ORIGINAL ARTICLE

Hydrometeorological Landslides on the Windward Side of Western Ghats – A Case Study of Kootickal, Kerala, India

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ABSTRACT

On the windward side of Western Ghats, the frequency of landslides has significantly increased in recent years. Kerala had catastrophic landslides and floods in 2018, 2019, 2020, and 2021, resulting in loss of lives and property. On October 2021, a cloudburst occurred in middle Kerala, causing multiple devastating landslides in districts of Kottayam and Idukki. The study focused on how the topographic, physical, geological, and anthropogenic factors in the windward slope of the Western Ghats influence the occurrence of landslides. The landslide susceptibility was analyzed using the frequency ratio method on the basis of recently occurred landslide locations in the Manimala river basin, with special reference to Kootikal. The impact of each factor was analyzed against the GPS coordinates of landslide locations to estimate the frequency ratio value. The findings revealed that the torrential rainfall experienced in Kerala and the anthropogenic activities, especially the watershed management work performed in the area, significantly increased landslide susceptibility of the basin. About 5% of Manimala river basin is highly susceptible to landslides, and this area comes under the Kootikal sub-basin. The study recommends a rigorous geophysical assessment on the influence of watershed management operations on a landslide and an EIA of roads in the Kootickal region.

1 Introduction

Western Ghats, the great escarpment of India, runs parallel to the western coast of the Indian peninsula in the direction of north to south along the western edge of the Deccan plateau, separating it from Konkan western coastal plain. It outstretches 1,500 km from the southward of Tapti River up to cape of Cameron (Kanyakumari) as a westward escarpment. The geological and geomorphological evidence implies that they are formed as a result of the breakup of Gondwana, the super continent, around 150 million years ago. After the breakup of Madagascar, the western coast has remained as an abrupt cliff of 1,100 m (3300 ft) (Soman, 2002). During the monsoon season, the western slope of the Western Ghats is highly susceptible to landslides (Kuriakose et al., 2009). The Western Ghats comprise of cretaceous basalts of Maharashtra, archean

hardware craton of Karnataka, and the granulitic fold belt of southern Kerala, and the feature witnessed different interludes of geological, geomorphological, and tectonic processes (Gunnell and Fleitout, 2001). The evolution of landforms has been triggered by the tropical condition under planation (Jayalakshmi et al., 2004). The landscape of Western Ghats is engraved by various geological and tectonic phenomena and the hydrologic action of streams.

Landslides are considered as one of the most devastating natural hazard causing thousands of causalities every year (Vijith and Madhu, 2008). Geologically, a landslide is defined as a gravity-driven movement of rock, debris, or soils as a result of fluvial or glacial erosion, and the spatial distribution of landslides is guided by various climatological, topographical, physical, and geological factors (Shafique et al., 2016). The northern and north-eastern mountainous regions of India including Eastern and Western Ghats are highly susceptible to landslides (Chandrasekaran et al., 2013). The Western Ghats experience a tropical climate, and it triggers chemical weathering and catastrophic landslides (Deepthy and Balakrishnan, 2005). In India, monsoon season rainfall accounts for over 80% of the country's yearly precipitation (Parthasarathy et al., 1994). Monsoon variability in timing, duration and intensity can affect the lives of people in India (Hunt and Fletcher, 2019). After 1924, Kerala experienced

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the worst mega flooding in 2018. The pernicious flood and coupled landslides had affected 5.4 million people and led to the death of 400 people (PDNA_Kerala, 2018). These floods are caused by a monsoon depression's passage, and generally, these depressions have an accountable impact on the monsoon rainfall in Kerala (Hunt and Fletcher, 2019).

