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ORIGINAL PAPER

Identification of landslide susceptible settlements using geographical information system of Yelwandi river basin, Maharashtra (India)

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Abstract
Landslides are one of the critical geological processes, which cause enormous damage to civil engineering structures and also lead to loss of life. The present study is an attempt toward the development of a landslide methodology by using geographical information system (GIS) and remote sensing techniques for landslide susceptibility mapping. This involves the generation of thematic data layers and their spatial analysis within the Yelwandi river basin in Maharashtra, India. A weight rating system for the factors was developed for spatial data analysis in a GIS. The resulting landslide susceptibility map divides the area into different zones of four relative susceptibility classes: high, moderate, low and very low. The susceptibility map was correlated by field observations. The 67 settlements present in Yelwandi river basin area were classified according to severity of landslide. It also gives guidelines for feature activities of planning.

Keywords Landslide · Yelwandi · Settlement · Zonation map · GIS

1 Introduction

Mass movement is the downward movement by gravity of rock, regolith and/or soil on the sloped top layers of the Earth's surface. It is an important part of the progression of erosion because it moves material from high elevations to lower elevations. It can be triggered by natural events such as rainfall, earthquakes and volcanic eruptions, but gravity is its driving force. Landslide is the type of mass wasting which is sudden, fast movements of a cohesive mass of soil, rock or regolith. Landslide is one of the natural disasters involving the movement of rock mass/debris/soil due to slope failure, under the influence of gravity. The intensity and magnitude of landslide events may vary and are purely governed by inherent causative factor. Water is invariably involved in the mass

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movements. Besides natural factors, anthropogenic activity is often involved in slope failure. It causes damage to structures, property and loss of life. These are generally isolated processes which individually may not be very large in size but can occur with high frequency (Van Westen et al. 2006). Landslide hazard is defined as the probability of occurrence of landslides within a specific period of time and within a given area (Varnes 1984). According to Cruden (1991), landslide is the movement of a mass of rock, debris or earth down a slope. According to Scheidegger (1994), it is the probability that a reasonably stable condition may change abruptly. Guzzetti et al. (1999) preferred the definition to include the area, volume and velocity of the expected landslide. Sharma (1996) emphasized that a complete hazard assessment and mapping should be based on where and how large a landslide will occur.

The problem of the landslide is severe in Western Ghat of Maharashtra mostly due to the topography, human interference including excavation for construction activities, heavy rainfall, etc. Upland region of Deccan Volcanic Provinces (DVP) is considered as a most vulnerable region for landslides activity in the Maharashtra state of India. The area shows thick flows of the Deccan Trap basalt of Upper Cretaceous to Eocene age. State Highway-70 is the lifeline of the Pune district and Raigarh district of Konkan. The part of the highway between Bhor and Mahad is highly landslide prone and often blocked during the rainy season. Considering the importance of SH-70, landslide susceptibility zonation studies along SH-70 between Bhor and Mahad were carried out by Khamkar et al. (2018). The landslide susceptibility study gives an overall idea of the stability condition of the slopes of the hill, so it can be used for planning any further construction activity and remedial measures. They carried out detailed exploration along the road section started from Bhor city, and it extended up to the Mahad, in Konkan region, by considering geotechnical and geological aspects. The remedial measures were suggested to avoid landslide at certain points.

Khamkar and Mhaske (2018) have identified the locations of the mass movement of the Varandha region and classified them into different categories depending on type of rocks, weathering actions, slope and type of divisional planes.

Singh et al. (2010) have done both the analyses, i.e., static and dynamic of a landslide of the Amiyan area, near Kathgodam, Nainital, Uttarakhand.

Ansari et al. (2014) focused on risk consequence analysis of rock fall locations along the SH-72 of Maharashtra region. Rockfall Hazard Rating System (RHRSI) is used to identify slopes, prone to rock falls so that proper remedial measure can be proposed to mitigate loss. Rockfall Hazard Rating System for India (RHRSI) is a modified system for Indian subcontinent and used to define overall strength of slopes in mountainous region or rock cut slopes. They considered that State Highway-72 (SH-72) connecting Poladpur to Mahabaleshwar, which is an important transportation corridor supporting high vehicle traffic within the well-known tourist area, was chosen for Rockfall Hazard Rating.

Savoikar and Choudhury (2010) considered the effects of cohesion and fill amplification on the seismic stability of municipal solid waste landfills. Mhaske and Choudhury (2010) have developed a methodology for the preparation of soil liquefaction susceptibility map of the entire Mumbai city during earthquake using geographical information system.

The Yelwandi river basin area is prone to landslide. The different landslide events took place in the area. The area is subjected to heavy rainfall. Figure 1 shows landslide due to heavy rainfall. Due to the heavy intensity of rainfall and steep slope, the boulders also blown away with the rain water. Figure 2 shows landslide due to failure of joints. Water enters into the joint and loses its strength. Figure 3 shows landslide due to subsidence. The height of subsidence is about 4 m, and it extends for the length of 50 m. Figure 4 shows gully formation due to heavy rainfall. Figure 5 shows erosion due to heavy rainfall.

Fig. 1 Landslide due to heavy rainfall

Fig. 2 Landslide due to failure of joints

It creates danger to the road. Figure 6 shows crack in wall of house due to settlement of foundation.

2 Study area

The study area consists of Yelwandi river basin. It lies in Bhor and Velhe taluka of Pune district having latitude N18°0′–18°15′ and longitude E73°30′–73°52′30″. The Bhatghar dam is constructed across the Yelwandi river, subriver of Nira in Krishna basin, and is a dual purpose project for power generation and irrigation. It is masonry gravity dam

Fig. 3 Landslide due to subsidence

Fig. 4 Gully formation due to heavy rainfall

constructed in 1927 of length 1.626 km and having catchment area 275.178 m^2. The basin area consists of hills, valleys, forests, farming, settlements, etc. The map shows the ridge line, i.e., boundary of study area. The location map of the study area is shown in Fig. 7.

3 Data used and methodology

The geographic information system (GIS) is a computer-based tool for mapping and analyzing geographic phenomenon that exist, and events that occur, on Earth. The data required for analysis are toposheets, images and non-spatial data. GIS software integrates general database operations such as query and statistical analysis with the exclusive visualization and geographic analysis benefits offered by maps. These abilities distinguish GIS from other information systems and make it considerable to a broad range of public and private firms for explaining events and planning events.

Fig. 5 Erosion due to heavy rainfall

Fig. 6 Crack in wall due to settlement of foundation

GIS has four main functional subsystems. These are:

a. Data input system.
b. Data storage and retrieval subsystem.
c. Data manipulation and analysis subsystem.
d. Data output and display subsystem.

The explorations were carried out to find out the past history and present conditions of the study area. The type of data and their sources are given in Table 1. Figure 8 shows the flowchart of the methodology.

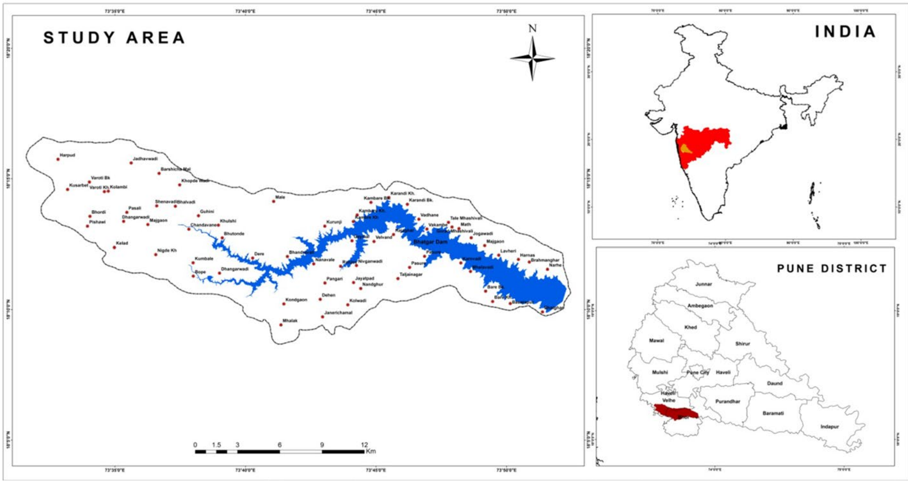

Fig. 7 Location map of study area

4 Data layer preparation

A thematic map is a sort of map particularly proposed to explain a particular theme linked with a specific geographic area. This is in difference to general reference maps, which regularly show the variety of phenomena—geological, geographical and political—together. The difference between them lies in the fact that thematic maps use the base data, such as coastlines, boundaries and places, only as points of reference for the phenomenon being mapped. General maps represent the base data, such as landforms, lines of transportation, settlements and political boundaries.

