JOURNAL GEOLOGICAL SOCIETY OF INDIA
Vol.90, September 2017, pp.301-311

Identification of Landslide Susceptible Villages around Kalsubai Region, Western Ghats of Maharashtra using Geospatial Techniques

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ABSTRACT

Heavy rainfall triggered landslides are on the rise along the Western Ghats making it a matter of priority to identify landslide-prone areas well in advance. The present effort is aimed at identifying landslide susceptible villages (LSV) around the Kalsubai region of Deccan volcanic province (DVP), Maharashtra, India from 8 weighted landslide parameters- rainfall, slope, lithology, land use and land cover (LULC), soil properties, relative relief, aspect and lineament. These parameters were combined with advanced remote sensing (RS) data and processed in geographical information system (GIS) as well as in image processing software, which are an integral part of geospatial techniques. Out of the total 59 villages, the study identified 9 villages are situated in very high, 13 in high, 12 in moderate, 11 in low and 14 in very low risk zones. Our data reveals incessant heavy rains and steep slopes are the dominant factors in triggering landslides, exacerbated by anthropogenic activity prevalent in the study area. The spatial and non-spatial database created will help to take effective steps in preventing and/or mitigating landslide disasters in the study area. The methodology can be applied to identify other landslide prone areas in a cost effective way.

INTRODUCTION

Global incidences of landslides are on the rise putting property and life at intense risk that inflicts heavy economic burden on the governments. Landslides manifest through movement that ranges over a wide spectrum, from barely discernible to catastrophic avalanching. This in itself is a reason to initiate landslide susceptibility mapping aimed at identifying potential areas at risk for this menace. In India the Western Ghats, Nilgiris and Himalayas are landslide-prone areas, wherein the Himalayas can experience landslides anytime of the year, while the Western Ghats mostly during the rainy season. These landslides are predominantly controlled by the physiographic and tectonic setting of the region. Landslides also occur because of rising population, which is hard to control; and unplanned settlement, whose relocation is becoming problematic by the day. According to our assessment, the effects can be mitigated by installing warning systems that depend on real time observation of hydrological variables like rainfall severity, intense precipitation that continues for two days or more, ambient temperature and humidity, water holding capacity of soil and other parameters to evaluate landslide triggering mechanism and its impact.

Landslides are commonly occurring natural hazards (Ahmad et el., 2014) damaging property and leading to loss of lives (Gutiérrez et al., 2010). Cruden and Varnes (1996) classified landslides based on types of movement (slide, flow, fall, topple and spread) and types of material (rock, debris, earth), such as rock slide, debris slide, debris flow, earth flow and rock fall. Topple is a rotational forward movement and spread is movement mostly on a flat ground. According to them, landslides can travel over long distances, though their movement can change during the process, which can be expressed as debris slide–debris flow and rock fall–debris flow. The rock and soil flow, or the sludge flow can be triggered by shear failure, when shear stress is equal to or greater than shear resistance on a slope. Consequently, these can be caused by either increase of shear stress, or decrease of shear resistance on the slope. Earthquakes, tectonic movement, volcanic activity, erosion and deposition and anthropogenic activity can cause an increase in shear stress. Decrease in shear resistance can be brought about by pressure exerted by water infiltrating into pores. Such a situation can develop on natural slopes by intense fall of precipitation which can act as catalyst in destabilizing the slopes. Hungr et al (2001) and Kuriakose et al., (2009) have also defined landslides, whereas International Geotechnical Societies' UNESCO working group on world landslide inventory (WP/WLI), contributed to the definition of international standards in landslide investigation (Brabb, 1991; Dikau et al., 1996). Baum et al. (2002) deciphered shallow landslides, often referred to as mudslides or debris flows, move downhill at speeds of 55 km per hour or more, killing people and destroying infrastructure. Terlien (1998) determined the role of weathering process, considered a conditioning mechanism, which has direct bearing on the occurrence of landslides. Wilson and Wieczorek (1995) feel rainfall to be the main trigger of landslide occurrence, whereas Coe et al. (2004) and Fabbri et al. (2003) found topography was the dominant control on occurrences of landslide. Dai and Lee (2002) and Lee and Min (2001) consider slope steepness has a dominant influence on shallow landslide, followed by soil texture and soil types. Other factors such as land cover (Larsen and Torres Sanchez, 1998), elevation (Coe et al., 2004) and lineament occurrences (Aher et al., 2014) can play a significant role in landslide prediction. The losses due to low-magnitude and high-frequency landslides are on the rise because of anthropological interference along hill slopes (Pasuto and Soldati, 1996) killing approximately 61,000 people worldwide from 1900 to 2009 (EM-DAT, 2010). Ho et al (2012) used spatial distribution of soil thickness to predict shallow landslides. Hong and Adler (2008) proposed a system

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to support landslide disaster preparedness and mitigation activities across the world. Dai et al (2002) have reviewed landslide risk assessment and management.

Landslides occur due to a plethora of reasons which are complexly intertwined with each other that range from the geological make up of the area, to the geomorphologic features it displays and its meteorological terrain. The first two factors have a local extent, but the third has a global context wherein regional characteristics sometimes play a dominant role. The factors generally responsible for this are topography, climate, lithology, geomorphology, slope angle, structure, drainage, seismicity, land use, land cover, anthropogenic activities and precipitation (Singh et al., 2014 ,Thigale and Bhavana, 2007). Hence, the information needed to tackle the landslide problem can be garnered through ground based surveys and from remote sensing data. Landslide prediction, in space and time, is an important task that may be ranked according to degree of potential landslide hazard (Saha et al., 2005). The integration of landslide susceptible (LS) parameters and past landslides can aid in assessing landslide risk intensity. Many studies are now being carried out along different LS parts of the world (Pourghasemi et al., 2012). The remote sensing (RS) data can be processed for a greater degree of objectivity and reproducibility in the GIS and image processing software. A number of transient variables are involved in generating landslides, making its prediction quite difficult (Dattilo and Spezzano, 2003). However, landslide hazard zonation (Arora et al., 2004) is a necessary imperative for planning preventive measures (Ercanoglu et al., 2004). GIS has the potential to delineate regional factors such as elevation, slope gradient, slope aspect and drainage pattern that are ultimately responsible for slope failure. The ability of GIS, in consonance with image processing capabilities, can effectively map LS areas in ecosensitive zones of Western Ghats. This terrain has experienced many landslides, the latest being that of Malin (30 July 2014) in Pune district of Maharashtra, India. Most of these landslides are rainfall induced. The mountainous terrains that have more slope angle are prone to landslide due to incessant rains. Hence, the present effort is significant in carrying out societal obligation through scientific methodology.

