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RESEARCH PROGRESS IN LANDSLIDE POTENTIALITY ASSESSMENT: A CASE STUDY OF THE SHIVKHOLA WATERSHED, DARJILING HIMALAYA.

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Abstract

This paper deals with the application of a factor-based approach, the Multi Criterial Evaluation Approach, 1-D Slope stability model and the Analytical Hierarchy Process to assess the spatial distribution of slope instability in the Shivkhola Watershed of Darjiling, Himalaya. Remote Sensing and GIS tools have been incorporated to prepare the various thematic maps processed in the present study and estimate the accuracy level of each landslide susceptibility map. We utilized Erdas Imagine (9.0), Arc Map, PCI Geomatica and MATLAB Software to fulfill the basic objectives. Results revealed that Analytical Hierarchy Process and 1-D slope stability model are very much accepted approach in landslide assessment and prediction.

Keywords: *Factor approach, Multi criteria approach, 1-D slope stability model, analytical hierarchy process, landslides.*

1. INTRODUCTION

Landslide hazard zonation involves the division of an area into several zones, which indicates progressive levels of landslide hazard. According to Varnes (1984), "the term zonation implies in the general sense to categorize the land surface into areas and arrange them according to degree and potential hazards from landslides and other mass movements on slope. The first good paper on *landslide hazard zonation* in India was published by Majumder (1980). The National Remote Sensing Agency (NRSA), Department of Space of the Government of India, Hyderabad, has recently published an Atlas on Landslide hazard zonation in two parts, Atlas vol. 1 refers to Uttaranchal, and Atlas vol.2 refers to Himachal Pradesh. Bureau of Indian Standards (BIS, 1998), proposed a guideline for landslide hazard zonation map on 1:25,000 or 50.000 scales. The zonation map of the Shivkhola watershed has been prepared here using the factor approach (landslide hazard evaluation factor-LHEF) rating scheme. For the preparation of the hazard zonation map of the Shivkhola watershed various factors viz. average slope, relative relief, lithology, drainage density, constant of channel maintenance, dissection index, ruggedness index, land use and others were considered. Without a thorough mapping of the sub-catchment and without assigning the weightage accordingly, the match between the inferred hazard rating and the observed hazard rating will remain elusive (Bhandari, 1987). Landslide analysis is mainly done by assessing Susceptibility, Hazard and Risk (Einstein, 1988). Guzzetti *et al.* (1999) have summarized many landslide hazard evaluation studies. Jibson *et al.* (2000); Praise and Jibson (2000); and

Zhou *et al*. (2002) have also applied the probabilistic models for landslide risk and hazard analysis. Recently, GIS based landslide hazard zonation approach had been studied by Saha, Gupta and Arora (2002); and Caiyan and Jianping (2009). Rowbothan and Dudycha, 1998; Donati and Turrini 2002; Lee and Choi 2003c; Lee et al., 2004a & 2004b; Lee and Pradhan, 2006, 2007; Pradhan and Lee , 2010a, 2010b, 2010c; and Pradhan et al., 2010a have studied and applied the probabilistic model for landslide susceptibility and risk evaluation. Atkinson and Massari, (1998); and Vijith and Madhu, (2008) applied the logistic regression model for landslide hazard mapping. Landslide hazard evaluation by using fuzzy logic, and artificial neural network models have been mentioned in the various literatures of Gokceoglu et al. (2000); Pistocchi et al. (2002); and Pradhan 2010. An integrated approach for landslide susceptibility mapping using Remote Sensing and GIS was developed by Sarkar and Kanungo (2004); Sharifikia (2007) Pande, Dabral, Chowdhury and Yadav (2008); and Nithya and Prasanna (2010).

The geotectonic factors of slope instability were studied in details by Brudsen, 1979; Windisch, 1991; Carson, 1975; Carson, 1977; and Borga et.al.1998. The hydrologic factors like daily rainfall threshold in connection with slope angle and regolith thickness (Gabet et.al.2004), practiced in the analysis of slope instability. Several approaches to assess slope stability and landslide hazards were put forwarded by Montgomery and Dietrich, 1989; Carrara et al., 1991; Hammond et al., 1992; and Montgomery and Dietrich, 1994. Montgomery and Dietrich (1994) combined a contour based steady state hydrologic model with the infinite slope stability model (simplified for cohesion less soils) to define slope stability classes based upon slope and specific catchment area. The models in connection to the slope stability, shallow and deep seated landslides were introduced and verified by Varnes, (1958), Young (1963), Vanmarcke (1977), Burton and Bathrust (1998), Bradinoni and Church (2004), and Vleeschauwer & Smedt (2002), Smedt (2005) and Bhattarai et al. (2001). The geotectonic factors of slope instability were studied in details by Brudsen, 1979; Windisch, 1991; and Borga et.al.1998. The geo-technical attributes include surface inclination (β), soil depth (z), cohesion (c), angle of internal friction (φ), soil saturation index (m), Soil density (γs) and density of water (γw). The present study incorporated various geo-technical parameters to prepare landslide susceptibility map of the Shivkhola Watershed in semi-saturated condition applying 1D slope Stability model on GIS platform.

Remote Sensing Technique and GIS tools have also been used for the generation of landslide susceptibility map on landslide inducing parameters like lithology, slope, aspect, curvature, lineament, drainage density, upslope contributing area, settlement density, landuse and land cover to assess the probability of landslide and its spatial distribution by applying both Multiple Criteria Evaluation Approach (MCEA) and Analytical Hierarchy Process (AHP). The qualitative or semi-quantitative methods are often useful for regional studies (Soeters and Van Westen, 1996; Guzzetti et al., 1999). The AHP process was first developed by Saaty (1980, 1990 & 1994) for landslide susceptibility mapping which was followed by Satty and Vargas (2001 & 2004), Mwasi (2001); Nie et al. (2001) and Yagi (2003). Indian researchers contributed a lot in landslide hazard assessment in the mountainous region (Table 1).

A comparative study was made between Factor Approach (LHEFA), 1-D Slope Stability Model, MCEA and AHP to understand the spatial distribution of slope instability in connection to the attributes of land, soil and water in an interacting combination with human actions in Shivkhola Watershed (Figure 1).

Table 1. Contribution of Major Indian Researchers on Landslide since 1980 in India**.**

Contributing Authors	**Landslide Research**
Majumder (1980), Basu and Sarkar (1985), Basu and Sarkar (1988), Basu (1989)	Landslide hazard zonation map applying in India
Bhandari (1987), Mondal and Maiti (2013)	Landslide hazard evaluation factor approach (LHEF)
Bureau of Indian Standards (BIS, 1998) through IS-14496 (Part 2)	Proposed a guideline for landslide hazard zonation map on 1:25,000 or 50000 scales in India.
Saha, Gupta (2002), Ramakrishnan (2002), Sarkar and Kanungo (2004); Gupta (2005), Kanungo (2005), Kanungo et al. (2006a), Kanungo et al. (2006b), Kanungo et al. (2006c), Kanungo et al. (2006d), Jaiswal (2006), Sharma (2006), Kumar et al. (2006), Ghosh et al. (2006), Kumar et al. (2008), Pande, Chowdhury and Yadav (2008); Ghosh (2009), Sharda (2010) and Nithya and Prasanna (2010), and others.	RS & GIS Based integrated approach for landslide susceptibility Mapping in Indian Context. Most of the landslide studies were carried out in the Himalayan Region.
Dubey et al. (2005)	3-D Digital Elevation Model for landslide assessment and Prediction in mountain area.
Anbalagan et al. (2008)	Geotechnical Evaluation on Landslide, Uttarakhan Himalaya.
Kanungo, Sarkar, Shaifaly and Sharma (2011)	Combined Neural Network Model with fuzzy, certainty factor approach and likelihood ratio concept for spatial prediction of landslides.
Evangelin and Rajamanickam (2011), Evangelin (2011a and 2011b).	Application of Fuzzy logic, Probalistic Frequency Ratio Model and Logistic Regression Model in landslide assessment
Vijith and Madhu, (2007, 2008)	Logistic regression model in landslide assessment.
Ghosh (2009)	Application of probabilistic Statistical model for landslide assessment in Drjiling District.
Sujatha et al. (2012)	Probabilistic Certainty Factor Approach
Mondal and Maiti (2012)	1-D Slope stability model
Mondal and Maiti (2012a, 2012b and 2013)	Analytical Hierarchy Process (AHP), Frequency Ratio Model (FR) and Landslide Susceptibility and landslide risk.
Mondal and Maiti (2013)	Integration between AHP and Frequency Ratio Model to assess landslide susceptibility in Darjiling Himalaya.