The thematic maps were prepared by compiling and collating the data on causative factors such as geology, geomorphology, land use and land cover and also the distribution of existing landslide processes. Extensive use of available maps, past statistical and census records, field and global positioning system (GPS) surveys, satellite remote sensing and GIS is made to create the thematic layer database. The most important inputs required for carrying landslide hazard zonation mapping at both the macro- and mesoscales have come from topographical and geological maps and remote sensing images. In India, the custodians of these data sources are the Survey of India (SoI), GSI, National Remote Sensing Center (NRSC) and Indian Meteorological Department (IMD). The SoI provides topographical maps at scales from 1:25,000 to 1:250,000 scales and is also expected to take up the task of generating topographic/contour maps at the scale of 1:5000 or 1:10,000 for the landslide-affected hilly regions of India. These agencies play a major role in providing data and hence are expected to be an integral part of any program on landslide hazard management and risk assessment in the country.

Prepared the thematic maps of slope, aspect, land use land cover, drainage, contour, soil, lineament,etc. using remote sensing image. These are analyzed and are numerically weighted based on their relative importance. For the preparation of thematic maps, the data are collected from various sources such as Survey of India Toposheet (SOI) Nos. E43H12 and E43H16 of scale 1:50,000; district resource of map of Pune, field data and various other sources were used.

Table 1 Type of data and their sources

Sr. no.	Type of data	Source	Utility
1	Spatial data	Toposheets of Survey of India No. E43 H/12 and E43 H/16 of scale 1:50,000	Location of water bodies, settlements, drainage network, etc.
2	Rainfall data	Hydrological Data Users Group (HDUG), Nashik	Rainfall trend in the study area
3	Satellite imagery	Google Image 2017	Land use and land cover
4	Digital elevation method	Shuttle Radar Topography Mission (SRTM) Data	Slope and aspect map
5	Geology	Pune district map of Geological Survey of India	Geology map of the study area
6	Ground trotting	Field visits	Location of landslides, types of soil, land-use pattern
7	Interaction	Local people	Discussion about events of landslide, probable reasons of landslides, location of landslides
8	Soil map	National Bureau of Soil Survey and Land Utilization Planning (NBSSLUP)	Soil map of the study area

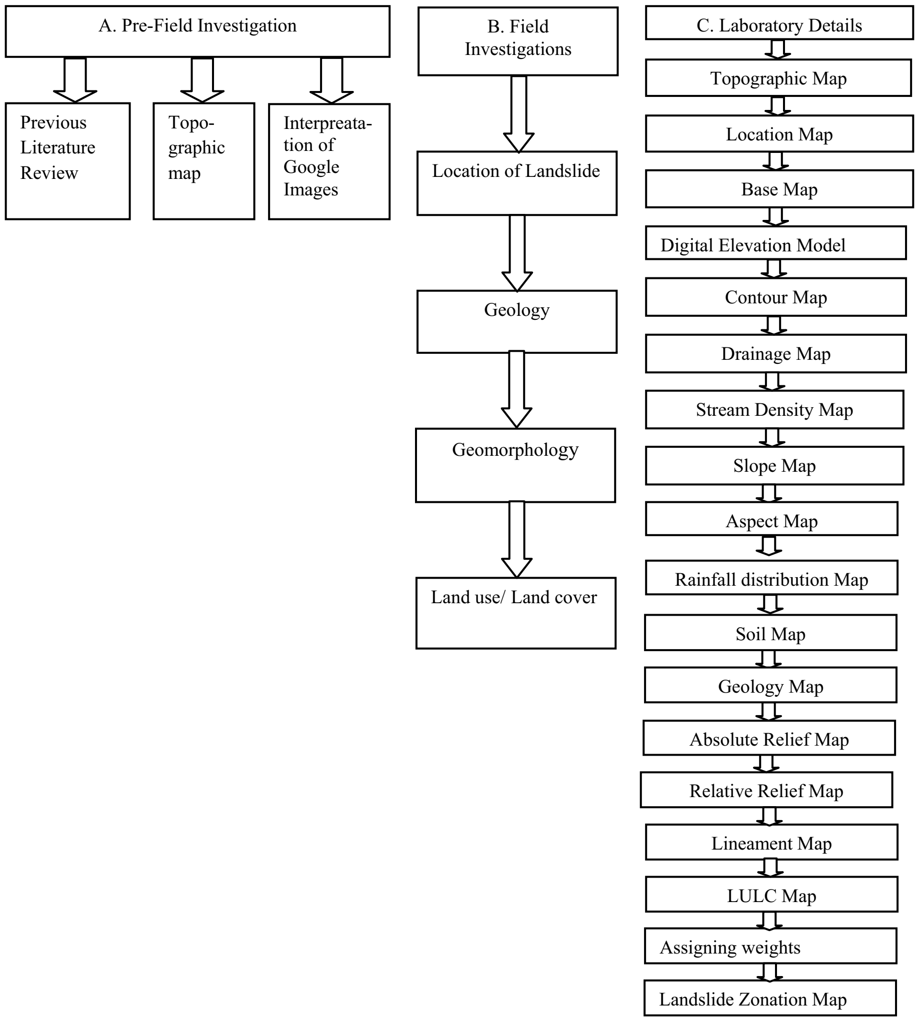

Fig. 8 Flowchart of the methodology

4.1 Base map

The Toposheet of Survey of India was used for the preparation of Base map. It gives the boundary of the study area. There were 67 settlements, and they occurred in the Yelwandi catchment area. The river Yelwandi is flowing from east to west. Base map of the study area is shown in Fig. 9.

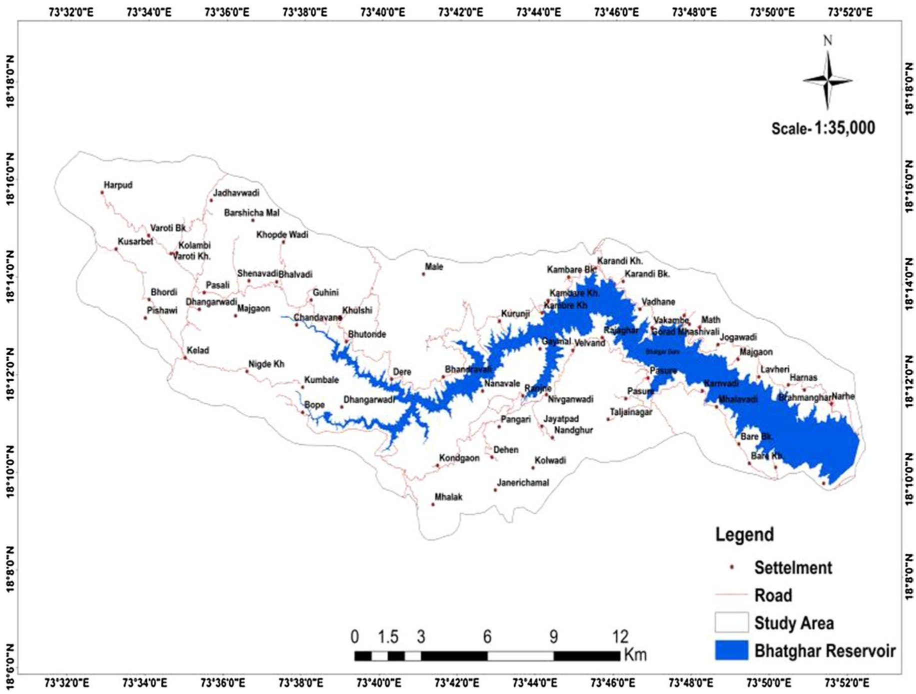

Fig. 9 Base map

4.2 Digital elevation method

The term digital elevation model or DEM is frequently used to refer to any digital representation of the topographic surface. However, most often it is used to refer specifically to a raster or regular grid of spot heights. Digital elevation model is digital records of terrain elevations of ground positions at regularly spaced horizontal intervals. These grids are derived from standard topographic quadrangle map using hypsographic data and or photogrammetric methods. Such grids are easily processed with the Arc-GIS. The digitized contour information is used to obtain the DEM. After interpolating the contours, the DEM is prepared. The DEM is used for extracting terrain parameters, volume calculations, creation of relief maps, rendering of 3D visualizations and terrain analysis in geomorphology and physical geography. In this study, the SRTM (Shuttle Radar Topography Mission) data have been obtained and processed using GIS software to prepare the digital elevation model (DEM) of the study area. The DEM shows that the elevation of the area rises to 1395 m. The DEM has been processed using GIS software to prepare the slope map of the study area. The slope map shows that the land slope of the study area varies from 0° to 87°. The aspect map has also been prepared from the DEM. Aspect shows the direction of the slope facing. The DEM has been processed to generate the contours and drainage of the study area. The drainage map shows that the study area has streams up to fifth order. The map of the digital elevation model is shown in Fig. 10.