STUDY AREA

The study area is part of Western Ghats extending from 19° 19' 56" to 19° 40' 00" N Lat. and 73° 30' 00" to 73° 59' 58" E Long. It is part of Kalsubai region (highest peak of Maharashtra at 1646 m) and located on leeward and windward side of the Western Ghats belonging to the Bhimashankar Formation (Subbarao and Hooper, 1988). It covers 1950 sq. km area which is part of the Shahapur, Murbad (Thane), Igatpuri (Nashik), Junnar (Pune) and Akole (Ahmednagar) tehsil of Maharashtra, India (Fig. 1). The topographical characteristics (Fig. 1)

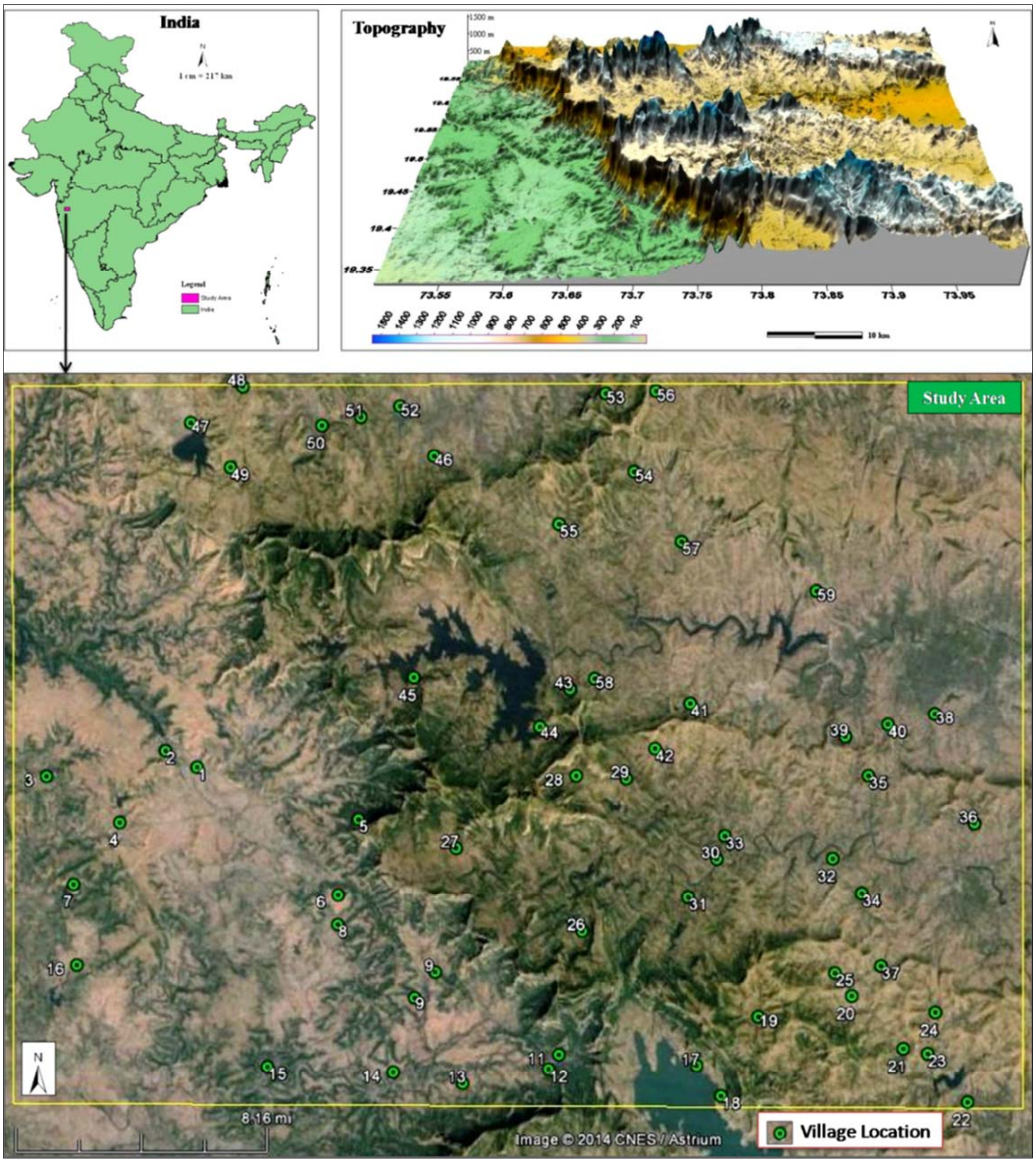

Fig.1. Location map showing the topography and superimposed village locations over satellite image of study area

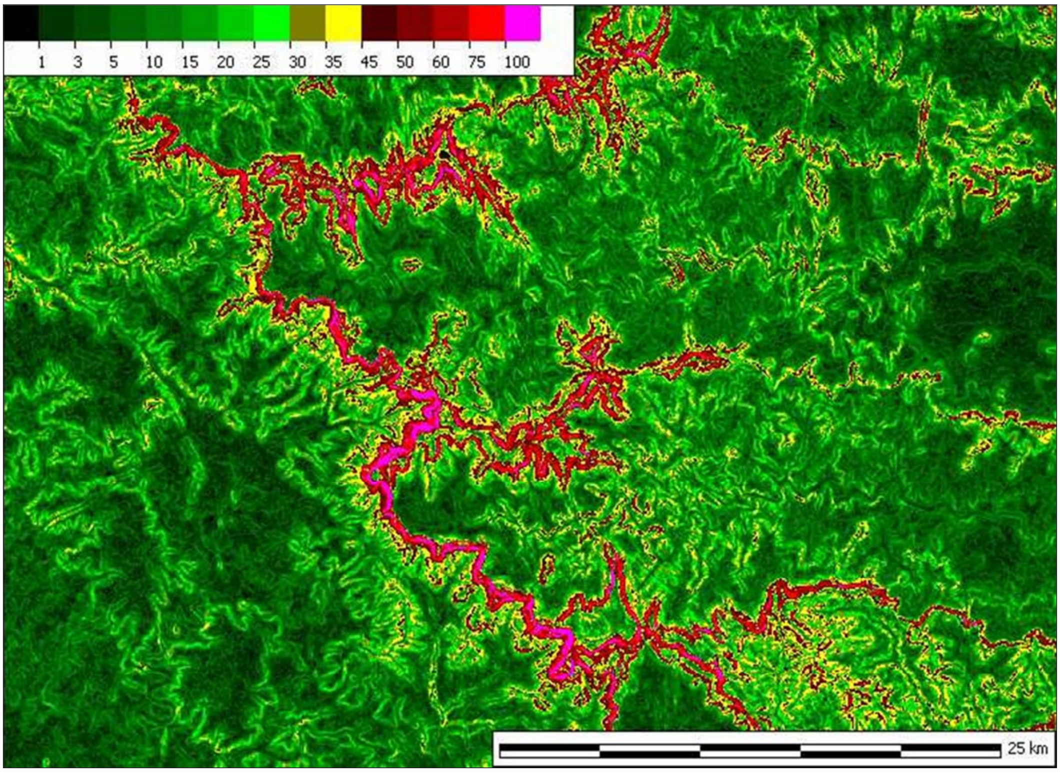

Fig.2. Map showing the slope situation (%) of the study area

define this tract of the Western Ghats to be highly undulating and hilly. It reveals a contrast in topography between the western and other parts of this region. The eastern part forms the foot of the plateau which exhibits jagged elevations interspersed in northern and central portions. The contrast in elevation is marked, sometimes amounting to almost 500 m and more. Map depicting the percentage of slope (Fig. 2) reveals an elevated line which runs from northwest to southeast branching out at the bottom, middle and top towards the eastern side. The intervening valley at the center depicts flowing water which is dammed at Bhandardara. The area has a dominant adivasi population and their hamlets are spread unevenly all over the study area.

