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# Landslide Zonation Mapping and Vulnerability Assessment of Satara and Raigad District

# Mapeamento de zonas de deslizamentos e avaliação de vulnerabilidade do distrito de Satara e Raigad

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**Abstract**

Geographic information (GIS) systems are the influential tools which facilitate the retrieval, collection, analysis, storage and the exhibition of spatial evidence. Remote sensing (RS) is generally defined as the procedure for acquiring evidence on the surface of the earth deprived of corporeal interaction to analyse the vulnerability of the landlside. Analytical Hierarchy (AHP) Process is executed for the analysis. GIS and RS has modernized the regulating measures of the regular hazards. In this contemporary research, Landslide Zonation Mapping and Vulnerability Assessment of the Satara and Raigad District is briefed. The research has investigated Latitude, longitude, soil, texture and the categories of landslides on the study region of Patan and Mahad. Also, the site visit was completed, sample of the soil was collected, DEM were reclassified, digital elevation (DEM) model formation executed, vulnerable susceptibility zones are pin pointed and finally the model is prepared. Rainfall analysis is executed since most of the landslides are caused because of the rainfall. Slope, aspect, flow direction of the study area, and finally the land use and land cover (LULC) mapping are conducted. Based on the research it is concluded that vulnerability of the locations is medium or high. Region with intermediate slopes, decreased rainfall, forest cover on the opposite side it is named as the least vulnerable regions of Patan. In Mahad, 059 % of the region is in higher risk, whereas the 49.336% is in the intermediate risk, then 41.462% is in minimum risk and 9% comes under the category of no risk.

**Keywords:**
Vulnerability, Mapping, Risk, landslide, susceptibility zones.

**Resumo**

Os sistemas de informação geográfica (SIG) são as ferramentas influentes que facilitam a recuperação, recolha, análise, armazenamento e exibição de provas espaciais. O sensoriamento remoto (RS) é geralmente definido como o procedimento de aquisição de provas na superfície da terra privada de interação corporal para analisar a vulnerabilidade do lado terrestre. O processo de

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hierarquia analítica (AHP) é executado para a análise. O SIG e o RS modernizaram as medidas reguladoras dos perigos regulares. Nesta pesquisa contemporânea, é resumido o Mapeamento das Zonas de Deslizamentos e a Avaliação da Vulnerabilidade do Distrito de Satara e Raigad. A investigação investigou a latitude, a longitude, o solo, a textura e as categorias de deslizamentos na região de estudo de Patan e Mahad. Além disso, a visita ao local foi concluída, foram recolhidas amostras de solo, o MDE foi reclassificado, a formação do modelo digital de elevação (DEM) foi executada, as zonas de suscetibilidade vulneráveis foram apontadas e, por fim, o modelo foi preparado. A análise da precipitação é executada porque a maioria dos deslizamentos de terras é provocada pelas chuvas. São realizados o declive, o aspeto, a direção do fluxo da área de estudo e, por fim, o mapeamento do uso e cobertura do solo (LULC). Com base na pesquisa conclui-se que a vulnerabilidade das localidades é média ou elevada. Região com declives intermédios, diminuição das chuvas, cobertura florestal no lado oposto é apontada como a região menos vulnerável de Patan. Em Mahad, 0,59% da região está em risco mais elevado, enquanto 49,336% está em risco intermédio, 41,462% está em risco mínimo e 9% está na categoria de nenhum risco.

**Palavras-chave:**
Vulnerabilidade, mapeamento de risco, deslizamento, zonas de susceptibilidade.

## I. Introdução

Landslide is considered as the outcome of huge diversity of the geo-environmental developments, that involves meteorological, ecological and the human activities. Most significant characteristic factors are bedrock geology (degree of weathering, lithology, and structure), geomorphology (relative relief, slope gradient, and aspect), soil (structure, depth, porosity and permeability), usage of land in addition to that the conditions of hydrology. Landslides occurred through multiple external causing factors like flash-floods, rainfall (SHAH; SATHE; BHAGAWATI; MOHITE, 2021), cloudburst, earthquake and drilling (ANBALAGAN; KUMAR; LAKSHMANAN; PARIDA; NEETHU, 2015). Due to a wide range of diverse forms, landslides in India have the potential to inflict substantial harm, including the loss of life and property. The Geological Survey of India estimates that around 65,000 communities in hilly or mountainous areas are vulnerable to landslides (GSI) (KUMAR; KUMAR; SINGH; ASHWANI; KUMAR, 2022). Nearly 12.6% of India's land area, according to the GSI, is in danger. Landslides damage the North-Western Himalayas, the sub-Himalayan topography of the North-East, the Western and Eastern Ghats, as well as 22 states and 2 union territories (GAWALI et al., 2017). Most landslides are caused by heavy rainfall. Landslides have become more frequent in India as a result of anthropogenic activities like climate change, which has resulted in major losses of human life, livestock, and property as well as harm to communication lines, human settlements, agricultural areas, and forest lands. Practically all of India's states often experience landslides, a serious geologic concern (KUMAR et al., 2022). Cities, towns, and counties must be aware of the nature of their possible exposure to landslide risks as people move into new areas with hilly or