In the high land of Kerala, the frequency of landslides has increased significantly in recent years (Jain et al., 2021). Kerala had cataclysmic landslides and floods in 2018, which caused the death of 500 people (Martha et al., 2019). In 2019, the Puthumala landslide caused the death of 81 people (Wadhawan et al., 2020), and 66 tea estate workers perished in the landslide that occurred in Pettimudi in 2020 (Achu et al., 2021). In 2021, the Kootickal and Kokkayar slides caused 18 deaths (Ajin et al., 2022; Sisira and Mohanan). Kerala has been affected by debris flow type landslides (Achu et al., 2021; Kuriakose et al., 2009). These flows are characterized by hasty movement and lengthy run-out distances in mountainous areas abruptly, along the slope (Huggett, 2011). The revitalization of already cropped up landslides is becoming a great threat (Thennavan and Pattukandan Ganapathy, 2020) and the revitalization takes place when the open crack becomes exposed to rainfall (Luo et al., 2020). The present study discusses the factors affecting landslide susceptibility of the Manimala River basin, with special reference to Kootickal village in Kerala.

2 Study area

Kootikal is a town at the base of Western Ghats Mountain ranges, situated on the eastern edge of Kerala's Kottayam District, at 610 m (2,000 feet) above mean sea level (MSL). The region is situated in the Manimala River basin, which spans the latitude range of 9° 21' to 9° 40' N and the longitude range of 76° 33' to 76° 58' E (Fig. 1). It is one of the 4 major rivers which does not have a direct outlet to sea, as these rivers (Pamba, Manimala, Meenachil, Achankovil) empty into the vast Vembanadu Lake. It originates from Kolahalamedu of Mothavara hills of the Western Ghats at a height of about 1,257 m from MSL. The Manimala River basin is composed of three zones geologically. The western coastal zone consists of recent sand and silt, the middle zone consists of residual laterite formed by the decomposition of Archean crystalline rocks, while the eastern zone consists of charnockite rocks of the Archean group. Physiographically, the river basin can be broadly classified into three distinct natural physiographic zones, viz; the lowland, the midland and the highland. The highlands are mostly reserved and protected forest with patches of tea, cardamom, coffee estates. The migrant settlers and lumberers looking for better fortunes had cleared most of the natural forest cover of the foot hills, and the land cover changed into cassava and other hill crops with coconut palm, which was later replaced by rubber (*Hevea Brasiliensis*) plantations. Cassava cultivation is well known to accelerate soil erosion (Putthacharoen et al., 1998). The land use practices are thought to be a catalyst for slope failures in the hill rangers of the region (GoI, 1956).
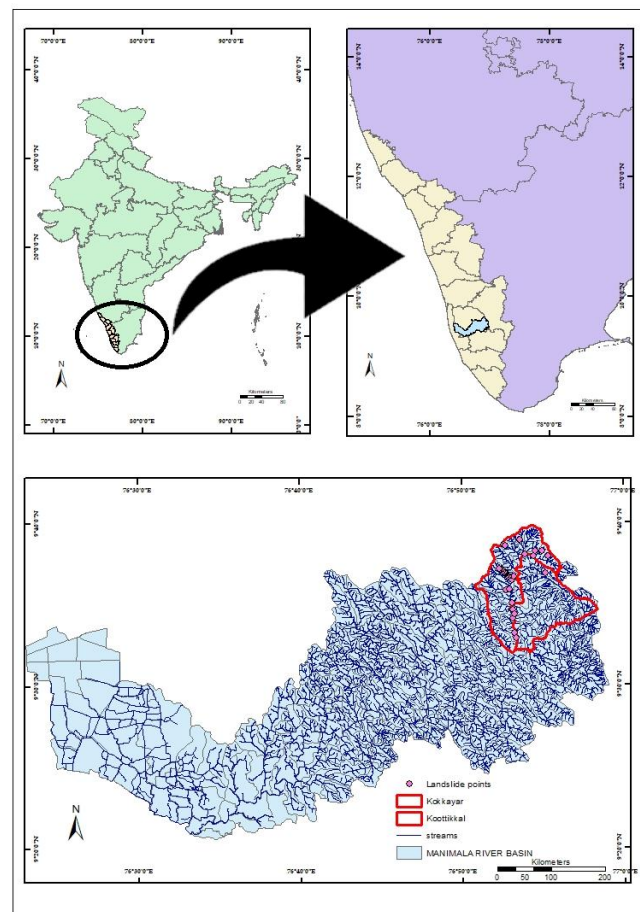

Fig. 1: Study area; Manimala river basin Kerala.