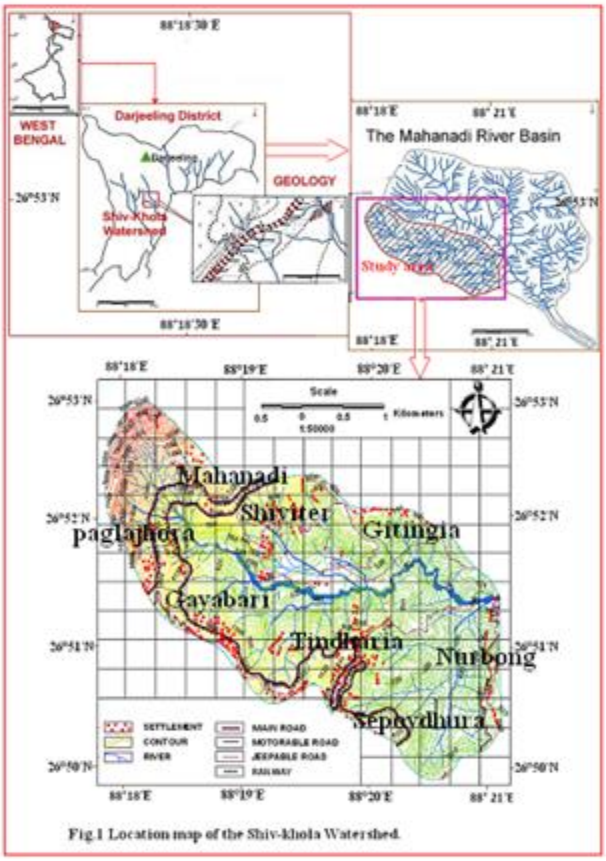

Figure 1. Location map of the Shivkhola Watershed

After analyzing the accuracy level of all the prepared landslide hazard maps, it was inferred that the sophisticated and scientific method of landslide hazard assessment was to be given more important in landslide research. Landslide hazard maps are required for developmental planners as scientific tools for efficient management of the land. To constitute the zonation map of slope instability it is necessary to understand the some triggering mechanism of landslides. The preparation of a landslide hazard zonation map is the first major step for combating such disaster and also is the major objective of my study. The difficulty in preparing the zonation map is the lack of collected data related to the causative factors such as topography, climate, geology, hydrology, seismicity and anthropogenic changes.

2. MATERIALS AND METHODS APPLIED IN LANDSLIDE STUDIES

2.1 Factor Approach in landslide susceptibility analysis

For the preparation of the hazard zonation map of the Shivkhola watershed the factor-mapping approach has been applied in which various factors viz. slope inclination, relative relief, drainage density, dissection index, land use, are considered. This approach offers tremendous flexibility to the whole mapping system because specialist team can work on different parameters independently or collectively. The information regarding landslides hazard evaluation factor (LHEF) of the Shivkhola watershed has been obtained from the interpretation of 1:50000 Survey of India -Topo-sheet, 1:50000 geo-coded LISS-III Satellite data, existing geological map and extensive field work. The following steps have been taken in to consideration for the preparation of the zonation map.

- To identify the factors/components responsible for slope failure.
- To arrange various factors according to their significance.
- To determine variables for each of the factors/components.
- Preparation of 0.25 sq. Km. grid of the basin.
- Grid wise assignment of ratings for individual variables.
- To estimate cumulative landslide hazard evaluation factor by adding all the ratings applied for each components.
- Preparation of the zonation map putting grid wise LHEF values.
- Estimation of the degrees of instability based on the map developed.
- Field validation by comparison with the actual landslide map.

In this approach 13 landslide inducing factors have been considered and on the basis of these factors 13 thematic maps have also been prepared following a suitable method. Maximum Landslides Hazard Evaluation Factor (LHEF) value or Landslide susceptible values (LSV) are assigned to every factor according to the apprehended importance of different factors. Slope is considered as the most important factor for slide as the rate of the release of kinetic energy directly depends on the steepness and this energy is responsible for the mass transfer with the help of gravity and so is assigned with 11. Upslope contributing area, Depth of soil and landuse are assigned with Landslide susceptible values 10 each. Upslope contributing area is the indicator of excess of water and concentration of both surface and sub-surface water and thus helps in the down-slope movement of materials by increasing weight of wet soil, reducing cohesion and increasing lubrication. Topographic Index is the ratio between contributing area and slope gradient and thus is the indicator of excess water and availability of energy for down slope movement and is one of the important factor of slope instability and thus is assigned with LSV of 10. Land use and land covers are assigned with different rating values according to their importance in soil and slope instability. Drainage channels are rated with maximum rating of 10 where as settlements, agricultural lands; bare lands are rated by 9, 6 and 8 respectively. The dense forest, degraded forest, mixed forest, open forest and jungles are rated with 2,5,3,4 and 4 respectively. Tea gardens are rated with the value of 4. The percentage share of all the land uses of every grid of 0.25 Km2 are analyzed carefully for calculating the rating value for each of the contributing land uses for those small grids. Ultimately all the rating values for the concerned grid are added for calculating the cumulative rating values and thus Land use Index Values are calculated.

The Land use Index is assigned with a maximum LSV of 10 and the relative importance of each grid is calculated accordingly. Human interventions are assigned with a maximum value of 9 and the relative importance of the different types of intervention to slope instability is reflected accordingly with assignment of Landslide Susceptibility Values. Ten of such land uses are identified and LSV is assigned to each of them according to potential effect on slope failure. Human intervention on slope is identified as few categories like road, jeepable road, road and settlement, settlement, slope clearance, drainage concentration and are assigned with the values ranging from 4 to 9 according to their possible effect on slope instability. Upslope contributing area and Topographic Index are two important factors are assigned with LVS ranging from 1 to 10 (Table 2).

Table 2. Terrain Factors and Landslide Susceptibility Values (LSV).

No. of Variables	Factors/Variables	Landslide Susceptibility Values(LSV)
1	**Slope Inclination**	**10**
2	**Road Contributing Area**	**10**
3	**Relative Relief**	**07**
4	**Drainage Density**	**06**
5	**Lithology**	**06**
6	**Presence of thrust/fracture**	**05**
7	**Dissection Index**	**07**
8	**Ruggedness Index**	**06**
9	**Constant of Channel Maintenance**	**08**
10	**Upslope Contributing Area**	**10**
11	**Depth of Soil**	**10**
12	**Land use**	**10**
13	**Human Intervention**	**05**
Total		**100**

Lithological compositions are also assigned with LSV of a maximum of 6. Depth of the soil is measured at the time of intensive field investigation and LSV ranging from 1to 10 were assigned for each grid according to their relative influence on slope instability.