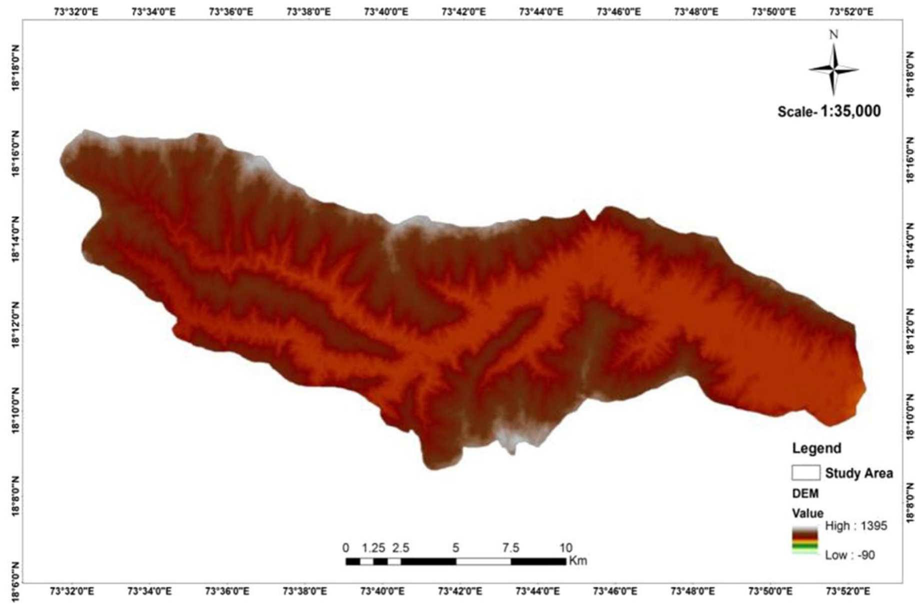

Fig. 10 Digital elevation model map

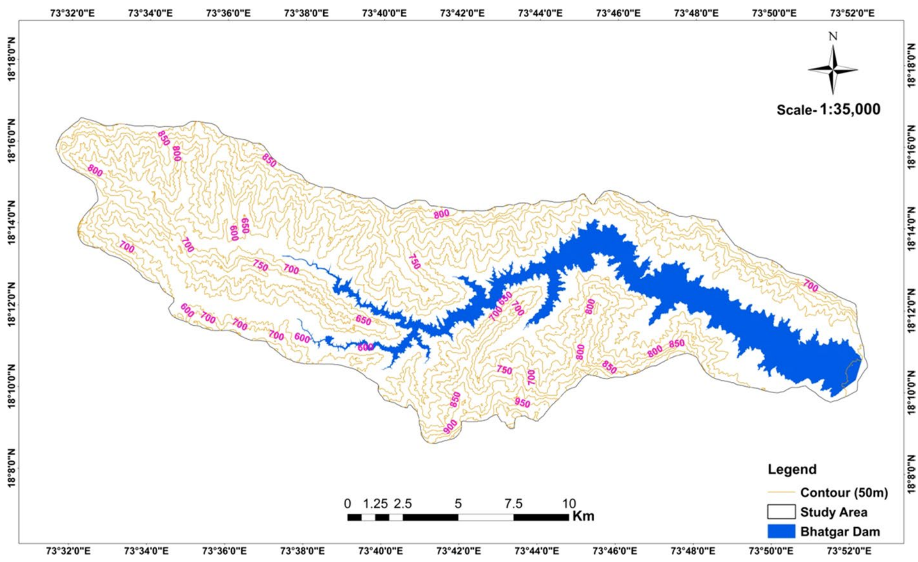

Fig. 11 Contour map

4.3 Contour map

The DEM has been processed to generate the contours at interval of 30 m of the study area. It gives idea about the undulations of the ground surface. Contour map is shown in Fig. 11.

4.4 Drainage map

The study area is sources from the Sahyadri uplands. The most of the tributaries are sources from very high elevated region. To know the catchment area, drainage map is important. The drainage map shows the flow of water throughout the study area. As the distance from the drainage line increases, the chances of occurrence of landslide also increase. Majority of the catchment area falls under medium- to high-density category. All tributaries are source from Sahyadri uplands and destined to the Yelwandi river and up to Bhatghar reservoir. Landslide activities are depending on the geology and geomorphic setting. The DEM has been processed to generate the drainage map of the study area. The drainage map shows that the study area has streams up to fifth order. Drainage map is shown in Fig. 12.

4.5 Stream density map

The drainage map was used to prepare stream density map based on the watershed area. Stream density or drainage density is a measure of the texture of the drainage basin. Stream density is the mean length of streams within a basin per unit area. Stream density map is shown in Fig. 13. Table 2 shows the stream density of the study area.