3 Materials and Methods

Landslide susceptibility assessment methods are classified into three categories: quantitative physically based approaches, quantitative data-driven methods and qualitative data driven methods (Corominas et al., 2014). Physically based methods forecast landslide susceptibility by analysing the mechanism and processes that control the initiation failure of landslides. Data driven methods focus on geo-environmental parameters of landslide prone areas. In knowledge driven approaches, landslide susceptibility is assessed by evaluating and weighting various landslide related criteria. Data driven methods are widely used for the analysis and they include bivariate method (Korup and Stolle, 2014) and have higher accuracy than other methods (Chen et al., 2016; Pradhan, 2010; Ramesh and Anbazhagan, 2015). Frequency ratio is a simple data driven quantitative method with clarified principles. The understandability of input, calculation and out procedures make frequency ratio more admissible for landslide susceptibility assessment (Lee and Pradhan, 2007).

3.1 Landslide susceptibility assessment and validation

The current study used a field survey to collect palaeoslide sites, and 52 landslide points were collected for analysis. From previous studies and field observations, the major

landslide inducing factors were selected. The extant landslide distribution data layer was compared with landslide inducive factors to compute the impact of each component on landslide susceptibility. The methodology adopted in the study is shown in Fig. 2. In order to generate weighted thematic maps, the frequency ratios of each factor class were calculated.

Frequency ratio is calculated by

$$FR = \frac{landslide\ occurence\ percentage}{area\ occurence\ percentage} = \frac{\frac{Npix(Si)}{\Sigma Npix(Si)}}{\frac{Npix(Ni)}{\Sigma Npix(Ni)}}$$

where Npix (Si) is the number of cells with landslides in factor class i.

Σ Npix (Si) is the total number of cells with landslides is the total number of cells (i.e., with and without landslides) in factor class i

Npix (Ni) is the total number of cells (i.e., with and without landslides) in factor class i

Σ Npix (Ni) is the total number of cells (i.e., with and without landslides).

The spatial analyst extension in ArcGIS was used to integrate all of the components. The landslide susceptibility index was calculated by evaluating the landslide inducing factors.

$$LSI = GMFR + LIFR + LDFR + SDFR + ASFR + DSFR \\ + SAFR + CRFR + BDFR + NDVIFR \\ + SMFR + PNFR + STFR + SDFR \\ + DQFR + DRFR + WSFR$$

Here,

$GMFR\ =\ frequency\ ratio\ of\ geomorphology$:

$LIFR\ =\ frequency\ ratio\ of\ lithology$:

$LDFR\ =\ frequency\ ratio\ of\ lineament\ density$:

$SDFR\ =\ frequency\ ratio\ of\ stream\ density$:

$DSFR\ =\ frequency\ ratio\ of\ distance\ to\ streams$:

$SAFR\ =\ frequency\ ratio\ of\ slope\ angle$:

$ASFR\ =\ frequency\ ratio\ of\ aspect$:

$CRFR\ =\ frequency\ ratio\ of\ the\ curvature$:

$BDFR\ =\ frequency\ ratio\ of\ the\ building\ density$:

$NDVIFR\ =\ frequency\ ratio\ of\ NDVI$:

$SMFR\ =\ frequency\ ratio\ of\ soil\ moisture$:

$PNFR\ =\ frequency\ ratio\ of\ precipitation$:

$STFR\ =\ frequency\ ratio\ of\ soil\ texture$:

$SDFR\ =\ frequency\ ratio\ of\ soil\ depth$:

$DQFR\ =\ frequency\ ratio\ of\ distance\ to\ quarry$:

$DRFR\ =\ frequency\ ratio\ of\ distance\ to\ the\ road$.