This region experiences tropical climate, where the average annual rainfall is between 2500 to 3000 mm (Akole, 2014). The monsoon precipitation, due to orographic effect, is seen to be higher in the western segment and along the windward slope, as against the leeward slope (Fig. 3). The eastern segment has scanty precipitation which is seen to gradually increase towards the western flank. The central topographic elevated corridor has moderate precipitation.

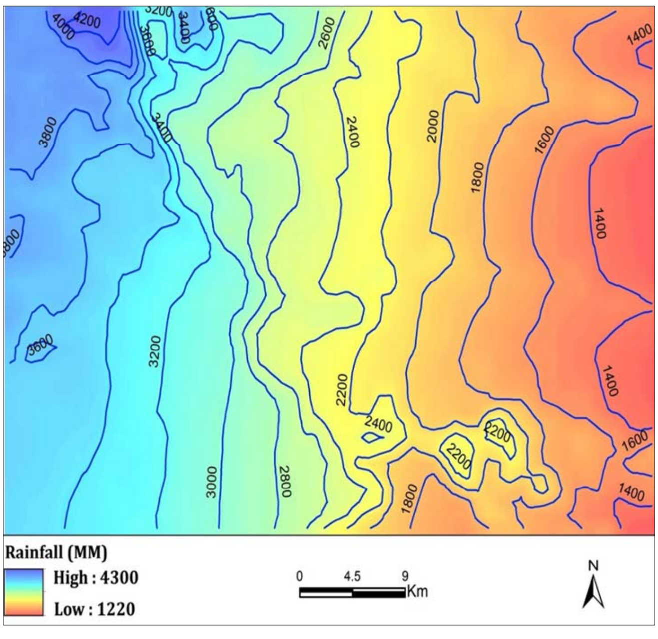

Fig.3. Spatial distribution of mean annual rainfall (cm) in the study area

GEOLOGY OF THE AREA

The western continental margin of India is an elevated passive margin represented by an escarpment (Radhakrishna, 2001) ~1 km high running for more than 1500 km. This is known as Western Ghat which formed at the time of separation of Seychelles microcontinent following the eruption of the Deccan trap lavas in late Cretaceous (Widdowson, 1997; Subrahmanya, 1998; Gunnell and Fleitout, 2000; Chand and Subrahmanyam, 2003). Denudational unloading and marginal isostatic uplift are also suggested by many to be still active (Widdowson, 1997; Gunnell, 2001), which has carved out the present morphology (Mathur, 1991). However, Valdiya (2001) has argued that the presence of this big escarpment cannot be ascribed to only isostatic uplift, but also to neotectonic resurgence. Sustained uplift along the western continental margin of India has been deduced by Athavale and Anjaneyulu (1972); Kailasam (1975); Powar (1981, 1993); Radhakrishna (1989, 1993); Subrahmanya (1998); Widdowson and Mitchell (1999); Gunnell (2001); Valdiya (2001); Gokarn et al (2003); Mishra et al (2004); Veeraswamy and Raval (2005); Tiwari et al (2006); Catherine et al (2007); Sheth (2007); Campanile et al (2008); Mukhopadhyay et al (2008). Kailasam (1975), based on bouguer anomaly, identified areas of uplift in Nashik and Sangola. Mahadevan and Subbarao (1999) and Widdowson and Mitchell (1999) attribute sporadic seismic activity to adjustments in response to denudational isostasy and the resulting activation of faults and fractures in this region.

Laterite occurring at higher elevations in the DVP is considered to be due to post-Deccan trap uplift (Widdowson, 1997; Sheth, 2007), for example the Mahabaleshwar and the Kas laterite plateau, which formed at lower altitude during the early Tertiary. Based on occurrences of lateritised palaeosurfaces, Widdowson and Cox (1996) identified significant post-Deccan trap uplift in the Nashik region leading to reversal of primary volcanic dips of the basalt flows in this part. Geomorphic signatures were also identified by Widdowson and Mitchell (1999) in the Konkan region of recent uplift. However, Kale and Shejwalkar (2008), based on geomorphic evidences, found scant evidence for western margin of India to have undergone uplift and tectonic deformation from Tertiary to Recent times. The DVP seem to have a spread of 500000 km^2 (Wadia, 1975) and the lava stratigraphy was established through palaeomagnetism (Cox and Hawkesworth, 1985; Beane et al., 1986; Subbarao, 1988; Lightfoot et al., 1990; Peng et al., 1994; Paul et al., 2008). Geochemical characteristics and field signatures have been used to divide the ~3000 m thick stratigraphic lava column into three subgroups and eleven formations (Subbarao and Hooper, 1988). The basaltic rocks are highly jointed and the hill slopes within the studied area, composed of weaker material capping jointed rock mass, are more prone to failure. Thigale and Khandge (1996) found variable thickness of regolith over the Deccan traps depending upon their position on planar or cliff surfaces. The regolith seem to have high ability to store and transmit water (Thigale, 1983) and their presence on jointed hill slopes make them prone to failure. Some of the recent heavy precipitation triggered landslides that occurred in the Maharashtra state are listed in Table 1.

MATERIALS AND METHOD

For the present study a total of 8 weighted landslide parameters, taken from different sources, were analyzed for their suitability in effecting landslides. Also, Survey of India (SOI) topographical maps (47/E/10, 47/E/11, 47/E/14 and 47/E/15) and geological maps were scanned and then georeferenced in Global Mapper software. Georeferencing process set the different dataset to a unique projection and scale (Aher et al, 2011). The Google image from Google earth software and orthorectified ASTER DEM from global land cover facility (GLCF) web portal were also downloaded. The exact locations of 59 villages were identified by combining topographical maps, satellite imagery, and ASTER DEM through onscreen digitization. Similarly, 30 x 30 arc-second resolution, precipitation data (tile-28) was downloaded from Worldclim web portal. ASTER DEM was used for identification of topography, elevation from mean sea level, slope, curvature and aspect. Google earth image of 2014 was processed in ILWIS 3.3 (integrated land and water information system) software for LULC information. However, in this study, village locations were mainly identified and digitized from topographical maps, whereas the changed/updated locations of few villages were referred from satellite imagery. For example, Ghatghar village in Akole Tehsil of Maharashtra is not located at a same/similar point on topographical and satellite imagery. This is because Ghatghar village has been shifted to another new location for constructing a reservoir.

Previous landslide record was obtained through field inventory and local interactions in study area. Index classes were prepared from rainfall and slope data. Correlation coefficient (CC) of first two weighted parameters (rainfall and slope) was calculated for validation of prepared index. Landslide susceptible (LS) area within the study region was identified in GIS software from processed digital database. Landslide susceptible villages (LSV) were identified from LS result, CC and incorporated digital data, which were also verified in the study area through field visit and local interaction. Population data of selected villages was collected from census 2011. Finally, risk susceptibility (very high, high, moderate, low and very low) with spatial and non-spatial database for 59 villages were assigned after the validation of 10 LS sample villages.