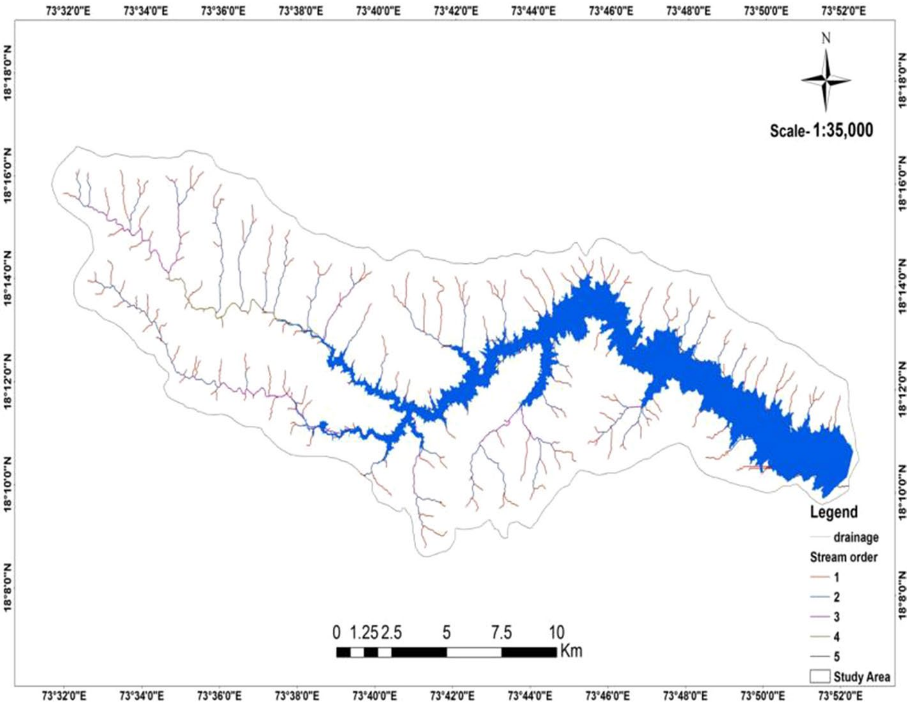

Fig. 12 Drainge map

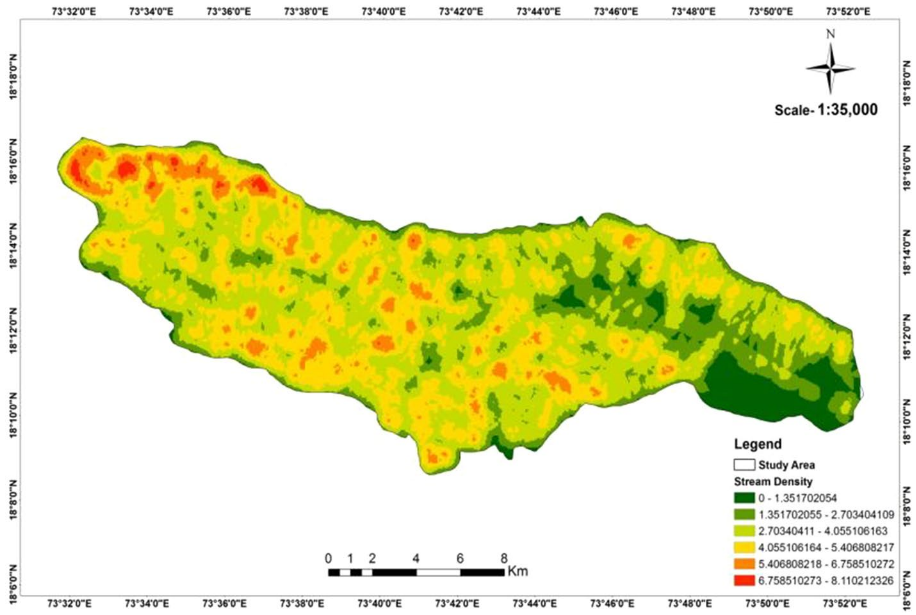

Fig. 13 Stream density map

Table 2 Stream density

Sr. no.	Stream order	Stream count	Length in km
1	1	1296	660.214
2	2	629	182.215
3	3	337	88.302
4	4	168	37.887
5	5	64	15.702
6	6	60	23.032

4.6 Slope map

The main parameter of the slope stability analysis is the slope angle, and because the slope angle is directly related to landslides, it is frequently used in preparing landslide hazard zonation maps. The slope map is derived from digital elevation model (DEM). The contour map is first converted to the DEM and then the slope map is prepared. The slope was categorized as 0°–5° gentle slope, 5°–15° moderate slope, 15°–27° steep slope and 27°–87° very steep slope. Slope map is shown in Fig. 14.

4.7 Aspect map

Aspect map is the compass direction that faces the slope. Aspect has a great influence on vegetation. The parameters such as exposure to sunlight, drying winds, rainfall and

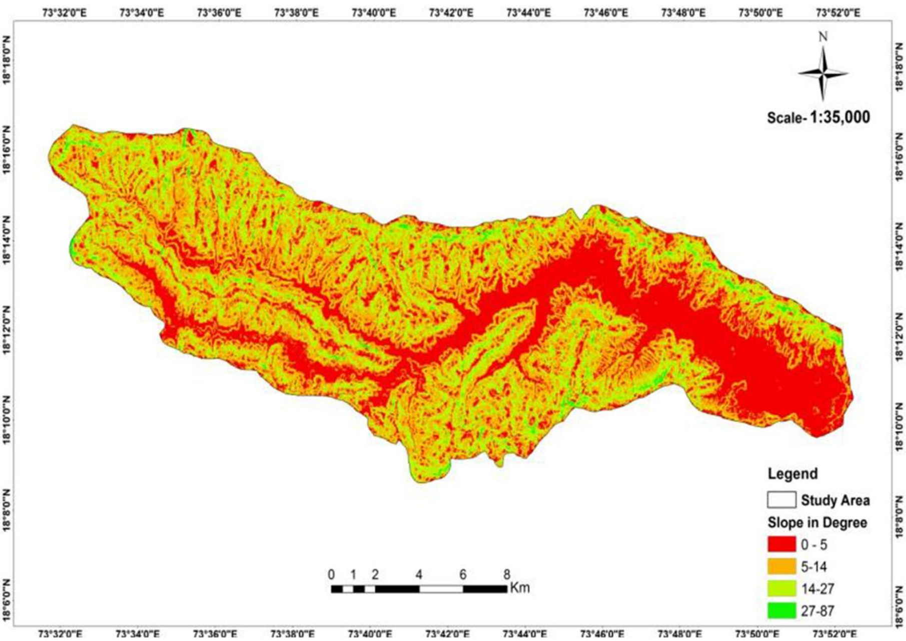

Fig. 14 Slope map

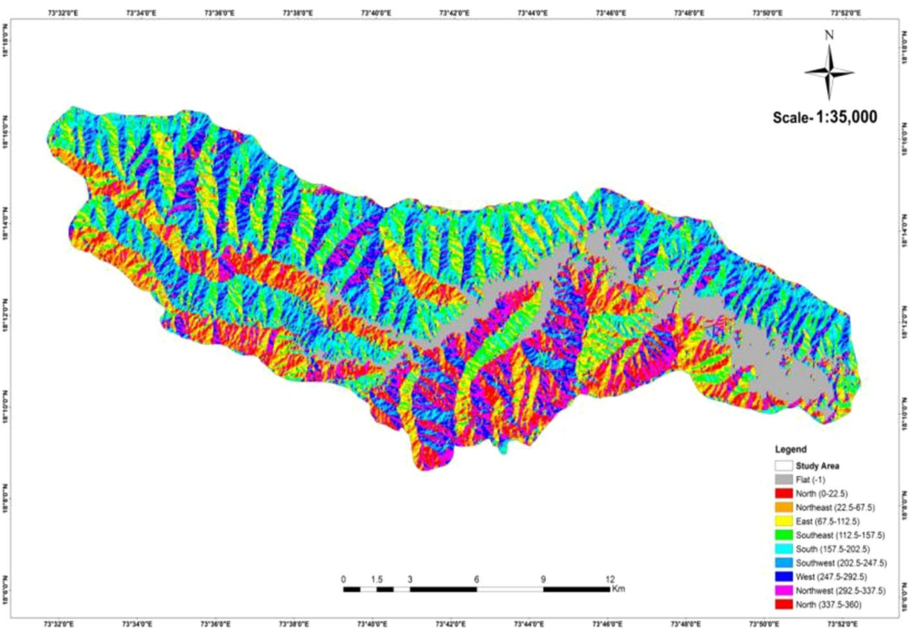

Fig. 15 Aspect map

discontinuities may control the occurrence of landslides. Aspect classes are N, NE, E, SE, S, SW, W, NW and flat (total nine classes at 45° interval). Slope gradient is one of the common factors for assessing slope stability condition, whereas slope aspect is also considered important due to the fact that aspect influences the amount of local rainfall and moisture content in the soil and thereby influences the slope stability condition. The aspect map for the study area is shown in Fig. 15.

4.8 Rainfall distribution map

The rainfall is one of the important factors responsible for the landslide. Due to wetting action of soil mass, its shear strength decreases and it may result into the failure of soil mass. The average rainfall data obtained from 'worldclim' database have been processed using GIS software to prepare rainfall distribution map of the study area. The average annual rainfall in the study area varies from 816 to 5353 mm. The rainfall is more along the western margin and decreases toward east. The distribution of the 30-year rainfall over the study area is shown in Fig. 16.

4.9 Soil map

The spatial distribution of soil types depends on its physiography and lithology. At the source area of streams, the thickness of soil is low, but as we go down the thickness of soil