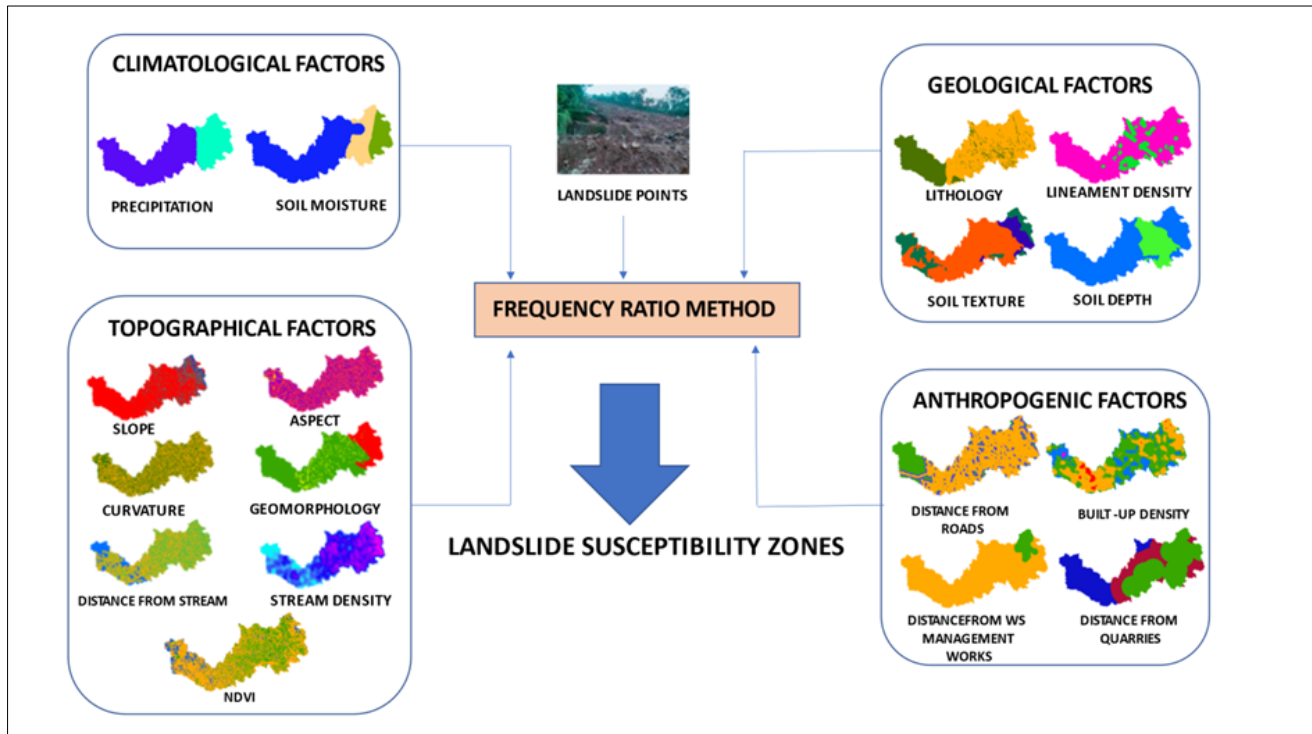$WSFR \\ =\ frequency\ ratio\ of\ watershed\ management\ works$

Fig. 2: Methodology adopted for the study.

4   Results and Discussion

Landslides are influenced by four types of factors: topographical factors, geological factors, climatological factors, and anthropogenic factors.

4.1   Topographical factors

4.1.1   Slope

The frequency and severity of landslides are determined by the slope's stability and instability. Slope degree is the primary parameter for assessing landslide susceptibility because it is directly related to slope stability (Ercanoglu and Gokceoglu, 2002). In this study, the frequency ratio is below 1 for slope angles less than 17^0, which indicates a lower chance of landslide in those locations. For slope angles greater than 17°, the frequency ratio is greater than 1, falling into a zone with high chances of landslide. Very high probability of landslide is found in the region of slope angle greater than 17^0 where the frequency is greater than 3. The majority of mass movements along the Western Ghats scraps have occurred in hill slopes >20^0 (Kuriakose et al., 2008).