LS zones or areas can be identified by different methodology ranging from statistic to deterministic to heuristic, which usually employ landslide inventory mapping to validate generated landslide susceptibility maps. In this paper the heuristic technique based on weighted score method is used, involving expert judgment in assigning the hierarchical role played by each parameter in the mechanism that leads to landslides. The highest score and weight assigned to a parameter depicts the highest influence of that parameter in bringing about a landslide. Thus, landslide parameter weighting (LPW) is a quantitative method for assigning landslide affecting parameters weightage along with ranking. The susceptibility analysis was generated through ArcGIS 10.0 software. Eight parameters- rainfall, slope, lithology, LULC, soil properties, relative relief, aspect and lineament, were employed in LS analysis. The weight and ranking assigned to each parameter are given in Table 2.

Rainfall is the dominant factor in this part of the region that affects landslide activity. This part of the Western Ghat has steep, high-rise escarpments varying in height from 500 m to 1500 m with regional slopes of around 17^0 and more. Slope stability studies carried out by different workers indicate LS to be dependent on slope angle, physical properties of material underlying slope, and trigger mechanism (Peshwa and Kale, 1987). Lithology represents the nature of parent material of area under study. The hard and massive rocks present in the study area are resistant to erosion and weathering. However, the jointing and fracturing prevalent in rocks of the study area can be a major influencing factor of sliding under the punishing torrent of monsoonal precipitation.

LULC has a very specific role in slides. Housing, barren land, less penetrative vegetation, and flat-surface farming have different scales of effects on triggering landslides. Soil properties pertain to its depth, texture, permeability and porosity. Soil with fine texture, especially the clayey soil, contains tiny pores which stores and then gradually

Table 1. Landslides at different places in Maharashtra

Time	Place in Maharashtra	Cause	Major losses/damage
30 July 2014	Ambegaon Taluka, Pune	Heavy Rainfall	134 dead
10 July 2013	Antop Hill, Mumbai	Heavy Rainfall	2 dead
23 June 2013	Vaibhavwadi, Sindhudurga	Heavy Rainfall	52 dead, 100 injured, train derailed
1 August 2012	Malshej Ghat, Ahmednagar	Heavy Rainfall	67 dead, highway blocked, motorist injured
July 2005	Sakinaka, Mumbai	Heavy Rainfall	100 dead, property damaged
July 2005	Belapur-Kharghar, Navi Mumbai	Heavy Rainfall	4 dead, property damaged
July 2005	Nerul, Navi Mumbai	Heavy Rainfall	14 dead, property damaged
25 July 2005	Jui, Dasgaon, Rohan and Kondivate, Mahad	Heavy Rainfall	190 dead
August 2005	Mandangad, Chiplun, Sangameshwar Talukas, Ratnagiri	Heavy Rainfall	Destabilization of slopes, Damage to property
17 June 2004	Karanjadi, Ratnagiri	Heavy Rainfall	20 dead, 100 injured, train derailed
13 July 2000	Ghatkopar, Mumbai	Heavy Rainfall	67 dead
July 1983	Ratnagiri	Heavy Rainfall	Highway blocked

Table 2: Allotted weight and ranking to parameter

Sr. No.	Parameter	Weight (%)	Ranking
1	Rainfall	20	1
2	Slope	20	2
3	Lithology	10	3
4	Land use and land cover	10	4
5	Soil properties	10	5
6	Relative relief	10	6
7	Aspect	10	7
8	Lineament	10	8
	Total	**100**	

liberates water after saturation. This property is not seen in other types and hence the clayey soil is more susceptible to slides after a prolonged spell of precipitation. The area under study has a pronounced relative relief wherein the eastern and western part have a considerable difference in altitude. This area also has many lineaments which are known to play a major role in landslide generation. To represent and interactively examine these parameters, the following equation was used to arrive at the final weights and then was allotted ranks to these weighted parameters, which are given in Table 2.

$$W_L = \frac{l}{L} \tag{1}$$

where, W_L is weight of parameter for LS, l is no. of literatures which included these parameters for LS and L is total no. of literatures surveyed for LS.

The selection of the eight parameters is based on extensive literature survey which dealt with the problem of landslides in this part of the geological terrain. Amongst all those studies, rainfall and slope was found to have significant weight while lineament turned out to be less significant parameter for LS assessment. This weight of parameter and its ranking was used to identify LS prone villages in the study area. After allotting specific weights and ranks to these parameters, the susceptibility levels were classified into five classes: very low, low, moderate, high and very high.

The results arrived at from equation 1, depict rainfall and slope parameters have higher weight. Using this information, base index were prepared by using the following equation from rainfall and slope data of 59 villages:

$$\text{Index} = r + s \tag{2}$$

Where, r is average annual rainfall of selected village and s is slope of selected village at risk direction.

For validation of prepared index, correlation coefficient (CC) was calculated from equation (3)

$$Correlation(x, y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}} \tag{3}$$

Where, x is rainfall of selected village and y is slope value direction of village at risk.

CC derived from equation (3) was positive (0.51), signifying prepared index to be valid for index and index class preparation from equation (2) between rainfall (x) and slope data (y) of selected villages.

RESULTS AND DISCUSSION

Geospatial Techniques

Satellite remote sensing (SRS) data and GIS software has a huge potential and wide application in assessing and categorizing natural hazards such as landslides (Yang et al., 2007), floods, river bank erosion (Aher et al., 2012), and glacier retreat processes (Aher and Dalvi, 2012). It is very difficult to identify LSVs, in field, because of mountainous terrain and prohibitive costs for manned surveys. Accessibility is also another limiting factor. Because of all these shortcomings, in such localities, SRS data is the only possible source for getting accurate information of earth surface features and LULC. The patterns and attributes are significant to understand earth surface processes.

Slope is a rate of change in elevation and aspect, the direction of steepness. The aspect map prepared for the area under study is given in Fig. 4, which depicts the aspect (direction) and degree (steepness) of slope of the terrain. This application helps improve our ability to visually interpret fine surficial features within the broader terrain. Aspect categories are symbolized using hues (e.g., red, orange, yellow, etc.) and degree of slope classes are mapped with saturation (or brilliance of color) so that the steeper slopes are brighter. Aspect identifies the down slope direction of the maximum rate of change in value from each cell to its neighbor. It can be thought of as the slope direction. The values of each cell in the output raster indicate the compass direction that the surface faces at that location. It is measured clockwise in degrees from 0 (due north) to 360 (again due north), coming full circle. Flat areas having no down slope direction are given a value of -1 (Burrough and Mcdonnel, 1998).