2.2 Spatial Raster Calculation Model or Multi-Criteria Evaluation Approach (MCEA) in Landslide Susceptibility Assessment

The data used in the present study are Satellite image (IIRS P6/Sensor-LISS- III, Path-107, Row-052, date-18/03/2010), modified SRTM data with scene size 10 lat. and 10 long. (date-5th April, 2008) and Google Earth Image (1st September, 2010), Geological Map (Geological Survey of India, East Kolkata) and Topographical Map (Survey of India, 78B/5). The thematic data layers were made in connection with ERDAS Imagine 8.5, Arc View and ARC GIS Software. The common method to study the landslide triggering factors is to use questionnaire (oral judgement) and empirical study of the landslide inside the watershed associated to intensive field works. Nine landslide triggering factors such as lithology, slope angle, drainage density, slope aspect, slope curvature, upslope contributing area (U.C.A.), Land use/land cover, road contributing area (RCA) and settlement density were selected for analysis, according to their regional importance and triggering intensity with subjective value judgement and experience.

2.2.1 Landslide Inventory Map and landslide frequency (%)

A Landslide Distribution Map (Figure 2) was prepared to determine landslide frequency/ events (%) for each class of the landslide inducing factors/factors maps in consultation with SOI Topo-sheet, Satellite Image (IRS LISS- III) and intensive field investigation with GPS. Then, it is digitized and converted into raster value domain on ARC GIS Platform.

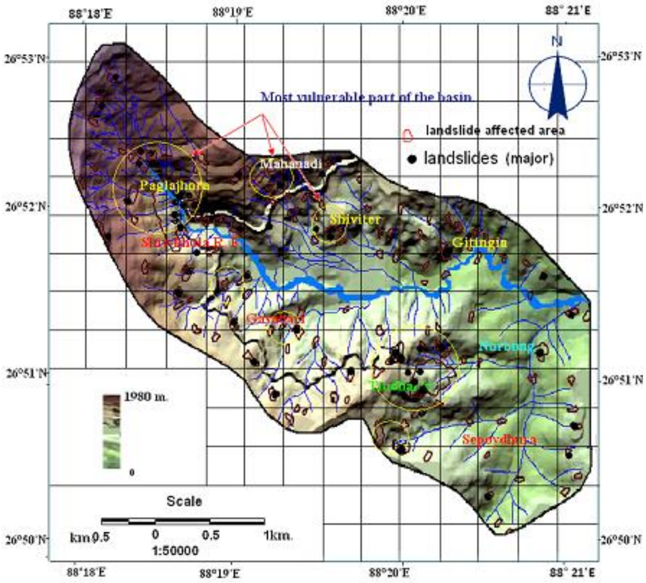

Figure 2. Landslide Inventory map

Landslide frequency (%) for each range/class of the landslide inducing factors was calculated with the help of equation 1. Ranking values/class weight values for each class were assigned on the basis of derived landslide frequency (%) value.

Landslide frequency (%)=(f2÷f1) ×100 (eq.1)

f_2= number of landslide location/class.
f_1= total number of landslide location in the study area.

2.2.2 Preparation of Landslide inducing factors maps

Firstly, the contour map was prepared and digitized from the SOI Topo-sheet (78B/5) and was subsequently transformed into Digital Elevation Model (DEM) or into GRID/Raster Surface at 23.5×23.5m resolution to the corresponding Satellite Image IRS-LISS-III (2010). Then slope, curvature and aspect maps were derived from DEM and designed in value domain using filtering technique. The lithological map of the concerned study area was prepared after Geological Survey of India (GSI), Kolkata (Eastern Region). Drainage density map was made on the grid resolution of 23.5×23.5mm. Upslope Contributing Area is an effective indicator of drainage concentration over space. The specific contributing area (total contributing area divided by the contour length) is computed by distributing flow from a pixel among its entire lower elevation neighbor pixel (Borga et.al., 1998). Quinn et al. (1991) proposed that the Fraction of Flow (Fi) allocated to each lower neighbor (i) is to be determined by equation 2.

$$Fi = \frac{\mathrm{SiLi}}{\Sigma \mathrm{SiLi}} \text{ (eq.2)}$$

Where the summation is for the entire lower neighbuor; S is the directional slope, and L is an effective contour length that acts as the weighting factor. [The value of L used here is 10 m of the pixel size of the cardinal neighbor and 14.14 m of the pixel diagonal for diagonal neighbor.]

An upslope contributing area map was prepared based on calculated contributing area value for a specific point for each o.25 sq.km grid and then it was divided into 6 equal classes. A road contributing area (RCA) map was made by multiplying road contributing length (RCL) with road contributing width (RCW) from 0.25 sq. km. grid of the watershed from the concerned topographical sheet and it was converted into raster value domain and was classified accordingly. Settlement Density Map was prepared by applying 3*3 karnel on ARC GIS platform and the whole basin was classified into seven equal density classes.

2.2.3 Value assignment/Quantification to each class of the factors map

Quantification of the factors and weighting their classes are done with regard to landslides frequency (%). By using remote sensing and GIS, all the prepared thematic maps were quantified and rasterized to specific pixel size. Each class of all the triggering factors was valued from 0 to 100 after Ahmadi, 2003 according to landslide frequency value. The class of each factor which had the maximum landslide contributing units was assigned the maximum value 100 and proportional with that all classes of individual factor were given different scores. This numerical scale was compressed to 1 to 10 and the entire factors map were reclassified using spatial analyst tools on ARC GIS platform. The value ‘1’ was assigned to lowest landslide contributing units whereas the highest landslide contributing units assigned as 10.

2.2.4 Application of Multiple Criteria Evaluation Approach (MCEA) and landslide susceptibility

The factor weight and class weight was assigned depending on the probability of landslide phenomena and their linear combination was performed in the following way to obtain landslide susceptibility coefficient value for each pixel.

Landslide Susceptibility (M) = [Geology*2.5 + Slope angle*3.00+Slope Curvature*0.5 + Land use & land cover *2.5 + Slope Aspect*0.5 + Drainage Density*1.5 + UCA*1.00 + RCA*1.00 + Settlement density*1.5].

2.3 Analytical Hierarchy Process and Landslide Susceptibility Assessment

In the AHP, different factor preference and their conversion into numerical value was accomplished with the help of comparative oral judgment and synthesis of priorities (Table 3). In this method, the preference of a factor/class as compared with the other factor/class is made to derive the priority rates, and for this, a pair wise comparison matrix was constructed carefully.

Table 3. Scale of preference between two parameters (Saaty, 2000).

Scale	Degree of preference	Explanation
1	Equally	Two activities contribute equally to the objective.
3	Moderately	Experience and judgement slightly to moderately favor one activity over another.
5	Strongly	Experience and judgement strongly or essentially favor one activity over another.
7	Very Strongly	An activity is strongly favored over another and its dominance is showed in practice.
9	Extremely	The evidence of favoring one activity over another is of the highest degree possible of an affirmation.

2, 4, 6 and 8	Intermediate values	Used to represent compromises between the references in weight 1, 3, 5, 7 and 9.
Reciprocals	Opposites	Used for inverse comparison.