4.1.2   Aspect

Slope aspect determines the compass direction of slope face. Regions can be divided into nine groups based on the slope aspect. Aspects show the slope face direction, where the north and south facings of the topography are more and less vulnerable to landslides, respectively, while the remaining facings (the North-East, North-West, West, East, South-East, and South-West) are moderately vulnerable to landslides (Pourghasemi et al., 2012). Aspect describes the implicit parameters such as wind directions, sunlight exposure, and rainfall, all of which contribute to the occurrence of landslides (Pascale et al., 2013). Aspects such as North, North-East and South-West are found as landslide probability zones in the area where frequency ratio is higher than one.

4.1.3   Distance to stream

A slope's stability is governed by saturation of the material that the slope is built from. Hence, the adjacency of the slope to drainage structures and rivers cause the erosion of the lowermost part and eventually the slope becomes weaker (Yalcin et al., 2011). In this case also, most of the landslides occurred within 100m from the streams and the frequency of landslides reduces as they move away from streams.

4.1.4   Stream density

Streams are the major sculptor of the earth surface as they play an unpropitious role in slope stability by undercutting them due to toe erosion and saturating the sliding toe, as a result of an increase in water infiltration (Gorum et al., 2011). Drainage density is defined as the total length of drainage per unit area. In this study, stream density in the landslide prone area varies between 3 and 4.

4.1.5   Curvature

The rate of change of slope gradient or aspect, usually in a distinct direction, is defined as curvature (Wilson and Gallant, 2000), It is broken down into two categories: concave (+1<) and convex (-1<). Profile curvature influences the acceleration and deceleration of downslope flows, as a result of erosional and depositional work that causes a landslide. Hence, the parameter is one of the influencing factors in the occurrence of landslides (Nefeslioglu et al., 2008). In this study, all landslides are observed in the convex or concave area, while none is observed in the flat surface.

4.1.6   NDVI

Normalized difference vegetation index (NDVI) is a major factor that determines landslides, as it accounts the quantity and intensity of vegetation. NDVI values vary between -1.0 and 1.0. The negative values represent cloud, water and snow, while a value near zero can be found for the exposed rock, barren land, and sand. Moderate NDVI values represent shrub and grassland while high values denote the dense forest. In the case of NDVI, higher number of landslides is found in the areas where NDVI varies between 0 and 0.3. The Maximum number of landslides is found in the classes between 0-0.2, which indicates an exposed rock area.

4.1.7   Geomorphology

The correlation of geomorphology and landslide occurrence indicates that the frequency ratio is greater than one only for denudational hills which cover a major area in the foothills of the Western Ghats. Similar observations were made by Vijith and Madhu (2008) from the Western Ghats of Kerala with greater chances of landslide occurrences in denudational hills. These hills are formed as a result of the peneplanation process, which brings down large mountain masses to a sequence of scattered knobs on the peneplain (Thornbury, 1957). This feature's preservation is due to its rigidity to denudation, hence whenever an immediate cause occurs, these areas becomes highly susceptible to landslides.

4.2   Geological factors

4.2.1   Lithology

Lithological features have a strong impact on the physical properties of the surface and subsurface material, such as strength and permeability, and thus influence the chances of land sliding (Kamp et al., 2008). In the study area, charnockite terrain shows the highest frequency of landslides.

4.2.2   Lineament density

Spatial distribution and nature of lineaments affects the underlying rock strength and the tendency to failure. The lineament density was calculated and the area with lineament density less than 0.3 promotes landslide susceptibility. From the field studies, it was observed that a

weathered lineament was present near the head of the slide.

4.2.3 Soil texture

Soil, the loose unconsolidated and weathered material, has a significant role in triggering landslides (Sajinkumar and Rani, 2015). The major texture types observed in the area are gravelly clay, clay loam, gravelly loam and sandy. Among these, gravelly loam is highly susceptible to landslides.