DEM is used to derive elevation, slope, aspects, curvature, hill shading, topographic features and qualitative classification of

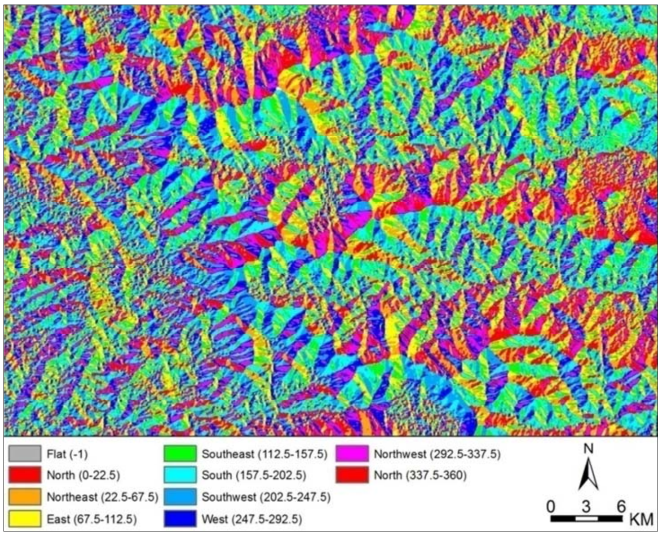

Fig.4. Map depicting aspect characteristics of the study area

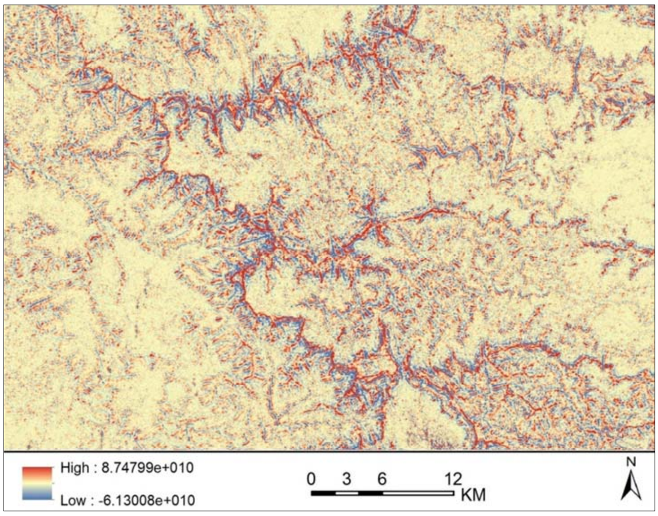

Fig.5. Aspect and curvature maps of study area generated from ASTER DEM

landforms (Fernandez et al. 2003). The minimum elevation in the study area is 50 m and maximum is 1646 m (Fig. 2). The curvature range is from -6.13 to 8.74 wherein steepness observed within the central part of the study area which is due to escarpment (Fig. 5).

Validation of training villages' landslide risk

The past landslide record, field inventory and information obtained from local population was considered for validating the acquired results. The study area has being experiencing landslides of varying scales, since 2001, impacting humans, forest and leading to road loss to damming the natural flow of streams. The mountainous terrain has abundant water bodies, out of which, a small natural stream was locked by debris fall along the stream path in July 2001. The landslide near Ratanwadi village of Akole tehsil, in August 2008, damaged state highway and uprooted considerable quantum of forest cover (Fig. 6). Four workers died in a massive landslide, in June 2005, at a tunnel erected for Ghatghar hydroelectric project in Akole tehsil (Fig. 7).

These effects have been listed in Table 3.

Table 3. Past landslide occurrences within the study area

Sr.	Locality	Year	Intensity	Impact
1	Near Chilewadi, Junnar	July 2001	Low	Stream lock, forest loss
2	Near Ghatghar, Akole	June 2005	High	Tunnel, forest, human loss
3	Near Kotewadi, Shapur	July 2008	Moderate	Forest loss
4	Near Ratanwadi, Akole	August 2008	Moderate	Road and Forest destruction
5	Near Fofsundi, Akole	July 2013	High	Forest and road destruction

Field inventory and local discussions were carried out at Fofsundi village, since debris fall and landslide incidences had occurred here in the recent past. This is one of the most landslide prone areas, since it experiences heavy rainfall during monsoon. It is also undergoing geological breakings and forming thick soil cover over hill slopes.

Fig.6. Google map showing the surface situation before landslide (2006) and after landslide (2009) that occurred near Ratanwadi, Akole

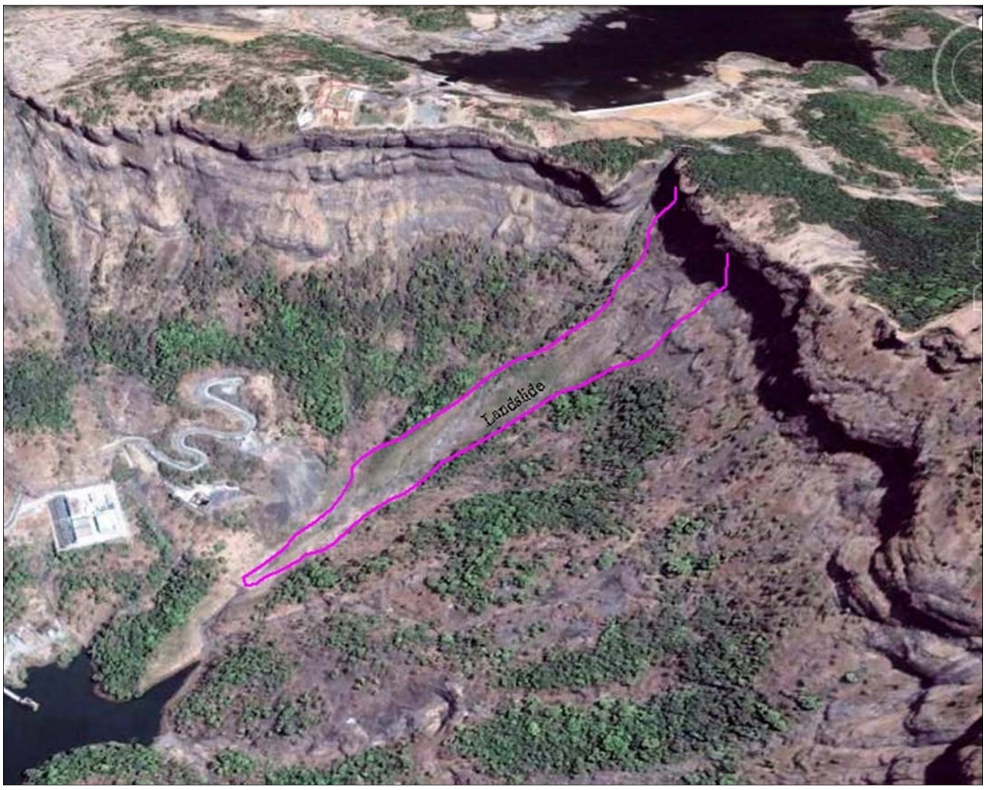

Fig.7. Effect of 2005 landslide seen near Ghatghar project.