2.3.1 Couple/pair Comparing of the factors and their priority based on the weighted mean (Factors Weight/Class weight)

To estimate the factors weight and class weight, it is necessary to develop pair-wise comparison matrix where each factor/class was rated against every other factor by assigning a relative dominant value ranging between 1 and 9. The value also varies between the reciprocals ½ and 1/9 for inverse comparison. Then, arithmetic mean method was applied to calculate each alternative weight of the landslide triggering factors and each class using MATLAB Software with reasonable consistency.

Here, an example of couple-comparing matrix for different data layers/factors is described below to determine the prioritized factor rating value (Table 4) and in the same way prioritized class rating value was also estimated accordingly.

Table 4. Calculation of Prioritized Factors weight.

	1	2	3	4	5	6	7	8	9	PFW*
Lithology	1	3	4	5	7	6	8	9	2	0.300
Drainage	1/3	1	2	3	5	4	6	7	1/2	0.149
Slope gradient	¼	½	1	2	3	4	6	7	1/3	0.110
Slope Aspect	1/5	1/3	½	1	3	2	5	7	1/5	0.080
Slope Curvature	1/7	1/5	1/3	1/3	1	2	3	4	1/7	0.047
U.C.A.	1/6	¼	¼	½	½	1	1/2	3	1/6	0.034
Land use/ land cover	1/8	1/6	1/6	1/5	1/3	2	1	1/2	1/8	0.027
R.C.A.*	1/9	1/7	1/7	1/7	¼	1/3	2	1	1/9	0.022
Settlement Density	1/2	2	3	5	7	6	8	9	1	0.231

*RCA-Road Contributing Area and *PFW-Prioritized Factor Weight.

2.3.2 Application of AHP Model and Landslide Susceptibility Map

In the AHP, landslide susceptibility co-efficient (LSC)/landslide susceptibility index (LSI) is derived using weighted linear combination model for each pixel by summation of each factor's weight (W_i) multiplied by class weight/ rating (R_i) of each referred landslide triggering factor, which is ascribed below.

$$LSC\,(M) = \sum_{i=1}^{n}(W_i \times R_i) \quad \text{(eq.3).}$$

To prepare the landslide susceptibility map of the Shivkhola Watershed, derived 'M' values have been classified using natural breaks algorithm to develop landslide susceptibility distribution map.

2.4 1-D Slope Stability Model and Landslide Susceptibility Assessment

Two forces are responsible to determine the stability condition i.e. driving force (shear stress) and resisting force (shear strength). Shear stress is given as, $\tau = \gamma D \sin\Theta \cos\Theta$ and shear strength of Mohr and Columb defined as, $S = c + \tau \tan\varphi$. Saturated slope material increases instability with increasing pore water pressure. The pore water pressure depends on unit weight of water (γ_w) and the height of water (D_w) above the failure plane surface. The height of the water shows the ground water condition in the soil. In this case the shear resistance of the soil is given by the following:

$$S= c(\gamma-\gamma_W m)\, D\cos^2\theta\tan\varphi \text{ (eq.4).}$$

Where, m is saturation index which shows the saturation condition of the soil.

If the value of 'm' equals to '1', the soil is completely saturated and the value of 0 indicates complete dry condition.

$$\text{FS (Translational)} = \frac{c+\gamma.z.\cos^2\beta*\tan\varphi}{\gamma.z.\sin\beta*\cos\beta} \text{(eq. 5)}$$

[Where, γ= unit weight of the soil; z= depth of the failure surface below the terrain surface; β= the terrain surface inclination; φ= angle of internal friction; c = cohesion.].

A simplified approach was considered by Soeters and Westen (1996) reducing 3D depth to 2D equivalent depth based on equal factor of safety. However, it is not simple to analyze 2D rotational slide due to variation in depth of sliding surface. Hence, 2D depth of rotational slide was again converted to equivalent translational depth (1D) (eq.6) keeping the same factor of safety.

The stability analysis could be done in 1D Stability Model without the impact of ground water using the following equation.6.

$$FS = \frac{c + (\gamma - m * \gamma_w) * \cos^2\beta * \tan\varphi}{\gamma * z * \sin\beta * \cos\beta} \qquad \text{(eq.6)}$$

[Where, γ=unit weight of soil; m=soil saturation index; Zw= height of water table above failure surface; Z=depth of failure surface below the terrain surface; γ_w=unit weight of water; β=the terrain surface inclination; φ=angle of internal friction and c= cohesion.].

The safety factor (FS) under the influence of ground water (semi-saturated) of cohesive soil has been considered in the present work applying the revised 1D slope stability model with the help of following relationship (eq.4).

2.4.1 Cohesion (c) and friction angle (φ)

The shear strength of the soil basically described as the function of normal stress on the slip surface, cohesion, and angle of internal friction. The angle of internal friction (φ) □□and cohesion are the two important physical properties of the soil which determines angle of rupture, shearing strength, safety factor as well as stability condition of the slope materials by developing *stress circle*. The relationship within all these properties to other characteristics of the soil has been introduced by Terzaghi (1950) and Wu and Siddle (1995). The geo-technical factors like angle of repose of the debris are measured after Bloom (1991) and Pethick (1984). All the tests were carried out under drained condition. The major stress (σ_1), minor stress (σ_3) and cohesion (c) were estimated through tri-axial soil testing mechanism (Figure 3) from Geo-technical Laboratory of GSI, Kolkata (22/com/soil/GTL/ER/O6-07) by Geologists Sufiyan, Sengupta, and Pramanik (2007).

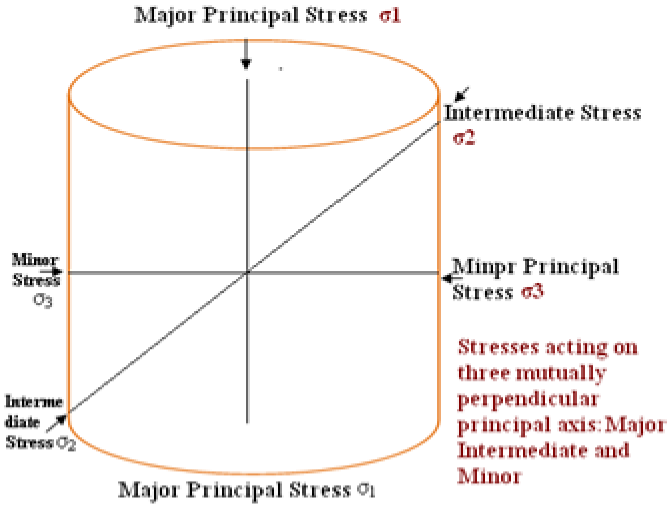

Figure 3. Soil testing mechanism through solid cylinder compression.

A Mohr Stress Circle was developed to obtain angle of internal friction and angle of rupture through σ_3 and σ_1 with the centre on the horizontal axis; the centre of the circle was obviously $(\sigma_1 + \sigma_3)/2$ and the radius was $(\sigma_1 - \sigma_3)/2$. The values of confining pressure, σ_3, and compressive stress, σ_1 were plotted on horizontal axis where stress difference is $\sigma_1 - \sigma_3$. On a plane parallel to the greatest principal stress axis ($2\alpha=0$) the normal stress across the plane was σ_3 and the shearing stress was 0. If the plane makes an angle of 45^0 with the greatest principal stress axis ($2\alpha=90$), the shearing stress is at a maximum and the normal stress is $(\sigma_1 + \sigma_3)/2$. If the plane makes an angle of 90^0 with the greatest principal stress axis ($2\sigma = 180^0$), the shearing stress is 0 and the normal stress is σ_1.