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mountainous terrain in order to plan land use, new construction, and infrastructure that will minimize the costs of living with landslides (KHAN, 2001). Geology research, superior engineering methods, and effective enforcement of land-use management rules can reduce the danger of landslides, even if many of their physical causes cannot be avoided (BELL; GLADE, 2004). It is essential to understand the science underlying landslides, including their causes, movement characteristics, soil properties, associated geology, and potential sites (KUMAR et al., 2022).

Analysis of vulnerability and hazard in the susceptibility of landslide region is the significant task for corporeal and the usage of land in specific, predominantly with the regards towards taking the resolution for the novel enhancement and the preventive measures (SHARMA; PATEL; GHOSE; DEBNATH, 2014). Losses caused through landslides can be decreased, the hazard has to be recognized first besides the difficulties or danger has to be evaluated suitably. Regions with a possible prone is having few probability of a potentially deteriorating landslide which happens among the area, in addition to that vulnerability is the prospective towards experiencing the negative influence on the native inhabitants, possessions, financial activities and the amenities of public etc. (EIDSVIG et al., 2011). Finding the size as well as the threat of landslide requires recognizing those regions that could be covered through evaluating the landslide probability (ZHANG; SLOAN; OÑATE, 2018). Using geo-informatics and a unique analytical modelling tool, a critical examination of the vulnerability and impact of projected landslides on the socio-economic development of Satara and Raigad district has been conducted. Two of the major landslide-prone regions in SAARC (South Asian Association of Regional Cooperation) countries lie in India viz. Himalayan region and Western Ghats (NDMA, 2009). Kolhapur region belongs to the list of districts where among all natural hazards the landslide activity brings the highest annual rate of economic losses and death toll (SINGH; PAL; KANUNGO; PAREEK, 2017). Unfortunately, the number of losses caused by landslides is often underestimated firstly because many times landslides are considered as a secondary disaster. Landslides can be categorized as toppling, sliding, falling, spreading, or flowing ones depending on the kind of movement of Rock, soil, or mixes of rock and soil can rapidly tumble to the ground as a result of human weathering or vibration as well as natural processes like gravity (KHAN; RAHMAN; SHAW, 2022). The dislodged debris will roll down the hill, bouncing and rolling, until the energy is contained. When a rock or piece of dirt is pushed forward and the forward mass ads up to axis zero, where gravity acts, linear acceleration happens. This occurrence is brought on by vibrations, weathering, and stream erosion.

A rise in water level brought on by the saturation of earth material causes the erosion of the base slope (rock or soil) (WANG et al., 2014). It may be brought on by other things besides earthquakes (KUMAR et al.,

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2022). The liquefaction of softer materials over level or gently sloping terrain can lead to the spread of coherent material across incoherent material. When a material is sufficiently saturable, it transforms from a solid to a liquid. The material above it might potentially break or fracture laterally, causing subsidence to spread across a wide region. The mechanism reacts to shaking, whether brought on by natural or artificial tremors.

To identify the study problem, landslides are recognized as the utmost catastrophic natural hazards worldwide. The entire region of the land that is susceptibility towards landslides is roughly around 3.7 million square kilometers globally, which is having the inhabitants of around three hundred million which is recognized as the five percentage of the global population. Merely 820,000 km² are comparatively categorized as vulnerable region which are occupied with a population of around sixty-six million (ABDULWAHID; PRADHAN, 2017). Landslide can induce huge harmful effects on the economic, environmental and social aspects of the country and its population specifically for the progressing countries, where the mitigation procedures and the initial warning strategy are considered to be minimal (SHARMA et al., 2014). Countries nearby the temporal zones and the equatorial regions are much vulnerable (ANDERSON; HOLCOMBE; HOLM-NIELSEN; DELLA MONICA, 2014). The regularity of the incidences has augmented substantially in the preceding years because of the varying configuration of weather, geographical deprivation, and huge growth in the population of humans, unexpected growth in infrastructure growth on the region of higher altitude (MICHAEL; SAMANTA, 2016). Individuals affected through the landslides have the long as well as the short-term impact in the emotive welfare because of the loss in livestock, family, crops and property. Landslides have a huge deteriorating effect on health of the humans and the essential amenities like electricity, communication lines and water (KUMAR et al., 2022).