Photos 1 and 2. (1) llustrating the characteristics, types of landslides and its impact on a place near Fofsundi village, Akole Tehsil. **(2)** Villages and hamlets susceptible to landslides near Eakdara, Akole Tehsil. Here LULC is a contributing factor for LS

Along the SW direction of this village a moderate scale landslide had occurred in July 2013 damaging nearby forest and roads (Photo 1). A total of 10 villages, such as Bojdhari, Ekdara, Guhire, Abitkind, Fofsundi, Ajoba temple, Kumshet, Bitaka, Devgaon and Mutkhel were visited to carry out field study to verify computed results. The actual visits to sites, armed with computational results, revealed villages at maximum risk were located along the hill slopes and foot hills. In the event of continued torrential rains such villages located on such terrain can experience mudslides (Photo 2).

Spatial and Non-spatial Parameters

Spatial and non-spatial data was compiled for 59 villages enumerating rainfall, elevation, slope and population, apart from its geographical details (Table 4). Of the 59 villages from the study area almost 23 are referred to as 'wadies' in the local language. These are mostly independent of the main village and are inhabited by the adivasi populace. The Shahapur tehsil of Thane district displays elevation ranging from 10 to 199 m at 6 villages; less than 100 m and more than 500 m at 1 village each. The Murbad tehsil of Thane district has 5 villages having elevation between 200 to 299 m; 3 villages between 100 to 199 m. Junnar tehsil of Pune district has elevation of more than 700 m at 1 village and a little less than 700 m at another. Only one village exists which is placed at more than 900 m elevation in Junnar. Bulk of the study area forms a part of Akole tehsil within Ahmednagar district wherein there exists only one village having elevation below 700 m; 19 villages between 700 to 799 m; 7 between 800 to 899; and 6 between 900 to 999 m. The highest elevation, 1038 m, is seen to exist at Eakdara village of Akole tehsil of Ahmednagar district. In the Igatpuri tehsil of Nashik district 4 villages lie at elevations between 600 to 699 m; 3 between 700 to 799 m; and 1 above 800 m. The degree of slope ranges from 7.91 to 21.55. LS area mapping was done using lithological parameters, overlay operations and DEM processing methods. The minimum value of calculated index derived from equation (2) was 142.52 while maximum was 376.50. Calculated base index values were then equated and grouped into 5 classes (334.0 - 381.9: Very high, 286.0 - 333.9- High, 238.0 - 285.9: Moderate, 190.0 - 237.9: Low and 142.0 - 189.9: very low). The computed data revealed risk direction and risk priority which has been given in Table 4.

Degree and intensity of LS villages in the study area

The values obtained from calculated index, calculated base index and other computational methodologies helped group villages into 5 classes. These are related to risk intensity or hazard zones (Table 5) and the risk priority is depicted in Fig. 8. It must be borne in mind that sometimes a bias creeps in determining landslide prone villages, even though it should solely depend upon the ground reality (Gorsevski, 2006). To avoid this bias, and to make the inventory as accurate as possible, field investigations were carried out in the study area before assigning the final risk priority to 59 villages, which are listed out in Table 5 and graphically presented in Fig. 9.

This study revealed primary criteria that influences LS in the study area was rainfall and slope, followed by lithology, LULC, soil properties, relative relief, aspect and proximity to lineaments. Rainfall-triggered landslides may mobilize into fast-moving mudflows, which generally present a greater hazard to human life than slow-moving, deep-seated slides (Hong and Adler, 2008). Most of the villages that are at risk of landslides are prone to that of debris- or mud-flow type. Landslides triggered by rainfall can possibly be predicted by modeling between rainfall intensity or by knowing its duration triggering a landslide (Keefer and Wilson, 1987). NASA with its Tropical Rainfall Measuring Mission (TRMM) reports regularly on heavy rainfall areas around the globe, on an almost real time basis. This information can be monitored closely when there is incessant and heavy rainfall in the Kalsubai region to take preventive measures. The population at higher risk can also be alerted to impending landslide risk. The data reveals most of the possible landslide occurrences are associated with high steep slopes and heavy precipitation. Field visits also revealed presence of weathered rocks and zones of lateritic soil in the study area.