In this way a series of experiments were being accomplished with different values of confining pressure (σ3). The Mohr Circle shows that as the confining pressure is increased, the stress as well as the stress difference must be increased to produce rapture. A line which is the tangent of the 'Mohr Circle' is called as the 'Mohr Envelope'. The angle that this line makes with the horizontal axis of the diagram is the angle of internal friction, φ (Figure 4).

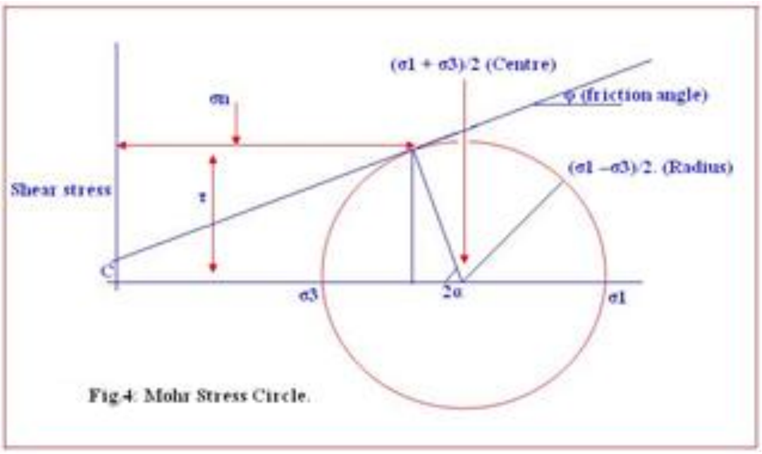

Figure 4. Mohr Stress Circle

Cohesion (C) is the attraction of particles to each other which is not directly governed by a FRICTION law but does provide a measure of strength of a material. Thus sands do not exhibit cohesion, while soil which contains clay show cohesion. It can be measured, as in soil mechanics, by the MOHR-COULOMB EQUATION.

$$C(cohesion) = \frac{\sigma 1 - \sigma 3 \tan^{2}(45 + \frac{\varphi}{2})}{2 + \tan(45 + \frac{\varphi}{2})} \quad \text{(eq. 7)}$$

2.5 Surface Inclination/slope (β)

Slope gradients are sometimes considered as an index of slope instability, and because of the availability of a digital elevation model, slope can be numerically evaluated and depicted spatially (Gao, 1993). Firstly, the contour map at 20 meter interval was prepared and digitized from the topographical map 73B/8 (1987) at the scale of 1:50000 and subsequently used for generating Digital Elevation Model on ARC GIS platform. Then slope gradient map was extracted from DEM at 25m grid cell size and it was the classified after Anbalagan (1992) and Dhakal et al. (2000).

2.6 Soil saturation Index/wetness index (m)

Simple models have been developed for estimating the soil saturation of the mountainous region as the wetness index is defined in TOPMODEL by Beven and Kirkby (1979). More acceptable soil saturation model was applied by Montgomery and Dietrich (1994), Borga et al. (1998) and Pack and Tarboton (1998). The model envisages that the soil saturation index can be determined with the help of topography, soil type, and rainfall intensity of the area to be studied. But in practical sense, the soil is not completely dry or fully saturated in the area, therefore it can be imagined that the soil is half saturated. The soil saturation index is either fixed for stationary scenarios i.e. dry, semi-saturated and full saturated soils, given by m = 0, 0.5 and 1.00 or can be calculated on the basis of available rainfall data (De Smedt, 2005). On the basis of this assumption, wetness index equation can easily be derived and it is possible to see the effect of few days' consecutive rainfall in one day, if the soil is half saturated. In the present study wetness index (m) value of 0.00, 0.50 and 1.00 under dry, half-saturated and full-saturated conditions were taken into account to make susceptibility maps.

2.6.1 Depth of failure surface/depth (z) of soil below the terrain surface

The depth of the failure surface was measured by holding a measuring tape at both the margins of scar and the other tape was allowed to hang, the reading was then taken from the base of the hanging tape. The margin of the scars was surveyed by prismatic compass. The intensive survey of the sliding scar for 50 different landslide locations was carried on by Abney's level at 0.5m interval along radial lines originating from lower most part of the scar. The altitude of the points at 0.5m interval along the radial lines is then estimated using Sine rule in reference to the central base point of known altitude determined by GPS (Basu and Maiti, 2001 and Maiti, 2007). The total thickness of soil and that of saturated soil for 50 sites during monsoon were measured from slope cutting. After estimating the approximate depth of all known points, a soil depth map (z/D) was made using Arc GIS tool.

2.6.2 Soil density (γ_s) and density of water (γ_w)

Specific unit weight of water and unit weight of the soil were estimated by examining the soil samples collected from 50 landslide locations during field investigation from the GSI

(Geological Survey of India, East Kolkata) laboratory. The density of soil and water varies from place to place due to in situ geo-hydrologic condition. The saturated soil density of rock was also consulted and adopted from the field experiences done by Deoja (Mountain Risk Engineering Handbook, 1991) and Specific Yield from Basic Ground-water Hydrology (Ralph C. Heath, 1991).

2.6.3 Application of 1 Dimension slope stability model and landslide susceptibility

With the help of derived geo-technical parameters i.e. cohesion, friction angle, slope angle, unit weight of the soil, unit weight of water, soil depth, and saturation index value from 50 landslide location points of the Shivkhola watershed the safety factor values (FS) for semi-saturated condition was being estimated by applying the 1D slope Stability model (eq. 7). The safety factor values were transformed into raster value domain on ARC GIS Platform. Finally, the landslide susceptibility maps/safety factor distribution maps were prepared by 'slicing' operation and then stability classes for semi saturated condition by studying the cumulative frequency and their abrupt change points of the safety factor values (the instability threshold boundaries). A 3×3 'majority filter' technique was also applied to all the prepared safety factor distribution maps as a post-classification filter to reduce the high frequency variation. Higher the value of 'FS', greater is the propensity of slope stability and vice versa. To assess the chances/probability of landslide phenomena in each class to all the prepared maps under various conditions frequency ratio (FR) was extracted by means of a ratio between landslide frequency/landslide events (%) and landslide susceptibility area (%). FR value is approaching to 1 indicates equal chances of landslide events, 0 indicates lesser chances and more than 1 shows greater probability of landslide events.

3. RESULTS AND DISCUSSION

3.1 Landslide susceptibility based on Factor Approach

The Total Rating Values or Total Estimated Hazard Values (TEHD) are grouped into 8 Classes (Table 5) ranging from < 30 to > 54 and assigned with the Susceptibility status accordingly.

Table 5. Landslide Hazard Zone on the Basis of Total Estimated Hazard Values (TEHD).

Zones	THED VALUES	Zonal Description
I.	Less than 30	Least susceptible to landslide
II.	30-34	Low susceptible to landslide occurrences
III.	34-38	Fairly susceptible to landslide occurrences
IV.	38-42	Moderate susceptible to landslide occurrences
V.	42-46	Moderately higher susceptible to slope failure
VI.	46-50	Fairly higher potentiality to slope failure
VII.	50-54	Higher potentiality to slope failure
VIII.	Greater than 54	Very susceptible to catastrophic lope failure

The lower one is least susceptible to landslide where as the upper one is Very susceptible to catastrophic slope failure. The zone of Very susceptible to catastrophic slope failure is located at PaglaJhora, Gayabari, Tindharia, Northern and central part of Shivitar T.E., Tindharia T.E., and Gitingia T.E. Maximum of the existing landslides are also located in those areas and thus demanding more attention from the habitants, planners and administrators. The Hill Cart Road has the possibility of damage near the approach to

Tindharia from Siliguri, near Gayabari and at Paglajhora. Shivitar T.E. Tindharia T.E. and Gitingia T.E. are already affected by huge landslide and so immediate attention is needed for site specific slope management for these regions (Figure 5).