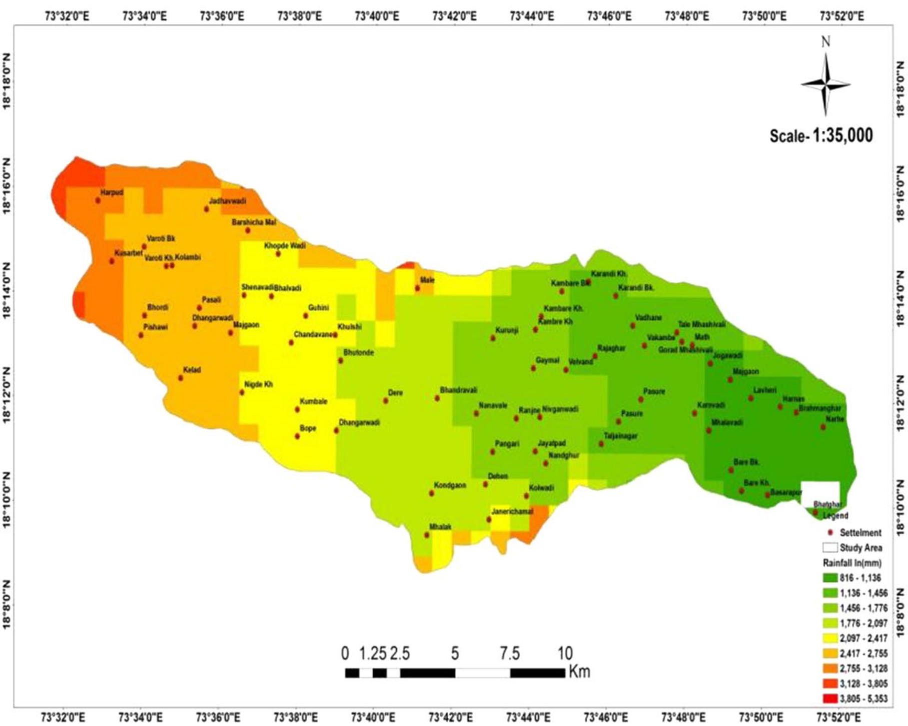

Fig. 16 Distribution of rainfall

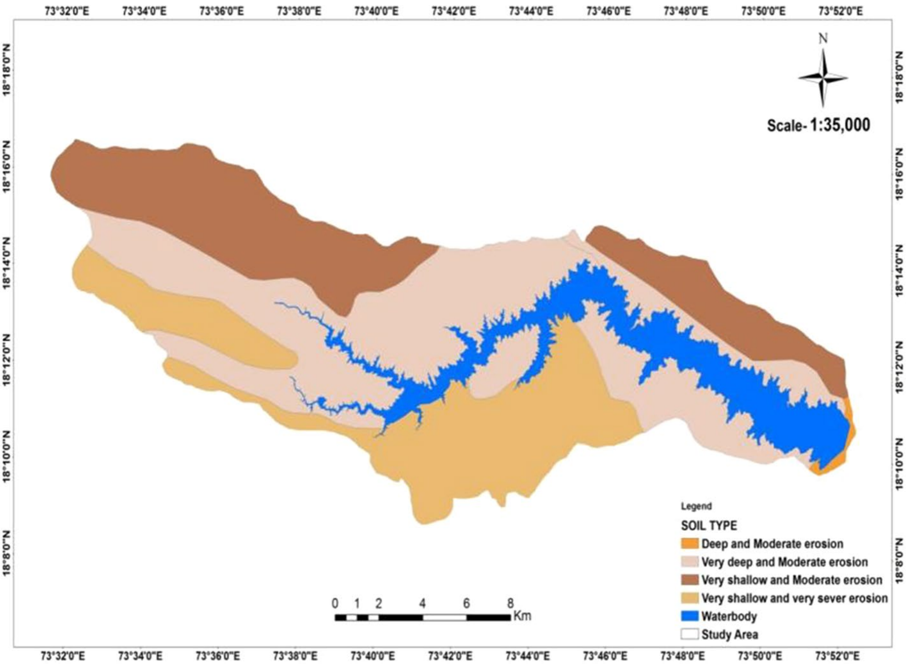

Fig. 17 Soil map

is high. The soil map obtained from NBSSLUP has been used to prepare the soil map of the study area. The area shows variety of soils, namely deep soil with moderate erosion, very deep soil with moderate erosion, very shallow soil with moderate erosion and very shallow soil with very severe erosion. Soil map of the study area is shown in Fig. 17.

4.10 Geology of study area

Geological survey of India mineral map of scale 1:50,000 was used for the preparation of geology map. The area was found to be highly disturbed and subjected to faulting. The study region consists of multiple layers of solidified fluid basalt and is more than 2000 m thick and formed between 60 and 68 million years ago during the Cretaceous period. The basaltic lava flow is estimated to be around 512,000 km^2.

The plateau after the catastrophic phase of faulting has remained relatively stable and has undergone a succession of cycles of erosion. The region has basaltic base on which there are alluvial deposits in river valleys on the terraces and an old flood plains. There is also one geomorphic lineament parallel to ridge. Fault lines are scattered throughout the study region, and these areas are minor earthquake prone. The map shows that the whole area is geologically made up of Basaltic lava flow with 50–350 m depth. Basalts generally consist of columns commonly hexagonal in shape that are separated by joints and fractures in the rock that formed when the rock contracted during cooling. In fact, these kinds of igneous rocks could be classified as high potential rock failures in nature specialty toppling ruptures. Basalts comparing other igneous rocks are more susceptible for weathering and largely composed of minerals with little resistance to decompose.

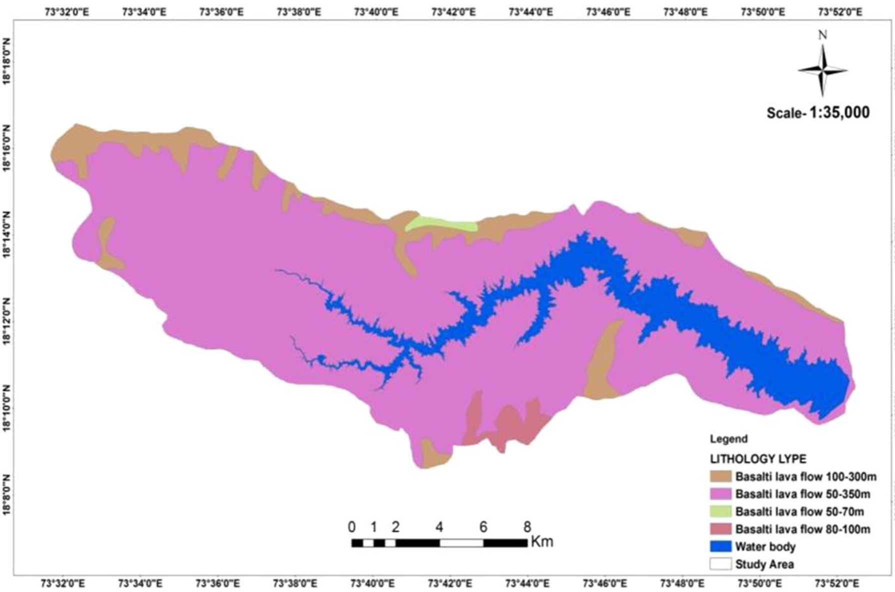

Fig. 18 Geology map

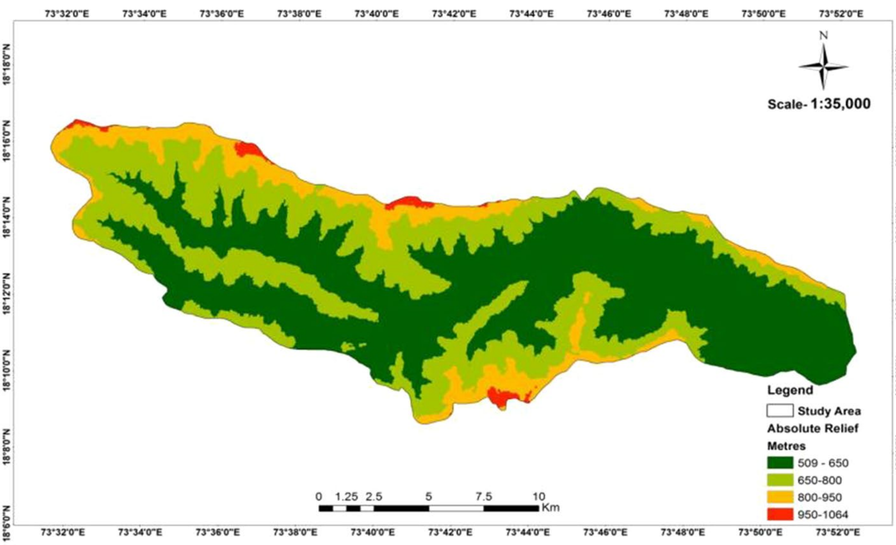

Fig. 19 Absolute relief map

Therefore, they tend to disintegrate faster than other igneous felsic rocks and the outcomes are highly expansive clay minerals. These two specifications of basaltic rock masses are the main factors of rock slope instability. The area mostly shows geomorphic lineaments parallel to drainage and structural lineaments, i.e., joint or fracture. Geology map is shown in Fig. 18.

