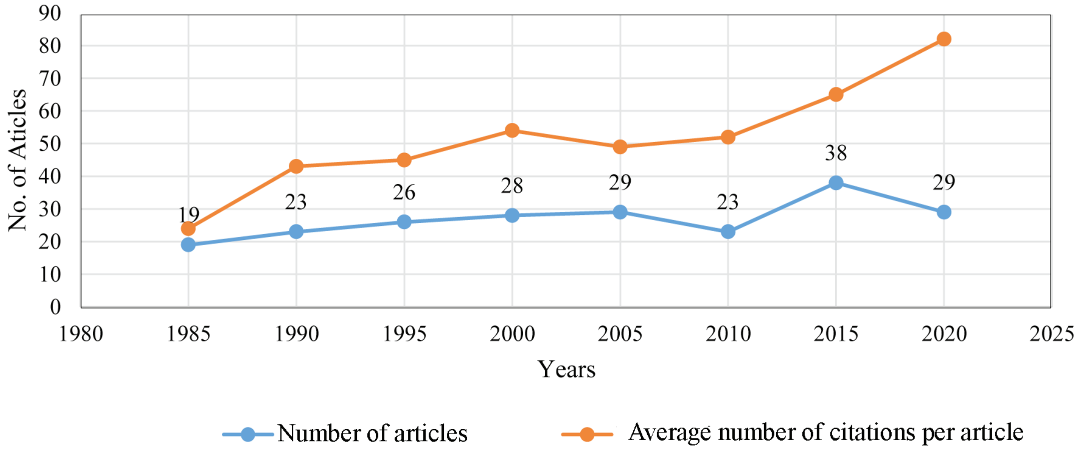

Figure. 2. Analysis of the literature database showing review articles and average citation of 215 articles in the 35 years period from January 1985 to January 2020.

references was taken note of. Considering our determining criteria the normal (median) reference rate was around 70 for each article.

Fig. 2 shows the trend of published articles and citation per article in different years. It is clear that the number of articles and number of citations used in articles increased in the field of landslide hazard and allied topics since the 1980s.

Study area

The data has been gathered in study region into subcategories. sub-classes: continent (C1a), country (C1b), geological location (C2), number of study areas (C3), spatial extent (C4), and geographical coordinates (latitude, longitude) of the centroids of the study area (C5) (Table 1). Of the 215 articles in the database, 92.7% articles had one investigation region, and 7.3% are based on 356 recently reported examination regions. These regions are not all unique to a study, i.e. a given region may be investigated in its entirety or to some extent by more than one article (Fig. 3). The 45 countries having study regions in the literature database are shown by light pink coloring. Dark Green Colored circles represent the number of landslide related study areas in each country, divided into five groups. The sizes of the circles are proportional to the number of articles in each country.

Landslide information

For each article in the database, we examined the attributes of the landslide data, including — (D1) number of inventories delivered or utilised (single or multiple), (D2) types of landslide maps, (D3) the year of the maps, (D4) the mapping techniques, (D5) the landslides types, (D6) the quantity of landslides, and (D7) the total landslide area (Table 1).

A given study area may have at least one inventory (D1). Most of the articles portrayed or utilised a single inventory and just a small number (19%) utilised at least two inventories. In a couple of articles, this data is obscure (3.4%) and did not take any stock for their susceptibility assessments (Anbalagan, 1992; Anbalagan and Singh, 1996; Pandey *et al.*, 2008; Zolfaghari and Heath, 2008; Haneberg *et al.*, 2009; Avtar *et al.*, 2011). In 38 articles, out of 215 (17.6%), authors have portrayed and utilised multi-temporal maps (covering a single region with landslides from various