4.2.4 Soil depth

Kerala's hill terrain is distinguished by a narrow stretch of unconsolidated soil resting above massive Precambrian crystalline rock (Sajinkumar and Anbazhagan, 2015). The contact plane of these two units becomes the slide plane (Istiyantii et al., 2021), hence soil depth plays a great impact in landslides. All landslide points were located at very high soil depths in the study area.

4.3 Climatological factors

4.3.1 Rainfall

Rainfall is the most prevalent trigger of any landslide event (Sajinkumar et al., 2011). Torrential rainfall and flood-like scenarios cause the slopes to get saturated and in turn cause an increase in pore water pressure, resulting in landslides (Sati 2014). In the high-risk zone of the study area, the annual rainfall average exceeds 2,600 mm. But the torrential rainfall (266 mm) in October 16 2021 (observed from Hyetograph of October 2021, observed from the Kanjirapally rain gauge, which is the nearest station in the study area) led to the saturation of the soil column and triggered a landslide.
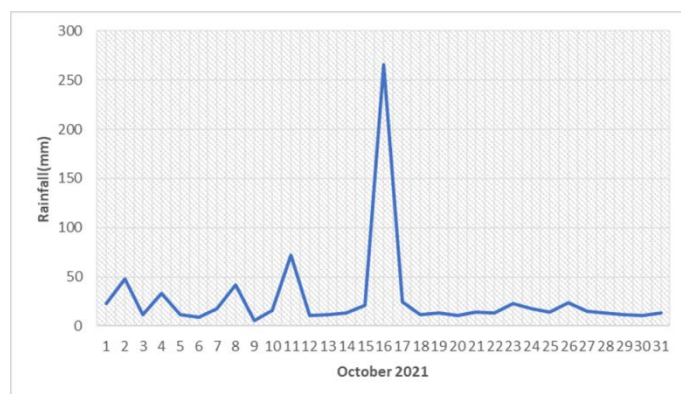

Fig. 3: Hyetograph of October 2021, observed from the Kanjieapally rain gauge, the nearest station with a rain gauge in the study area.

4.3.2 Soil moisture

Precipitation plays a critical role in controlling the soil moisture content of an area. As the precipitation increases, the soil moisture content also increases. In this study, the annual soil moisture is low but when the torrential rainfall occurred, the pore water pressure increased and

subsequently the soil moisture increased. The slope becomes unstable due to the increase in soil moisture.

4.4 Anthropogenic activities

4.4.1 Built up density

The frequency of landslides and built up density are directly related. Changes in land use land cover have affected landslide susceptibility of the area. Transformation of rural and woodland into urban areas, increase in building density and decrease in slope for the infrastructure development are becoming major causes of landslides (Biswas et al., 2021).

4.4.2 Distance to road

In hilly regions, the construction of infrastructures such as railway and roads result in slope destabilization, and subsequently land sliding (Shafique et al., 2016). In this region, the landslide susceptibility is quite high within a 500 m distance from the road network, and it decreases away from the road network.

4.4.3 Distance to quarry

The landslide points are within 5 km from the quarry locations. The blasting and crushing will cause ground vibrations in and around the quarry and crusher site, the effects of which will be determined by the intensity and magnitude of the blast and the resulting vibration. Clearance of vegetation, removal of top soil, drilling, blasting, gathering of rock pieces, selective size reduction at quarry site, transfer of rock pieces to crusher, crushing, transportation of final products, debris dumping, and operation of generators and heavy machinery in quarry area may result in terrain instability (Kuriakose et al., 2008).

4.4.4 Distance to WS management works

Field observations revealed that watershed management works has a great impact in landslide susceptibility. In the vulnerable slope, numerous rain pits were made (with the genuine concern of collecting rainwater and thus supplementing groundwater, which is often used for irrigation). As per the construction rules of interconnected surface drains, every effort must be made to ensure that the surface water on a slope is swept away from the slope (Holtz and Schuster, 1996). From this study, it is observed that most of the landslides are within 1,500m from the watershed management sites.