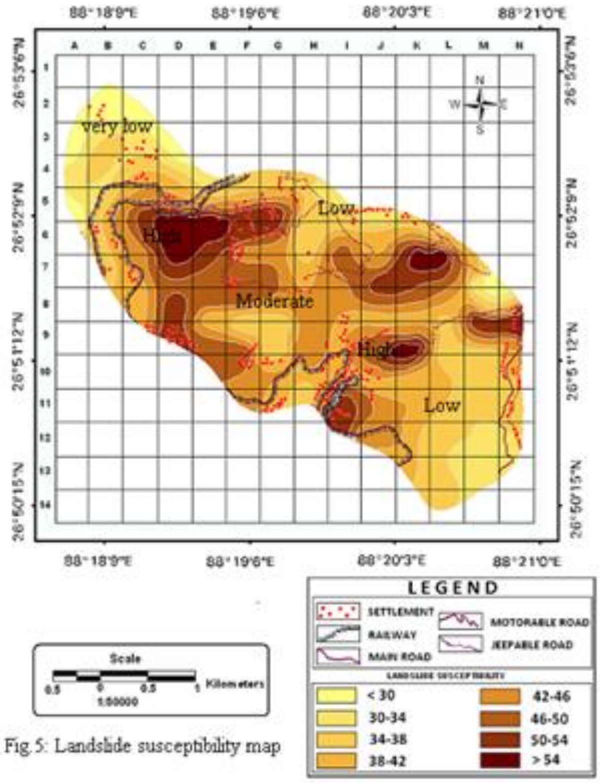

Figure 5. Landslide susceptibility map

The relationship between the factors inducing slope instability i.e., relative relief, drainage density, constant of channel maintenance, ruggedness index, dissection index, Upslope contributing area (UCA), Topographic Index (T.I.), Road contributing area (R.C.A.) Landuse Index (L.I.) and Landslide Susceptibility Index Value has been made statistically by using the software Origin (8.00). The fit-statistics of the factors (X) and L.S.I.V. (Y) is depicting the R square, Co-efficient of variation, Root-MSE and Data mean. The R square is equal to the square of coefficient of correlation between two variables. It is also called the coefficient of determination. The value of the coefficient of determination shows that 97.78, 99.36, 99.09, 98.97, 96.97, 99.04, 97.50, 96.61 and 98.63 percent of the total variation in LSIV (Y) is already being explained by X variables and a minimum and a considerable percentages (2.22, 0.64, 0.91, 1.03, 3.03, 0.96, 2.50, 3.39 and 1.37) of variations in Y are yet to be explained. On an average 98.21% of Y variable is being explained by the corresponding X one. So, the result of R square shows that the independent variables of X taken here is giving a good explanation of Y variables.

3.2 Landslide susceptibility based on Multiple Criteria Evaluation Approach (MCEA)

In MCEA, Shivkhola watershed is classified into seven landslide susceptibility zones i.e. very low, low, moderately low, moderate, moderately high, high and very high (Figure 6). The maximum area of the watershed has been characterized by moderate landslide susceptibility, which is followed by moderately high, moderately low, high, low, very low and low landslide susceptibility (Table 6).

Table 6. Areal distribution of Landslide susceptibility (%), landslide affected area (%) and Frequency ratio (FR).

Susceptibility Classes	Area (pixels)	% of area	Landslide affected Pixels.	Landslide affected area (%)	Frequency Ratio (FR)
Very low (VL)	107	0.37	0	0	0.00
Low (L)	1575	5.51	0	0	0.00
Moderately low (ML)	8145	28.47	752	22.29	0.81
Moderate (M)	8722	30.49	932	27.63	0.91
Moderately high (MH)	8349	29.19	895	26.53	0.91
High (H)	1407	4.92	654	19.39	3.94
Very high (VH)	302	1.05	104	3.08	2.93

Frequency Ratio (FR) was calculated to produce an idea about the chances of landslide occurrence by means of ratio between the landslide events (%) and the landslide susceptibility (%) for each and individual classes. The FR value ranges from 0 to 3.94. The value '0' indicates lower the chances of landslide occurrence within the watershed. Ratio value of '1' considered the area having the equal chance of landslide occurrence for the entire area. The estimated ratio value of 3.94 and 2.93 for high and very high landslide susceptibility zones of the watershed reveals the higher probability landslide activities compared to others landslide susceptibility classes in the Shivkhola Watershed. Frequency ratio analysis suggests around 6% area with higher probability, around 60% with equal chances, 30% area with moderate chance and remaining less than 6% area with no chances of landslide phenomena.

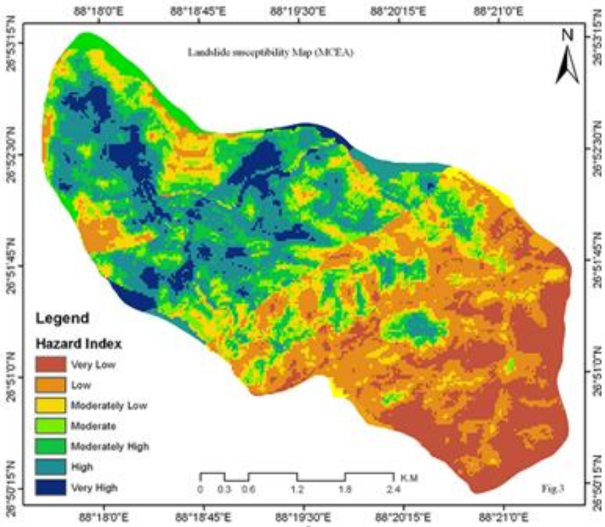

Figure 6. Landslide Susceptibility Map (MCEA)

The comparison between assumed true data recorded from 28 landslide locations of the Shivkhola watershed and randomly selected data from the classified image shows that the overall classification accuracy is 88.89% (Table 7).

Table 7. Accuracy Assessment/Comparison of MCEA based landslide susceptibility with field data:

Class name	Classified total	Number correct	Producers Correct	Users Accuracy	Accuracy Total.
Very low	0.00	0	0	----	----
Low	0.00	2	0	----	----
Moderately low	0.00	2	0	----	----
Moderate	12	10	10	83.33%	100.00%
Moderately high	2	2	2	100.00%	100.00%
High	11	9	8	72.73%	88.89%
Very high	3	3	2	66.67%	66.67%
Total =	28		28	22	
Overall classification Accuracy = 88.89%					
Overall Kappa Statistics = 0.8625					

3.3 Analytical Hierarchy Process (AHP) based Landslide Susceptibility Analysis

The Shivkhola watershed is classified into very low, low, moderately low, moderate, moderately high, high, and high landslide susceptibility zones (Figure 7) which conclude that Lower Paglajhora, Shiviter and Tindharia are very highly susceptible; Upper Paglajhora, Gayabari, 14 Miles Bustee and Nurbong T.E. are characterized by high susceptibility; Mahanadi and Giddapahar are of moderate potentiality; and marginal waxing slope of water divide and low-central wanning slope experiences low landslide susceptibility.