4.11 Absolute relief map

The basic step to study the geomorphological features or morphometric study of any area is analysis of its relief feature. The change in earth surface or a part of it becomes focus of a geomorphic study of landforms. Absolute relief represents the highest area of any region. The analyses of absolute relief of a region may be done in two ways. Absolute relief map is shown in Fig. 19.

4.12 Relative relief map

Relief is the difference between the maximum and minimum elevations in an area, a measure of the ruggedness of the terrain. The landslide occurrences are directly related to the relief pattern in area. The difference in elevation between the highest and lowest contour within each grid sq.km is measured and plotted. It represents a measure of general steepness, though, not of local steepness. On the basis of relief, the region is divided into four zones ranging from 0 to 161 m above sea level. Relative relief map is shown in Fig. 20.

4.13 Lineament map

Lineaments representing the faults, fractures, shear zones, etc. are the most obvious structural interpretations on the satellite imaginary. Lineaments control the occurrence and movements of groundwater in hard rock terrain. They occur in parallel sets of different directions indicating different episodes of tectonic disturbances. Lineaments appear as

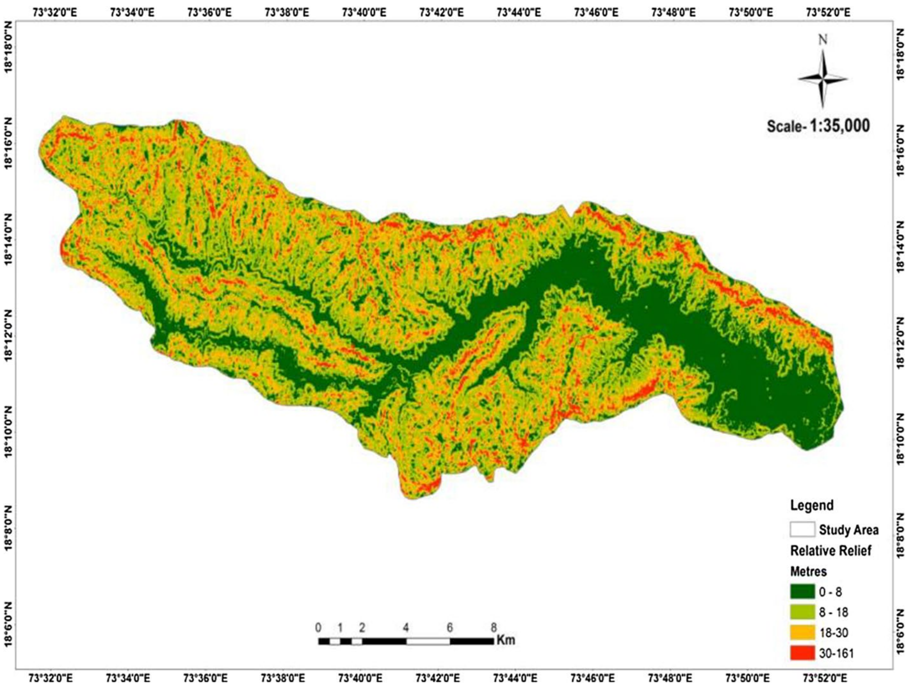

Fig. 20 Relative relief map

linear to curvilinear lines on the satellite and are often marked by the presence of moisture, alignment of vegetation, straight streams/river courses, alignment of tanks/ponds, etc. These lineaments can be further subdivided into faults, fractures, shear zones and thrusts based on the image characters and geological evidences.

The lineament map shows the formation of lineaments in the study area due to the geological conditions. Water flows through the cracks and the soil over this lineament may slide, and hence, this triggers the landslide. A lineament map was prepared by visual interpretation of the satellite data and district map of Geological Survey of India by identifying the fractures and fault lines. The map shows the two types of lineaments, i.e., drainage lineaments and ridge lineaments. With the help of lineament study, the hill trending can be known. In the given map, most of the ridge liniments are trending E–W, NE–SW and NW–SE. The drainage lineaments indicate the major fractures occurred in the area. To know the topographic settings, the lineament analysis is important. The lineament map is shown in Fig. 21.

4.14 Land-use–land-cover (LULC) map

Land cover indirectly indicates the susceptibility of slopes to mass movements. The different types of land-cover pattern present in the study area are shown in land-use–land-cover map. Barren and sparsely vegetated areas exhibit faster erosion and greater instabilities than forests. Vegetation cover is a main factor which influences the occurrence and movement of the rainfall which triggers the landslide. It is almost universally accepted that has a favorable effect on slope stability. The catchment area is characterized by the agriculture,

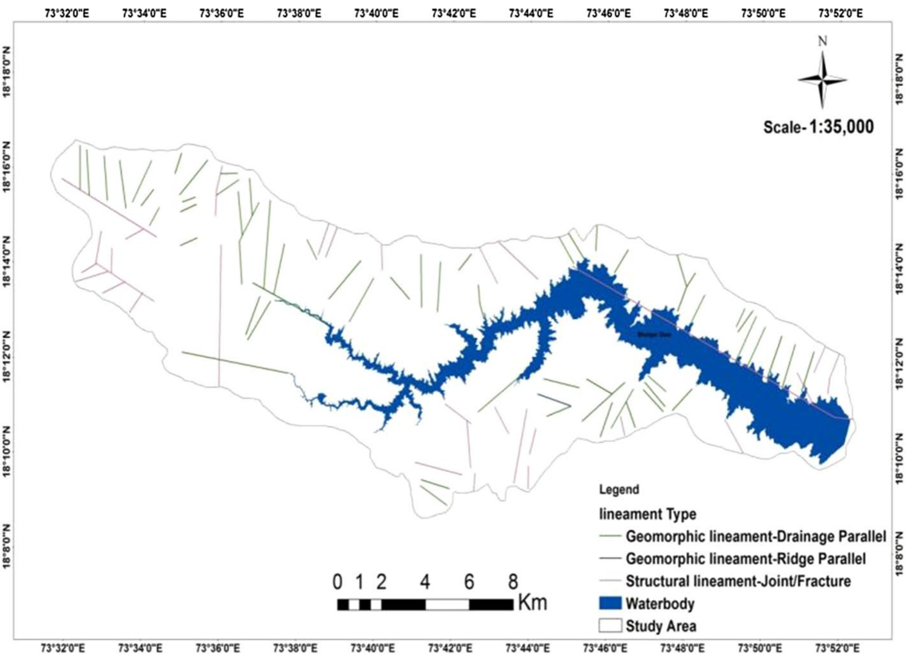

Fig. 21 Lineament map

scrub, settlement, forest and water bodies. Land-use and land-cover information is the most vital input for monitoring and assessing the changes taking place in basin due to climate changes to support the prediction of landslides. The area is divided into five major classes. The various land use and land cover could be identified by visual interpretation techniques.

For the interpretation of false color composite and preparation of user-friendly land-use and land-color, four different years FCCs are downloaded from www.bhuvan.org Web site. In this study, the land-use–land-cover map of the study area has been prepared by the digital classification of the imagery generated from the satellite data. FCC (false color composite) image has been generated from the satellite data using image processing software. The LULC map shows that 52.08% area is under vegetation cover, 16.80% area under agriculture, 11.33% area under reservoir and only 0.44% area under settlements. The land-use and land-cover map is shown in Fig. 22.