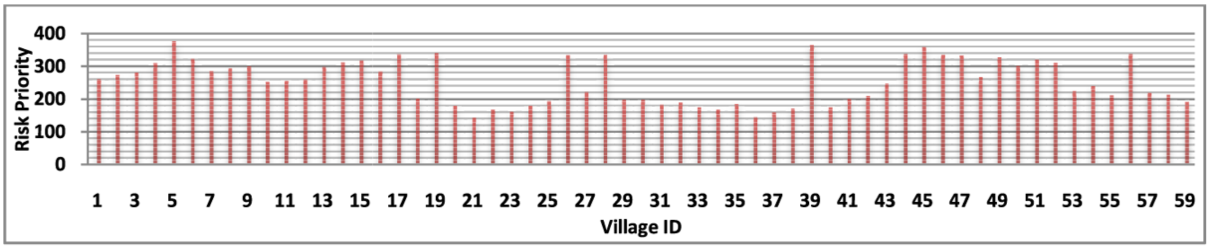

Fig.8. Risk priority of selected village calculated from index value

Table 4. Spatial and non spatial database for 59 villages in the study area

ID	Village Name	Location(Lat. : Long.)	Tehsil(District)	Rainfall (cm)	Elevation (MSL)	Slope (Degree)	Population (2011)	Risk Direction	Risk Priority
1	Hedavali	19°29'24.32"N:73°35'31.31"E	Shahapur (Thane)	250	199.24	11.25	342	NE	M
2	Katodwadi	19°29'5.54"N:73°34'35.30"E	Shahapur (Thane)	263	159.39	10.00		South	M
3	Babare	19°29'8.71"N:73°31'0.80"E	Shahapur (Thane)	270	154.37	11.17	271	East	M
4	Kharade	19°27'50.90"N:73°33'12.87"E	Shahapur (Thane)	295	543.88	15.18		NE	H
5	Ajuba Temple	19°27'57.28"N:73°40'22.93"E	Shahapur (Thane)	355	185.25	21.55		SE	V.H
6	Kotewadi	19°25'50.43"N:73°39'44.39"E	Shahapur (Thane)	312	130.55	10.12		SE	H
7	Payarwadi	19°26'7.52"N:73°31'49.67"E	Shahapur (Thane)	275	143.07	10.04		North	M
8	Kundachiwadi	19°25'0.49"N:73°39'43.27"E	Murbad (Thane)	276	246.85	18.33		SE	H
9	Mudhalwadi	19°23'42.32"N:73°42'38.46"E	Murbad (Thane)	282	253.08	18.57		SE	H
10	Mirdi	19°22'58.18"N:73°42'0.95"E	Murbad (Thane)	240	281.72	13.52		NW	M
11	Thitbi	19°21'23.63"N:73°46'18.28"E	Murbad (Thane)	241	260.63	15.23		NE	M
12	Khadkwadi	19°25'50.43"N:73°39'44.39"E	Murbad (Thane)	249	248.82	10.79		SE	M
13	Nirgudpada	19°20'35.39"N:73°43'26.53"E	Murbad (Thane)	287	146.78	10.95		East	H
14	Nyahadi	19°20'53.53"N:73°41'21.95"E	Murbad (Thane)	301	197.74	10.40		NE	H
15	Chasole	19°21'1.70"N:73°37'35.71"E	Murbad (Thane)	303	190.19	14.92		NE	H
16	Apte	19°20'53.53"N:73°41'21.95"E	Shapur (Thane)	276	88.34	8.26		East	M
17	Vaghyachiwadi	19°20'53.53"N:73°41'21.95"E	Junnar (Pune)	320	718.66	16.27		NE	V.H
18	Gavarwadi	19°20'19.77"N:73°51'5.41"E	Junnar (Pune)	184	689.44	17.49		East	L
19	Phophsundi	19° 22'33.10"N:73°52'10.17"E	Akole (A.Nagar)	311	962.21	21.55	635	West	H
20	Jaglyachiwadi	19°23'6.51"N:73°54'54.88"E	Akole (A.Nagar)	168	966.56	11.21		NW	V.L
21	Ghotkarwadi	19°21'39.18"N:73°56'25.85"E	Akole (A.Nagar)	132	706.83	10.52		East	V.L
22	Chilewadi	19°20'7.98"N:73°58'20.80"E	Junnar (Pune)	158	929.77	10.11		SW	V.L
23	Umravihare	19°21'19.97"N:73°57'9.03"E	Akole (A.Nagar)	151	889.07	10.40		West	V.L
24	Bangarwadi	19°22'39.34"N:73°57'22.61"E	Akole (A.Nagar)	169	969.14	10.45		West	V.L
25	Umbrewadi	19°23'42.90"N:73°54'24.56"E	Akole (A.Nagar)	183	971.09	10.64		West	L
26	Panchnai	19°24'24.52"N:73°47'0.89"E	Akole (A.Nagar)	324	846.94	11.10	514	East	V.H
27	Kumshet	19°27'10.79"N:73°47'18.45"E	Akole (A.Nagar)	210	754.94	11.36	631	East	L
28	Warliwadi	19°29'10.86"N:73°46'50.22"E	Akole (A.Nagar)	324	918.53	11.29		NW	V.H
29	Damanwadi	19°29'6.01"N:73°48'18.03"E	Akole (A.Nagar)	186	771.79	12.11		North	L
30	Dhodwadi	19°26'52.59"N:73°50'58.37"E	Akole (A.Nagar)	185	754.13	12.75		East	L
31	Waghdari	19°25'49.52"N:73°50'7.92"E	Akole (A.Nagar)	169	770.11	14.28	553	East	V.L
32	Paithan	19°26'52.59"N:73°54'23.35"E	Akole (A.Nagar)	178	760.65	11.68	1552	East	V.L
33	Padliwadi	19°27'30.92"N:73°51'11.71"E	Akole (A.Nagar)	163	782.53	11.99		NE	V.L
34	Ambhol	19°25'55.34"N:73°55'14.29"E	Akole (A.Nagar)	157	747.48	10.86	1,563	SE	V.L
35	Thalawadi	19°29'10.86"N:73°55'26.42"E	Akole (A.Nagar)	173	763.62	12.30		East	V.L
36	Mogras	19°27'50.81"N:73°58'33.44"E	Akole (A.Nagar)	134	698.42	10.36	1107	SE	V.L
37	Abitkhind	19°23'55.57"N:73°55'47.04"E	Akole (A.Nagar)	146	850.60	12.96	891	SW	V.L
38	Ambad	19°30'52.90"N:73°57'25.18"E	Akole (A.Nagar)	158	725.44	12.41	2242	SE	V.L
39	Bhojdari	19°30'15.44"N:73°54'45.35"E	Akole (A.Nagar)	349	716.88	16.24	354	South	V.H
40	Nirgudwadi	19°30'35.97"N:73°56'1.35"E	Akole (A.Nagar)	164	710.26	10.47	567	SE	V.L
41	Kelungan	19°31'10.47"N:73°50'11.49"E	Akole (A.Nagar)	188	886.07	12.17	1344	South	L
42	Savarkhute	19°29'55.35"N:73°49'9.03"E	Akole (A.Nagar)	196	754.96	13.57	1222	North	L
43	Daryachiwadi	19°31'33.73"N:73°46'38.99"E	Akole (A.Nagar)	230	770.26	16.45		East	M
44	Mutkhel	19°30'31.71"N:73°45'45.27"E	Akole (A.Nagar)	320	771.63	18.00	672	NE	V.H
45	Bholewadi	19°31'53.60"N:73°42'3.38"E	Akole (A.Nagar)	339	769.80	20.1	594	SE	V.H
46	Indore	19°38'0.07"N:73°42'39.63"E	Akole (A.Nagar)	320	831.62	16.10	1844	SE	V.H
47	Tamadmal	19°38'56.85"N:73°35'25.47"E	Igatpuri (Nashik)	323	743.88	10.4		South	H
48	Junavanachiwadi	19°39'56.25"N:73°36'58.07"E	Igatpuri (Nashik)	260	703.49	7.91		SW	M
49	Gahunde	19°37'40.85"N:73°36'37.11"E	Igatpuri (Nashik)	315	763.96	12.73		North	H
50	Nirpan	19°38'53.35"N:73°39'17.84"E	Igatpuri (Nashik)	289	811.13	12.66	670	SE	H
51	Manjargaon	19°39'7.33"N:73°40'58.7"E	Igatpuri (Nashik)	307	675.26	13.53	751	West	H
52	Kananwadi	19°39'23.93"N:73°41'36.74"E	Igatpuri (Nashik)	296	653.53	14.56	751	North	H
53	Bitaka	19°39'41.40"N:73°47'41.89"E	Akole (A.Nagar)	212	865.87	12.89	217	South	L
54	Shenit	19°37'33.86"N:73°48'31.24"E	Akole (A.Nagar)	229	798.13	11.27	1151	West	M
55	Warnghushi	19°36'8.25"N:73°46'18.90"E	Akole (A.Nagar)	200	980.22	10.67	3062	North	M
56	Eakdara	19°39'45.77"N:73°49'50.99"E	Akole (A.Nagar)	319	1038	19.00	799	West	V.H
57	Devgaon	19°35'38.55"N:73°49'56.42"E	Akole (A.Nagar)	208	822.94	12.07	1,070	NE	L
58	Guhire	19°31'51.42"N:73°47'22.67"E	Akole (A.Nagar)	202	762.00	10.59	906	SW	L
59	Pimpalgaon Nak.	19°34'18.18"N:73°53'53.59"E	Akole (A.Nagar)	182	771.89	10.11	1935	West	L

Note: 1) Lat: Latitude and Lon: Longitude. 2) VH: Very High, H: High, M: Moderate, L: Low, VL: Very Low

Table 5. Landslide susceptibility priority for 59 villages in study area

Sr.	Index class	Village Id	Total Village	Final Priority
1	334.0 - 381.9	5, 17, 26, 28, 39, 44, 45, 46, 56	09	Very High
2	286.0 - 333.9	4, 6, 8, 9, 13, 14, 15, 19, 47, 49, 50, 51, 52	13	High
3	238.0 - 285.9	1, 2, 3, 7, 10, 11, 12, 16, 43, 48, 54, 55	12	Moderate
4	190.0 - 237.9	18, 25, 27, 29, 30, 41, 42, 53, 57, 58, 59	11	Low
5	142.0 - 189.9	20, 21, 22, 23, 24, 31, 32, 33, 34, 35, 36, 37, 38, 40	14	Very Low