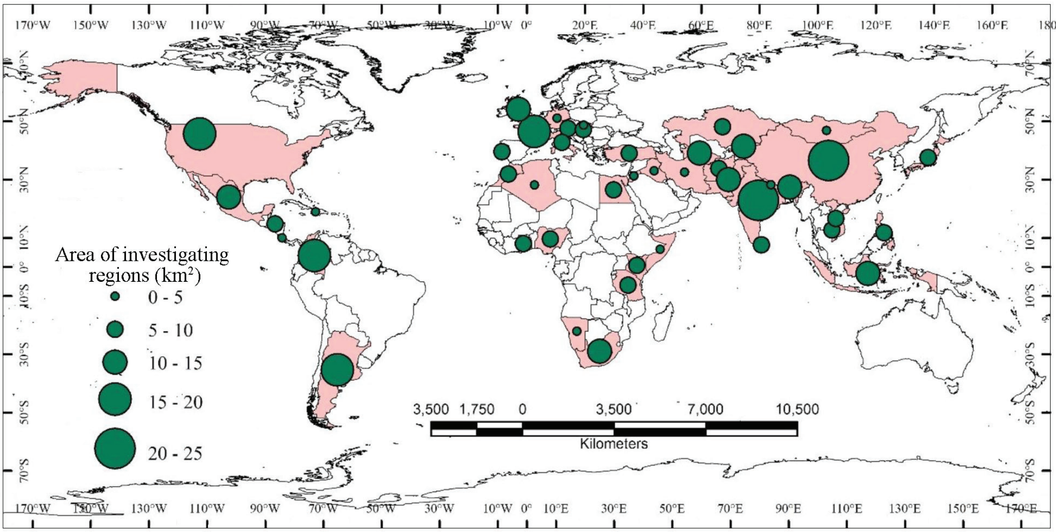

Figure. 3. Map showing the geographical distribution of the 434 study areas, including duplicates, listed in the literature database (Source: prepared by the author)

time spans), or arranged inventories utilising various methods; that may be, in various cases the 'same' or fundamentally the same (with indistinguishable period and spatial coverage) as was utilised and represented in various articles.

Susceptibility model production

Searching the literature database, information was extracted on the production of the susceptibility models including, (E1) the input thematic variables, (E2) the ground resolution (pixel size) of the DEM, (E3) the scale of the thematic data, (E4) the mapping units, (E5) the pixel size, if different from the DEM pixel size, and (E6) the model type (Table 1).

THEMATIC VARIABLES

Generally speaking, the authors have used a total of 226 diverse topical factors. These factors are extracted from 215 review articles published in the last few decades. Every factor was assembled by two principal criteria — 1) Topical variable names that had equivalent words were gathered; for instance, 'gradient' and 'slope' were assembled into the class 'gradient'. 2) Topical factors identified with comparable descriptors (yet not really similar) were assembled; for instance, 'geographical age' and 'land development' were gathered into the class 'geo-lithology'.

MAPPING UNIT

Determination of the mapping unit is a significant pre-essential for demonstrating slope failure (Guzzetti *et al*., 1999; Guzzetti, 2005). Looking through the database, three basic mapping units (E4) were recognised — pixels incline units, and one-of-a-kind condition units. Pixels, utilised in 86.4% of the articles, were the most well-known mapping unit. The other mapping units were less consistent, with incline units utilised in 5.1% of the articles, and condition units utilised in 4.6% of articles. In 3.9% of the articles, writers utilised different sorts or blends of these three distinctive mapping units (Carrara and Paik, 2008; Van Den Eeckhaut *et al*., 2009; Erener and Düzgün, 2012).

MODEL TYPE

Out of 215 articles, around 27% (58

Articles) of the articles used only one type of landslide susceptibility model. The remaining used two or more model types, and the maximum is eight different model types (Vorpahl *et al.*, 2012). The 126 model types were reclassified into different classes. The reclassification was not straightforward, and required multiple iterations. Identification and reclassification of the model types had to be done carefully as different authors used different names for the same model type, or the same name for different models might be used with different meanings.

The results of the re-classification are given in Fig. 4, with four model types

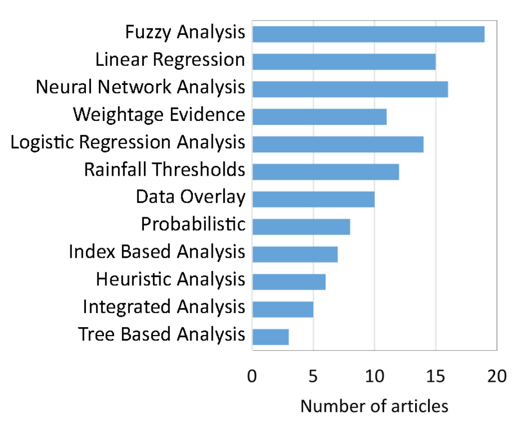

Figure 4. Horizontal bars showing the count of 12 model types reclassified from the 126 model names used by the authors in the articles considered in the literature database.

accounting for 27% of all the occurrences, among these logistic regression analysis has been used in 15% of the articles, data overlay in 10%, neural network in 16 %, and index-based models in 7 % of the articles, included in the database. Temporally, for more than a decade since 1984, data overlay was the main model used for landslide susceptibility studies, with few applications of logistic regression analysis and heuristic analysis (Fig. 5).