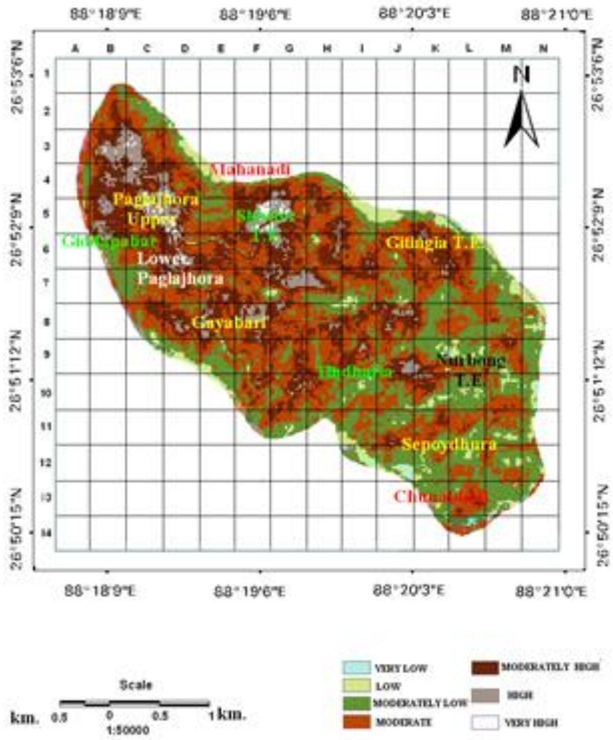

Figure 7. Landslide susceptibility map

The study revealed that more than 60% of the total area of the Shivkhola watershed is classified as being in the moderate to very high landslide susceptibility zones and that constitutes more than 75% of the landslide affected areas. Rest of the watershed experiences moderately low (29.93%), low (6.51%) and very low (0.45%) susceptibility. Moderately low, low and very low susceptibility zones together accommodate 10% of the landslide phenomena (Table 8).

Table 8. Areal distribution of Landslide susceptibility (%), landslide affected area (%) and Frequency ratio (FR).

Susceptibility Classes	Area (pixels)	% of area	Number of Landslide points.	Frequency Ratio (FR)
Very low (VL)	125	0.45	0 (0%)	0.00
Low (L)	1828	6.51	1 (2%)	0.30
Moderately low (ML)	8402	29.93	4 (8%)	0.27
Moderate (M)	9951	35.45	9 (18%)	0.51
Moderately high (MH)	5997	21.37	15 (30%)	1.40
High (H)	1604	5.71	12 (24%)	4.20
Very high (VH)	746	2.66	6 (12%)	4.51

The calculated frequency ratio (FR) value of 4.51 and 4.20 for very high and high landslide susceptibility zones of the watershed depicts the higher probability of landslide activities compared to zones having less than ratio value of '1' (VL, L, ML, and M). Here, frequency study shows that more than 8% area is experienced with high landslide probability, around 50% with moderate landslide probability and remaining area with low landslide probability.

3.3.1 Accuracy Assessment/Comparison of AHP based landslide susceptibility with field data

In AHP, the overall classification accuracy is 92.86% and overall Kappa Statistics is 0.8919%. The class wise accuracy result is shown in Table 9.

Table 9. Accuracy Analysis.

Class name	Classified total	Number correct	Producers Correct	Users Accuracy	Accuracy Total.
Very low	0.00	1	0	----	----
Low	0.00	0	0	----	----
Moderately low	0.00	0	0	----	----
Moderate	12	11	11	91.67%	100.00%
Moderately high	2	2	2	100.00%	100.00%
High	11	11	10	90.91%	90.91%
Very high	3	3	3	100.00%	100.00%
Total =	28	28	26		
Overall classification Accuracy = **92.86%**					
Overall Kappa Statistics = **0.8919**					

3.4 1D slope stability model and Stability analysis under semi-saturated soil Condition

The Shivkhola Watershed exhibits a wide range of elevation (300 m to 2400 m). Slope ranges between very gentle of 7 0 and very high of 650. The central middle section and lower section of the watershed is attributed with very gentle slope gradient of less than 200 whereas marginal part and extreme north, south and west are characterized by very steep slope of more than 500. Angle of internal friction varies between 180 and 330. Slope materials having coarse grains over the steep slope shows lower friction angle than the materials with finer particles deposited along the foothills zone. At Lower and Upper Paglajhora, Tindharia Upslope, Shiviter and Nurbong the friction angle and cohesion of the soil is very low. Cohesion of the soil is high in the mid and lower part where more than 50% particles are composed with finer particles. The derived geo-technical parameters area in detain in the Table 10.

Table 10. Result of field measurement and laboratory test of soil samples observed and collected from different location of the watershed.

Sample no.	(Z in m.)	(ϴ)	Φ	(c) kg/cm^3	(γ in KN/m^3).	(γ_w -KN/m^3)	FS (semi)
1.	1.55	42°	28°	0.42	1.86	0.92	0.737
2.	1.45	54°	23°	0.21	2.13	1.01	0.378
3.	1.40	37°	27^{0}30′	0.11	1.89	0.89	0.6146
4.	1.25	38°	31^0	0.65	1.97	0.82	1.2019
5.	2.00	39°	26°	0.45	2.01	0.90	0.6963
6.	1.35	39°	19^0	0.02	2.01	1.12	0.3218
7.	2.75	49°	19^{0}30′	0.03	2.25	1.09	0.2430
8.	1.15	35°	25^{0}15′	0.60	2.05	0.85	1.0756
9.	0.85	66°	24°	0.04	1.95	0.76	0.2245
10.	0.75	64°	29°	0.71	2.04	0.79	1.3958
11.	1.85	67°	24°	0.02	2.36	1.08	0.1584
12.	2.95	22°	28°	0.65	2.21	0.99	1.3085
13.	0.55	65°	21^{0}15′	0.01	2.00	0.84	0.1670
14.	0.65	46°	22^0	0.32	2.05	0.82	0.7927
15.	1.20	51°	23^0	0.79	1.88	0.77	0.9893
16.	3.75	59°	28^0	0.67	2.06	0.78	0.4554
17.	3.50	57°	29°	0.66	2.10	0.76	0.4675
18.	3.25	15°	22°	0.33	2.22	0.81	1.4157
19.	0.95	63°	25°	0.25	1.98	0.77	0.5199
20.	0.75	64°	22°	0.04	2.35	1.01	0.2123
21.	1.25	48°	21°	0.05	2.23	0.98	0.3058
22.	1.20	52°	20°	0.07	2.22	0.88	0.2822
23.	0.45	46°	26°	0.91	1.99	0.85	2.4044
24.	1.55	20°	29°	0.52	2.03	0.73	1.7634
25.	3.15	24°	25°	0.06	2.11	0.75	0.88551
26.	2.10	13°	24°	0.58	2.13	0.74	2.18508
27.	0.65	36°	27°	0.86	1.96	0.69	1.99742
28.	0.90	26°	25°	0.10	1.90	0.68	0.784422
29	1.20	37°	25°	0.25	2.30	0.91	.6021
30	2.20	28°	31°	0.81	2.22	0.87	.8131
31	1.70	38°	24°	0.41	1.99	0.54	.7423
32	1.30	36°	29°	0.75	1.97	0.53	1.2178
33	2.65	27°	23°	0.06	2.11	0.77	2.9152
34	1.75	35°	32°	0.48	2.05	0.81	1.000
35	1.15	39°	27°	0.51	2.40	1.05	.7582
36	2.18	44°	21°	0.09	2.44	1.11	0.2627
37	1.72	64°	22°	0.25	2.15	0.98	0.3237
38	1.65	49°	33°	0.24	1.89	0.66	0.6214
39	1.40	61°	24°	0.08	1.97	0.53	0.2820
40	1.35	25°	19°	0.06	2.02	0.72	0.6642
41	1.49	30°	21°	0.09	2.55	1.09	0.5774
42	1.40	42°	31°	0.17	2.48	1.09	0.6191
43	0.85	51°	20°	0.35	1.85	0.61	0.7013
44	1.45	23°	30°	0.40	1.93	0.65	1.5285
45	1.50	55°	20°	0.22	2.04	0.96	0.3479
46	0.95	66°	27°	0.15	2.58	1.29	0.3348
47	0.65	49°	25°	0.08	2.47	1.22	0.4059
48	1.15	38°	18°	0.29	2.00	0.72	0.6009
49	1.23	47°	27°	0.32	1.79	0.50	0.7002
50	3.05	18°	26°	0.78	1.99	0.60	1.7121