Landslides will cause financial, social and the ecological damage. Resources of the agriculture and forest are found to be lost; substructures and the sites of heritage are demolished. Rivers can be blocked, downstream sedimentation can be increased besides the probability of the risk of floods are the significant factors in affecting the landslides. Hence, in order to prevent the landslides, research has to be conducted. Thus, we rise the research objectives: Assess the vulnerability of the geographical regions which are at risk from landslides in the reference of Satara and Raigad District; Determine the at mospheric, global climatic change factors and the hazardous mapping regions of Satara and Raigad District; Evaluate the impact of the rainfall and soil's viscosity in Satara and Raigad District; Evaluate the factors of landslides that is associated with topographical, land-cover transformation, hydrogeological in the specified regions.

Evaluation of hazard in landslide delivers apparent expertise on the forthcoming failures in slopes for the entire stakeholders involved in determining the usage of land as well as the management in disaster.

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Minimum, 90% of the losses in landslide could be evaded if the difficulties were recognized prior the event; henceforth, there is a requirement for the landslide hazard evaluation at several spatial scales (GEBRU; GEBREYOHANNES; HAGOS, 2020). Besides with the vulnerability assessment and threat because of the landslides, socio-economic damages of the specific area has to be determined since few losses are noticeable and few are not noticeable, in addition to that results are demonstrated after the assured period.

## II. Literature Review

The conventional study (SINGH et al., 2016) had examined the investigation of the field also the numerical analysis of the landslide, which affects the Malin rural community of the Pune constituency in Maharashtra, India. The rural community of Malin was destroyed because of the landslide happened on 30th of July, 2014; anyhow, merely a primary school and some houses were safe while the time of event, and huge people were buried in wreckage of slide. To investigate the main reason for the occurrence of the event, field research was executed. Illustrative models of geomaterials that are formed through slope was gathered from three sites of the hill. L1 (bottom region), L2 (middle region), L3 (top region) alongside the vesicular and massive basalt towards the purpose of the geotechnical characteristics in the research laboratory. The predicted geotechnical properties was utilized for the numerical sampling in the regards to the slope of the hill which was executed to examine the extreme displacement, direction of displacement, factor of safety and the accrued extreme shear strain along with the assistance of the arithmetic programs on the basis of the technique of limit equilibrium besides the approach of finite element method, correspondingly. This research depicts that the slope of the hill was not really stable in FOS and susceptibility towards the failure. It was induced through several human activities also the usual factors such as heavy rainfall, unscientific building activities at the topmost of the mountain and nearby the hill, cultivations that are unplanned and the absence of drainage strategy. Finally, the outcome of the arithmetical analysis could have been effectively employed towards minimizing the frequency and influence of the landslide in the region of comparable morphology.

The prior study (PATIL; GOPALE, 2018) had investigated the landslide incidence on the mountain areas in the rural community of Malin. The external and the descending movements of the combined besides the unconsolidated soils in addition to the rock particles from any geomorphic characteristics because of the common catastrophe or the cause of the human activity were named as landslide. Displacement or else the transposition happens under the impact of the gravitational force's existence of the water significantly assists the occurrence since it is making the soils as well as rocks much weaker and moveable. Landslide happens when

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the portion of the general slope was not able to maintain their individual weight because of the general or anthropogenic causes. Landslide occurred in the rural community of the Malin. The research area was found to be vertical towards 850 slope in few spots also the left over slopes were existing with the lowest magnitude of 450 slopes that is also the main reason for the landslide in the period of rainfall. This investigation was written on environmental research of the landslide incident in the areas of hilly region. The landslide happens multiple times because of the natural and human activities. The research had examined the soil test outcomes and determined the variation in rainfall in the preceding 5 years in the period of monsoon.