5 Results and discussion

The weights are assigned as given in Table 3. Landslide hazard zonation map was prepared for the Yelwandi river basin area. Geographic information system software was used for integrating different thematic maps. These thematic maps were quantified by giving them a relative weight. In this process the different thematic maps which carry the rasterization were used. The validation of each parameter was carried out with the existing landslide map, and finally, the weight for each class of them was assigned. The settlements were

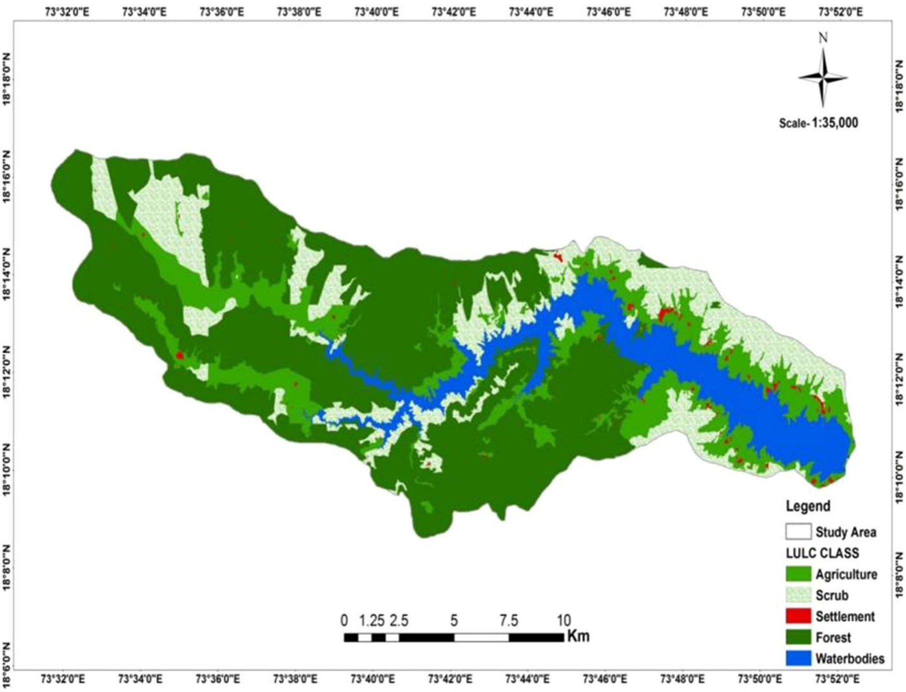

Fig. 22 Land-use–land-cover map

Table 3 Weight assigned

Sr. no.	Class name	Weight in (%)
1	Rainfall	10
2	Land use–land cover	12
3	Stream	20
4	Road	10
5	Slope	30
6	Relative relief	5
7	Geology	5
8	Soil	8
	Total %	100

classified into different categories considering different factors. Table 4 shows the landslide zone of settlements. The land zonation map is shown in Fig. 23.

6 Summary and conclusion

The Yelwandi river basin lies in Bhor and Velhe Taluka having area 275.178 m^2. The basin area is divided into four divisions depending upon the severity of landslide. The field observations were done to validate the results obtained. The properties of soil differ from location to location. The heavy and prolonged rain is the prominent factor to cause landslide in this area. The rainfall data show that in India rainfall mainly occurs in the months of June, July, August, September and October of every year. It was observed that the landslide took place during rainy season. The rainfall and landslide events are co-related. The rainfall and runoff plays an important role in the sliding of soil mass. The higher intensity of rainfall produces higher quantity of runoff. The water enters into cracks and joints of rocks and weakens that portion which causes landslide.

The 67 settlements were observed in the study area. By considering different factors, they can be categorized. Depending upon landslide potential, villages were classified as very low, low, medium or high prone to landslide. The landslide zone and its area in square kilometer are given in Table 5.

It is clear that the delination of the vulnerable zones will be more helpful for the sustaianble construction activities and implementation of protection measures to prevent landslides in the Ghat Section during rainy season. The efforts should be taken to stabilize road cutting to prevent the landslides.

- The number of villages occurring in high landslide-prone area is two.
- The number of villages occurring in medium landslide-prone area is 30.
- The number of villages occurring in low landslide-prone area is 33.
- The number of villages occurring in very low landslide-prone area is two.

The important aspects of landslides management are to prepare the hazard zonation map and to initiate the preparedness process in the hazardous areas. Landslide hazard zonation maps highlight the location of landslide and provide opportunity to take the proper precautions. The preparedness process includes:

Table 4 Landslide zone of settlement

Sr. no.	Taluka name	District name	Village name	Latitude	Longitude	Rainfall (in mm)	Landslide zone
1	Bhor	Pune	Dehen	18°10′23.535″N	73°42′51.895″E	1776	High
2	Velhe	Pune	Kusarbet	18°14′35.492″N	73°33′11.462″E	3128	High
3	Khandala	Satara	Bhatghar	18°9′54.602″N	73°51′22.464″E	1136	Medium
4	Bhor	Pune	Basarapur	18°10′13.915″N	73°50′8.504″E	1136	Medium
5	Bhor	Pune	Bare Kh.	18°10′18.581″N	73°49′27.913″E	1136	Medium
6	Bhor	Pune	Bare Bk.	18°10′42.230″N	73°49′11.686″E	1136	Medium
7	Bhor	Pune	Pangari	18°11′1.152″N	73°43′2.700″E	1776	Medium
8	Bhor	Pune	Jayatpad	18°11′2.162″N	73°44′8.376″E	1776	Medium
9	Bhor	Pune	Bope	18°11′16.845″N	73°38′0.141″E	2417	Medium
10	Bhor	Pune	Mhalavadi	18°11′27.740″N	73°48′37.075″E	1136	Medium
11	Bhor	Pune	Narhe	18°11′32.630″N	73°51′33.986″E	1136	Medium
12	Bhor	Pune	Nanavale	18°11′44.958″N	73°42′36.871″E	1776	Medium
13	Bhor	Pune	Karnvadi	18°11′47.291″N	73°48′14.876″E	1456	Medium
14	Bhor	Pune	Kumbale	18°11′47.537″N	73°37′59.847″E	2417	Medium
15	Bhor	Pune	Brahmanghar	18°11′49.315″N	73°50′52.120″E	1136	Medium
16	Bhor	Pune	Harnas	18°11′55.338″N	73°50′27.155″E	1136	Medium
17	Bhor	Pune	Bhandravali	18°12′1.945″N	73°41′36.357″E	2097	Medium
18	Bhor	Pune	Lavheri	18°12′5.069″N	73°49′41.951″E	1136	Medium
19	Bhor	Pune	Velvand	18°12′35.712″N	73°44′55.234″E	1776	Medium
20	Bhor	Pune	Vakambe	18°13′4.429″N	73°46′56.897″E	1456	Medium
21	Bhor	Pune	Gorad Mhashivali	18°13′9.111″N	73°47′54.586″E	1456	Medium
22	Velhe	Pune	Majgaon	18°13′14.764″N	73°36′15.858″E	2755	Medium
23	Bhor	Pune	Tale Mhashivali	18°13′19.804″N	73°47′46.435″E	1456	Medium
24	Bhor	Pune	Vadhane	18°13′26.979″N	73°46′38.379″E	1456	Medium
25	Velhe	Pune	Khopde Wadi	18°14′45.825″N	73°37′28.927″E	2417	Medium

Table 4 (continued)

Sr. no.	Taluka name	District name	Village name	Latitude	Longitude	Rainfall (in mm)	Landslide zone
26	Velhe	Pune	Harpud	18°15′44.882″N	73°32′49.425″E	3128	Medium
27	Velhe	Pune	Dhangarwadi	18°13′22.252″N	73°35′20.210″E	2755	Medium
28	Bhor	Pune	Dhangarwadi	18°11′23.655″N	73°39′0.400″E	2417	Medium
29	Bhor	Pune	Mhalak	18°9′24.801″N	73°41′21.526″E	2097	Medium
30	Bhor	Pune	Janerichamal	18°9′43.132″N	73°42′57.295″E	2097	Medium
31	Bhor	Pune	Nivganwadi	18°11′41.344″N	73°44′15.075″E	1776	Medium
32	Bhor	Pune	Pasure	18°12′2.459″N	73°46′51.546″E	1456	Medium
33	Bhor	Pune	Kondgaon	18°10′12.926″N	73°41′28.266″E	2097	Low
34	Bhor	Pune	Nandghur	18°10′48.385″N	73°44′24.918″E	1776	Low
35	Bhor	Pune	Taljainagar	18°11′11.250″N	73°45′50.377″E	1776	Low
36	Bhor	Pune	Pasure	18°11′36.948″N	73°46′17.143″E	1456	Low
37	Bhor	Pune	Dere	18°11′58.387″N	73°40′16.561″E	2097	Low
38	Velhe	Pune	Nigde Kh	18°12′6.401″N	73°36′33.984″E	2755	Low
39	Velhe	Pune	Kelad	18°12′22.401″N	73°34′58.873″E	2755	Low
40	Bhor	Pune	Majgaon	18°12′26.389″N	73°49′9.706″E	1136	Low
41	Bhor	Pune	Bhutonde	18°12′44.079″N	73°39′6.705″E	2417	Low
42	Bhor	Pune	Jogawadi	18°12′44.336″N	73°48′38.713″E	1136	Low
43	Bhor	Pune	Chandavane	18°13′4.161″N	73°37′49.999″E	2417	Low
44	Velhe	Pune	Pishawi	18°13′11.004″N	73°33′57.069″E	2755	Low
45	Bhor	Pune	Khulshi	18°13′13.341″N	73°38′57.733″E	2417	Low
46	Velhe	Pune	Bhordi	18°13′33.649″N	73°34′2.786″E	2755	Low
47	Bhor	Pune	Guhini	18°13′34.970″N	73°38′12.030″E	2417	Low
48	Bhor	Pune	Kambare Kh.	18°13′36.770″N	73°44′16.681″E	1776	Low
49	Velhe	Pune	Pasali	18°13′42.867″N	73°35′27.505″E	2755	Low
50	Velhe	Pune	Bhalvadi	18°13′56.897″N	73°37′18.905″E	2417	Low