[Z=soil depth; ϴ=slope angle; φ= angle of internal friction; c=cohesion; γ=specific yield of soil; γ_w= unit weight of water; and m* =wetness index with 20 year return period of rainfall intensity;]

The depth of soil varies from 0.45m to 3.75m in the Shivkhola Watershed. The central mid-section and lower part of the watershed are registered with maximum soil depth whereas marginal part (north, south and western part) is attributed with minimum soil depth. Due to steep slope and active soil erosion process, the marginal area is associated with close slip surface below the slope surface due to which soil layers get saturated very easily and causes shallow debris slide. Tindharia, Gayabari Upper, Sepoydhura Upslope, Upper Paglajhora, Mahanadi, Shiviter, Gitingia are existing in the marginal minimum soil depth area of the Shivkhola watershed. On the other hand, Shivkhola R.F., and both sides of the main river is characterized by maximum soil depth with low intensity of landslide phenomena. It can be inferred that shallow seated slope instability is intimately related with minimum soil depth with steep slope. Under semi-saturated condition 0.88 sq.km area is attributed with high landslide susceptibility. The area of high and very high landslide susceptibility has been increased in saturated soil condition and around 2.5 sq.km area is registering high landslide susceptibility with high frequency ratio. For dry and semi-saturated condition, the area under high and very high landslide susceptibility is 5.36 sq.km. and 8.5 sq.km. respectively and the area under low to very low landslide susceptibility is around 9 sq.km. and 5 sq.km.

Table 11. Frequency Ratio analysis for semi-saturated soil condition.

Safety Factor	Landslide susceptibility	Area in sq.km.	% of area	landslide frequency	Frequency Ratio
0.158-0.40	Very high	0.88796	4.38	9 (37.5%)	8.56
0.40-0.70	High	7.691486	37.88	10 (41.67%)	1.10
0.70-1.00	Moderate	6.393539	31.47	4 (16.67%)	0.53
1.00-1.50	Low	4.15209	20.44	1 (4.16%)	0.20
1.50-2.83	Very low	1.169058	5.76	0 (0.00%)	0.00

Under semi-saturated condition the value of safety factor varies from 0.158 to 2.58 and 4.38 % area is under very high landslide susceptibility that is around 2.50 % greater than dry condition (Figure 8).

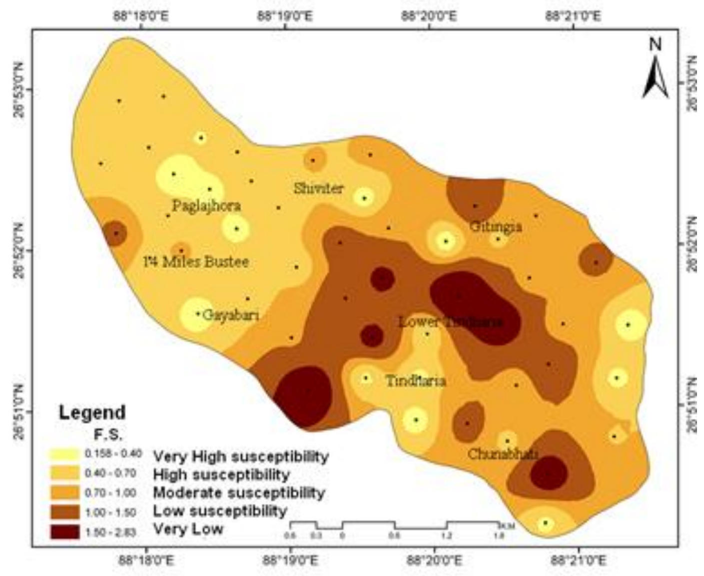

Fig.8: Landslide Susceptibility Map under semi-saturated condition.

Figure 8. Landslide Susceptibility Map under semi-saturated condition.

Large part 37.88% area of the basin is dominated by high landslide susceptibility and 31.47 % area is registered with moderate landslide susceptibility and equal chances of landslide occurrence phenomena. More than 25 % of the watershed is exposed with low to very low landslide susceptibility condition. Frequency ratio value under semi-saturated condition revealed that the probability of landslide occurrence was very high in the area of very high landslide susceptibility which was followed by high, moderate and low. Under dry condition moderate, low and very low landslide susceptibility area had shown more or less absence of expected landslide phenomena as the derived frequency ratio values were approaching towards the value of '0'. The overall classification accuracy of 1-D slope stability model based landslide susceptibility map is 94.58% (Table 12).

Table.12: Accuracy Analysis of 1-D Slope stability model.

Very low	0	6	0	0.00	0.00
Low	0	7	0	0.00	0.00
Moderate	13	10	9	76.92	90.00
High	20	16	16	80.00	100.00
Very High	17	16	15	94.12	93.75
Total =	50	50	40		
Overall classification Accuracy = 94.58%					
Overall Kappa Statistics = 0.8919					

4. CONCLUSION

The present work identifies such susceptible zones where the stability is expressed as a function of a numbers of factors. The site specific management of slope is necessary and that can save the region from potential destruction and the proper execution of the suggestion made may save the resources and ultimately the society and thus the present work will find social relevance. The factor based approach considered 0.25 sq km. grid and corresponding landslide triggering factors where the areal extension is too large and it is not possible to assess landslide inducing parameters. The spatial zonation of landslide susceptibility did not take into account pixel domain which is very much essential at present day landslide research. In Multi Criteria Evaluation Approach (MCEA), arbitrary values were assigned to each factor and class to derive landslide susceptibility coefficient value whereas in AHP consistent value judgment has been made by developing couple-comparing matrix to extract prioritized class rating value and prioritized factor rating value. The frequency study shows that in both case landslide probability is pronounced in high and very high landslide susceptibility zones. The accuracy analysis depicts that the overall classification accuracy in MCEA is 88.89% and in AHP it is 92.86%. Based on the accuracy result we can infer that quantitative value judgement is of utmost importance in landslide susceptibility mapping or in any geographical research. AHP is to be assumed as scientific and reasonable approach in landslide susceptibility mapping. The derived prioritized factor rating values also depicts that lithology and concentration of human settlements are the dominant landslide triggering factors which are followed by drainage density, slope gradient, slope aspect, slope curvature, upslope contributing area (UCA), land use and land cover (LULC) and road contributing area (RCA). Finally, it is to be concluded that arbitrary value judgment must be avoided and consistent value judgment process as in AHP should be followed for similar studies. But in land sliding the assessment of geotechnical parameters of soil have become much more significant at the present day. By integrating all the geotechnical parameter maps on GIS Platform using 1-D Slope stability model, a landslide susceptibility map was made under semi-saturated condition. In 1-D Slope Stability Model, a comparison between assumed true data and randomly selected data from the classified image shows that the overall classification accuracy for semi-saturated condition is 94.58% and this is greater than MCEA and AHP. Finally, based on the accuracy result it could be assumed that AHP and 1-D Slope Stability Model are the two important approaches for landslide susceptibility research at recent period.

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