Discussion

Extent and location of the study areas

Analysis of the literature database of 215 articles uncovered that specialists have arranged avalanche models and maps in 356 investigation zones; non-remarkable, and not thinking about mainland/ worldwide scale. The landslide susceptibility studies are situated in 45 distinct countries and in seven continents. A couple of authors have directed or examined landslide susceptibility assessment at mainland scale in Europe (Van Den Eeckhaut *et al.*, 2012; Günther *et al.*, 2013, 2014). Similarly, only a few articles have attempted for global, synoptic-scale assessments of landslide susceptibility (Nadim *et al.*, 2006; Hong *et al.*, 2007). Barring the mainland and the worldwide investigations, the study areas vary in size from a few to hundreds to thousands of km^2, with a large portion of the study regions having an area around 100 km^2, and covering a total of 4.6 million km^2, or 0.03% of the Earth's surface. The total area was estimated by considering all landslide events even the issue of non-uniqueness of study territories was not taken into consideration. The total area is fundamentally not exactly the region to be secured via avalanche stock maps (Guzzetti *et al.*, 2012).

Between 1985 and 2020, landslide susceptibility appraisals were applied and tested successfully on different sites (with the test area coverage <100 km^2) in four countries Italy (2), Japan (1), India (4) and Jamaica (1). The number of the test destinations and their geological inclusion expanded essentially after 2005, when the normal size of the explored zones also expanded. Fig. 6 shows the the considered territories, with majority of the landslide susceptibility zones in Asia followed by North America, Africa, South America, Central America, and Oceania. In spite of the way that the geological inclusion of avalanche has expanded in the ongoing time frame, for large areas of the world (e.g., Africa, South America, Oceania) the quantity