4.4.5 Landslide susceptibility zonation

Landslide susceptibility was estimated by assuming that future landslides are possible to predict based on past landslides. Frequency ratio values of considered factors indicate that a slope angle greater than 17° facing N, NW denudational structural hills of charnockite terrain with moderate NDVI and stream density are landslide prone. Anthropogenic activities contribute to landslide to a great extent. Increased built up density, unscientific construction of roads and watershed management activities in unstable

slope are the major triggering factors. Landslide susceptibility map (Fig. 4) indicates that about 5% of the total area was considered as very high susceptible zone which covers about 49 km² of the total area , while 4% (47km²) is considered as high susceptible zone. LSI is moderate for 28% of the study area (303 km²) and low for 63% of the total study area (667km²).
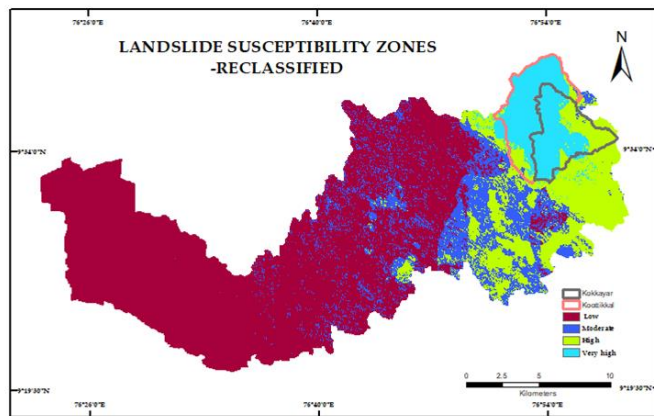

Fig. 4: Landslide susceptibility.

4.5   Validation of obtained susceptibility map

The validation of obtained landslide susceptibility zones was done with the acquired landslide points using cumulative frequency diagram (Fig .5). Results of validation show that 10% of the area has 90% landslides and 25% of the area has 98% landslides. The very highly susceptible area is only 5% of the total Manimala river basin, but these areas consist of 90% of Kootickal Panchayath, hence the area becomes highly susceptible to landslides.
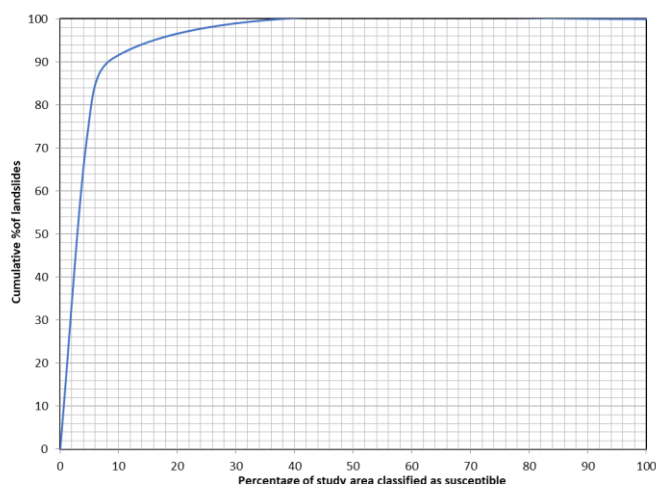

Fig. 5: Cumulative frequency diagram.

5   Conclusion

The torrential rainfall and unscientific watershed management works have become an immediate cause of landslides. Hence a detailed study of influence of watershed management activities on landslide by geophysical methods is recommended. Addionally, an Environmental Impact Assessment (EIA) of the roads and watershed management works is also recommended. Further watershed management works must be done after studying the vulnerability of slope. A liable slope as in Kootickal is least suitable for rain pits because these will promote infiltration and will lead to increases in pore water pressure. Landslide hazard zonation deserves critical importance in civil protection and urban planning. The obtained results can be used for disaster management through a cost benefit basis

Author Contributions

Conceptualization, formal analysis, methodology, visualization, writing-original draft – A.S.A., investigation, supervision, validation, writing-review and editing – A.V., data curation, formal analysis – S.P., supervision – B.K.R. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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