The stability of slope is based on slope angle, properties of underlying material and trigger mechanism (Peshwa and Kale, 1987) of trap rocks, that turn them from being stable to unstable, increasing their susceptibility to failure. The faults, fractures and joints weaken the rocks by lacerating them sometimes fastening the weathering rate. A thin deposition of weathered material and soil can be seen over gentle concave slopes, prevalent in the study area. The kind of landslide that occurs depends upon the thickness of the loose unconsolidated topsoil. The prevalence of tropical climate enriches chemical weathering processes (Sajinkumar et al., 2011). Because of high temperature and heavy rainfall, chemical weathering dominates, altering the primary minerals to clay. The trap rocks are usually altered by weathering, to laterite or bauxite and the soils formed mainly contain (in the clay fraction) smectite (up to ~ 80%) with kaolinite and illite (Somayajulu et al, 1993). Sundarajan and Sajinkumar (2012) reported thick column of soil over the Precambrian crystallines in the study area. Thus, the presence of steep and convex slopes, active physical and chemical weathering, thick and thin deposits of weathered material on hill slopes, heavy precipitation during monsoon, active erosion and weathering processes, presence of joints, fissures, fractures and lineaments as well as anthropogenic activities are responsible for landslides. According to Thigale and Umrikar (2007) the rains before any landslide, suck out the air from pores by filling them with water, as a consequence of which the pore-water pressure and weight of the slopes increases. This increases the possibility of slope failure leading to landslides. The 59 villages selected for LS zonation are located over the leeward and windward slope of Western Ghats, characterized by rugged hills and erosional topography (Joshi and Nagare, 2009). From the SRS data steep slope and deep valleys can also be deciphered. Consequently, this area is susceptible to landslides and field visits

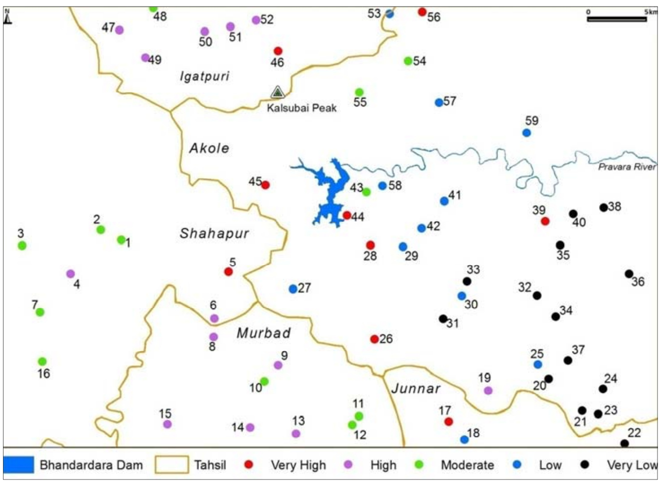

Fig.9. Degree and intensity of landslide susceptible villages in the study area

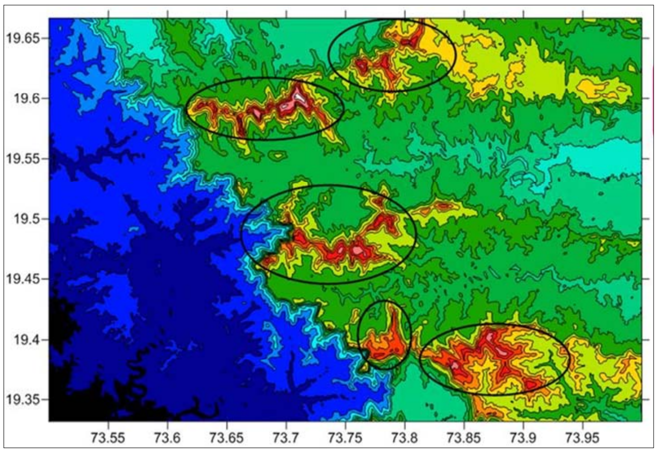

Fig.10. Landslide susceptible zones earmarked in the study area

revealed evidences of past landslides. Mathew et al (2007) found slope and slope aspect plays an important role wherein the stability or failure of the terrain depends on the decrease or increase of slope, in the Himalayan region. They found slopes in the range of 35–60° to be prone to landslides, since the colluvial accumulations are formed around 35° of slope. Thigale and Khandge (1996) found around 81% of the landslides they analyzed occurred on > 30° of slope. The present study found monsoon to be the dominant triggering mechanism of landslides, where steep slopes are present. Wilson and Wieczorek (1995) revealed continuous rainfall on loose surface causes shallow landslides, typically soil slip and debris flow, due to transient loss of shear strength resulting from an increase in pore-water pressure. Changing physical environment and land alteration activities, such as development of agricultural activity, agro tourism (Thorat et al, 2012) and transportation is also seen to aid in generation of landslides in the study area.

We have not given the timeframe, or rather are not able to predict the time of landslide. The ‘where’ has been answered, though. Almost 15% of the total studied villages fall in very high risk and 22% in high risk zone, with 20% in moderate risk zone and the remaining in low (19%) and very low (24%) risk zone. The ‘when’ resides and is dormant in the excessive and continuous rainfall that may hit these villages. Hence, the villages that face the maximum risk, according to our study, need to be monitored closely to avoid any mishaps.

CONCLUSION

Geospatial techniques were used to quantify LS of 59 villages around the Kalsubai peak of Maharashtra in the Western Ghats. The study area has high contrast in elevation marked by jagged topography and steep slopes with copious rainfall. Landslide susceptible areas have been marked based on heuristic technique based on weighted score method. Our data reveals most of the impending landslide occurrences correlate well with steep slopes and heavy precipitation. Along with these natural factors the anthropogenic effects are also creating conditions conducive for triggering landslides. 9 and 13 villages are respectively identified to be in very high to high risk landslide susceptible zones where more than 5000 people reside in the shadow of imminent danger. They are likely to experience debris flow or mud slides which have been seen to move downhill at speeds of 55 km or more per hour. This can have devastating effect on life and property. Hence, these and other villages that are at moderate risk need to be monitored closely to take effective measures to avoid any mishap, especially during heavy rainfall that continues incessantly for two or more days. The spatial and non-spatial database creation will help in preventing and/or mitigating landslide disasters in areas near Kalsubai peak. An inventory of landslide prone villages can be made for the entire Western Ghats by applying the present methodology.

Acknowledgements: Director, IIG, Prof. D. S. Ramesh is thanked for constant encouragement and support as well as for giving permission to publish this research article. SA, RG, SA, SB would like to thank S.N. Arts, D.J.M. Commerce, B.N.S. Science College, Sangamner for support and extending necessary research facilities. The anonymous reviewer is also thanked for suggestions that have greatly improved the manuscript.

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(Received: 27 March 2015; Revised form accepted: 27 February 2017)