Table 4 (continued)

Sr. no.	Taluka name	District name	Village name	Latitude	Longitude	Rainfall (in mm)	Landslide zone
51	Velhe	Pune	Shenavadi	18°13′57.795″N	73°36′36.215″E	2755	Low
52	Bhor	Pune	Karandi Bk.	18°14′1.178″N	73°46′12.109″E	1456	Low
53	Bhor	Pune	Kambare Bk.	18°14′5.808″N	73°44′48.326″E	1776	Low
54	Bhor	Pune	Male	18°14′7.991″N	73°41′4.849″E	2097	Low
55	Bhor	Pune	Karandi Kh.	18°14′16.800″N	73°45′29.583″E	1456	Low
56	Velhe	Pune	Varoti Kh.	18°14′30.439″N	73°34′35.987″E	2755	Low
57	Velhe	Pune	Kolambi	18°14′31.533″N	73°34′44.875″E	2755	Low
58	Velhe	Pune	Varoti Bk	18°14′52.471″N	73°34′1.467″E	2755	Low
59	Velhe	Pune	Barshicha Mal	18°15′12.341″N	73°36′41.618″E	2755	Low
60	Velhe	Pune	Jadhavwadi	18°15′36.354″N	73°35′37.424″E	2755	Low
61	Bhor	Pune	Kolwadi	18°10′10.886″N	73°43′55.201″E	1776	Low
62	Bhor	Pune	Ranjne	18°11′39.459″N	73°43′38.755″E	1776	Low
63	Bhor	Pune	Gaymal	18°12′37.366″N	73°44′4.795″E	1776	Low
64	Bhor	Pune	Kambre Kh	18°13′21.567″N	73°44′7.879″E	1776	Low
65	Bhor	Pune	Math	18°13′5.420″N	73°48′10.568″E	1456	Low
66	Bhor	Pune	Rajaghar	18°12′51.768″N	73°45′40.248″E	1456	Very low
67	Bhor	Pune	Kurunji	18°13′11.076″N	73°43′2.360″E	1776	Very low

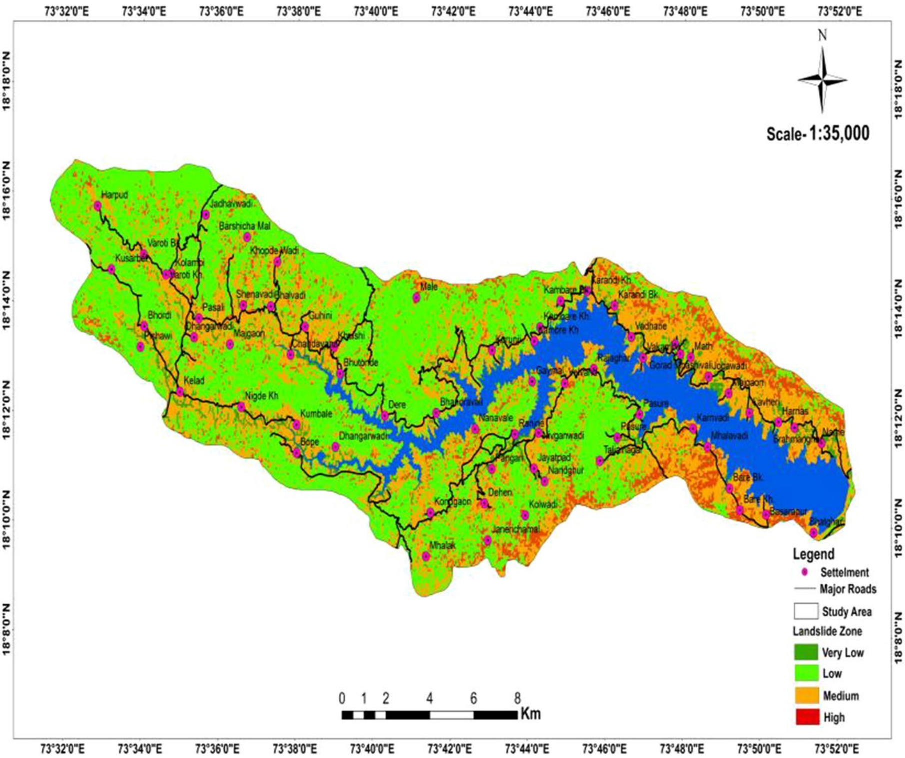

Fig. 23 Landslide zonation map

Table 5 Landslide zonation with area

Sr. no.	Land slide zone	Area in km^2	Percentage
1	High landslide-prone area	16.360	5.95
2	Medium landslide-prone area	97.379	35.37
3	Low landslide-prone area	125.501	45.62
4	Very low landslide-prone area	35.939	13.06
	Total	275.178	100.00

- To make the strategy to overcome the problem.
- To execute the plan carefully for controlling landslides or restraining them.
- To begin the network of warning system.
- To accomplish the appropriate awareness program involving people. Government, schools, colleges and non-government organizations.
- To make adequate medical facilities in the area.

The landslide hazard zonation maps of the Yelwandi river basin have provided valuable information about hazardous zones.

- The number of landslides occurred within the months June, July and August, while no landslide was reported in other months. These observations signified the importance of correlating the imitations of landslide occurrences in Yelwandi river basin area with rainfall infiltrations.
- The results of the present work may serve as a useful information and database for the planners, decision makers, geotechnical engineers and geologists for the planning of further construction activities.

References

Ansari MK, Ahmad M, Singh R, Singh TN (2014) Rockfall hazard rating system along SH-72: a case study of Poladpur–Mahabaleshwar road (Western India), Maharashtra, India. Geomat Nat Hazards Risk 7:649–666

Cruden DM (1991) A simple definition of a landslide. Bull Int As Eng Geol 43:27–29. https://doi.org/10.1007/bf02590167

Guzzetti F, Carrara A, Cardinali M, Reiehenbaeh P (1999) Landslide hazard evaluation a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology 31:181–216

Khamkar DJ, Mhaske SY (2018) Investigation of the mass movement in Varandha region, Western ghat of Maharashtra using geospatial technique. Int J Civ Eng Technol (IJCIET) 9(7):2011–2027

Khamkar DJ, Mhaske SY, Sabale PD (2018) Geotechnical and geological investigation of landslide in Western Ghat of Maharashtra, India. Int J Eng Technol 7(3.29):524–528

Mhaske S, Choudhury D (2010) GIS-based soil liquefaction susceptibility map of Mumbai city for earthquake events. J Appl Phys 70:216–225

Savoikar P, Choudhury D (2010) Effect of cohesion and fill amplification on seismic stability of municipal solid waste landfills using limit equilibrium. Waste Manag Res 28:1096–1113

Scheidegger AE (1994) Hazards: singularities in geomorphic systems. Geomorphology 10:19–25

Sharma VK (1996) A probabilistic approach of landslide zonation mapping in Garhwal Himalaya. In: Proceedings international symposium on landslides, Trondheim, 17–21, pp 381–386

Singh TN, Varma AK, Sarkar K (2010) Static and dynamic analysis of landslide. Geomat Nat Hazards Risk 1(4):323–338

Van Westen CJ, Van Asch TWJ, Soeters R (2006) Landslide hazard and risk zonation—Why it is still so difficult? Bull Eng Geol Environ 65:167–184

Varnes DJ (1984) Landslide hazard zonation: a review of principles and practice. Natural hazards. UNESCO, Paris, pp 1–63