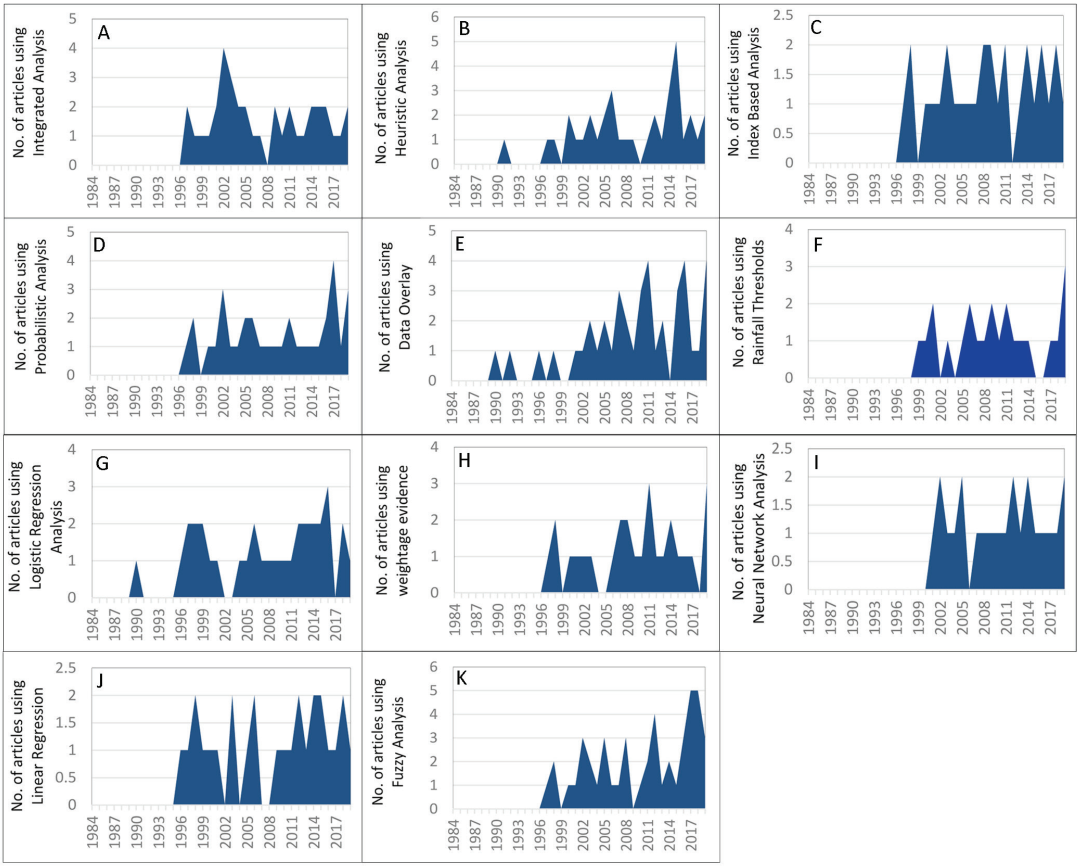

Figure 5. Landslide susceptibility model types used in the articles in the literature database from 1984 to 2017, where A) Integrated analysis, B) Heuristic analysis, C) Index-based analysis, D) Probabilistic analysis, E) Data overlay, F) Rainfall threshold, G) Logistic regression analysis, H) Weightage evidence, I) Neural network analysis, J) Linear regression and K) Fuzzy analysis.

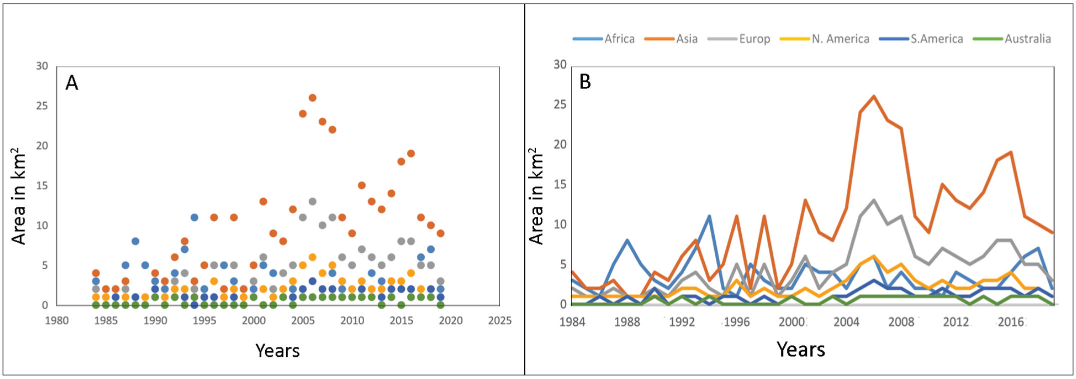

Figure 6. Size of the study area: A) the distribution of the areal extent of study area per year and B) areal extent of the study areas distributed in different countries

of avalanche vulnerability evaluations stays restricted (Fig. 6). In Africa, South America and Central America, helplessness appraisals were less rich and constrained to territories of smaller than normal size. The investigation regions were generally larger in Europe, especially in the period 2010–2015.

Future challenges

The development of a landslide susceptibility model and zonation for a very broad region will be challenging due to a lack of accurate or authentic data. If the area is considered a continent, it will be difficult to bring precision in the work and analysis.

Assessing the predictive susceptibility models at all scales remains a difficult and intractable process. This is due to difficulties in testing spatially dispersed forecasts of landslide susceptibility (Guzzetti *et al*., 2006; Lobo *et al*., 2008; Frattini *et al*., 2010; Rossi *et al*., 2010), owing to lack of legitimate data to test the models reliably, particularly of multi-transient avalanche stock maps (Guzzetti *et al*., 2012).

The appropriation of normal guidelines for positioning and depicting landslide susceptibility may encourage the examination of various models for a similar region.

Serious research is required to plan and test techniques and strategies for the susceptibility territory zonation for various landslide types.

Conclusion

The critical literature review using extensive literatures provided evidence for describing the heterogeneity of landslide and thematic data types, scales and modeling approaches. This also evaluates the criteria to be used for the analysis. The very common method of susceptibility assessment were logistic regression, neural network analysis, data-overlay, index-based and weight of evidence analyses, with a preference towards technical learning methods in recent years.

Adopting the Susceptibility Quality Level index (Guzzetti *et al*., 2006), the quality of most of the susceptibility models were analysed, and found that this has improved over the years, but top quality assessments remain rare. To improve the quality of the models, it is recommended that besides assessing the model fit and prediction performances, both becoming common in the literature, the uncertainty of models and zonation should be measured quantitatively.

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