The prevailing study (KHAMKAR; MHASKE, 2019) had made an attempt in the direction of developing the landslide procedure through utilizing the geographical (GIS) information scheme as well as the procedures of remote sensing towards the susceptibility of landslide mapping. Landslides has been considered as the dangerous geological progress that would cause huge impairment towards the infrastructures also the human loss (BANUZAKI; AYU, 2021). It includes the generation of the thematic data layers also the spatial analysis among the Yelwandi river in Maharashtra. A process of rating the weight towards the factors was established for the analysis of spatial data in a GIS. The resulting map of the landslide susceptibility splits the region into diverging zones of the comparative classes of susceptibility like low, high, very low and moderate. The map of susceptibility was interrelated through observing the field. The 67 settlements that was already existing in Yelwandi river zone were categorized in accordance with the rigorousness of landslide. It also delivers the guidelines towards the characteristic activities of the planning.

The preceding study (DAS; SARKAR; KANUNGO, 2023) had conducted the investigation on mapping of landslide susceptibility (LSZ) zonation. Himalayas in India is hugely prone to landslides due to the rugged topography, slopes that are steep, complex geology amplified through the seismo-tectonic activities and huge rainfalls which frequently induce losses in life through enormous commercial damages. Hence the mapping of LSZ has provided an active resolution for the end-users towards evaluating the range of the vulnerability and determining the possible significances. Up to date, various procedural outline wa instigated in the regards of spatial modelling and towards predicting the prospective landslide plots for attaining their own respective needs. Therefore, it is required and significant towards conducting a review of the contemporary state of the research articulated towards the LSZ mapping in the region of Himalaya. On the basis of this evidence, the contemporary paper reviews 144 study articles which was published in the previous decade towards having the insights about the modern trends, procedures besides the practices accepted through researches. Alongside the process of review, few critical points were highlighted with long- and short-term revelations on the basis of the

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difficulties concentrated by several investigators; hence, the research had tried to make certain that this assessment work depicts much more common discussion on the mapping of LSZ that is much appropriate for the world-wide practitioners. In the same way, this specific review also acts as the appropriate database for the researcher as well as scientist who is having work in the area of landslide specifically in the zone of Himalayas.

### Research gap

Patil & Gopale (2018) had investigated the incidence of landslide in the season of rainfall only in the rural community of Malin. They could have concentrated in the other regions as well.

## III. Materials And Method

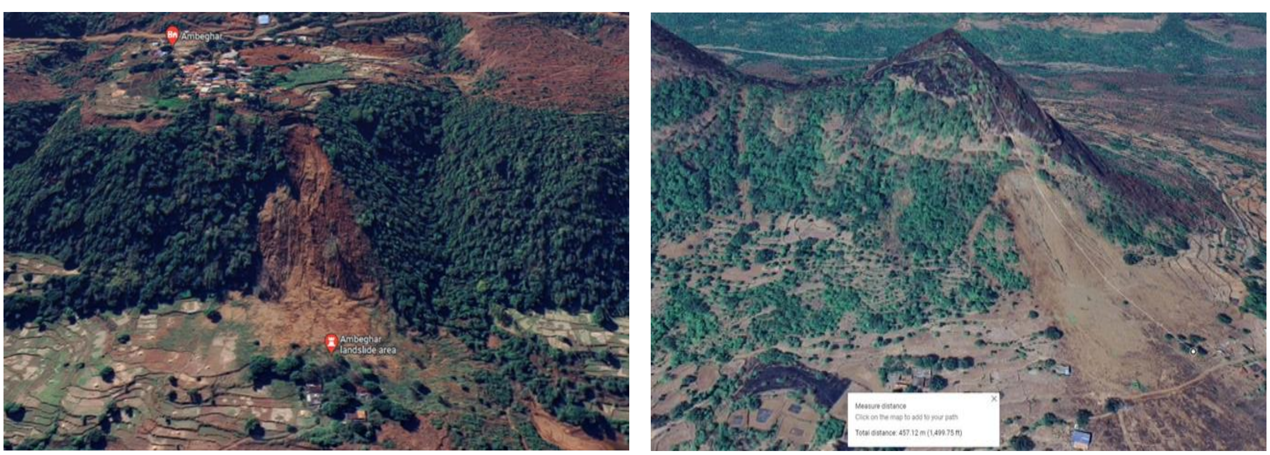
### Study Area: Patan & Mahad

Table 1 and Figure 1 show the study area location and general landslide examples, respectively.

Table 1- Study Area: Patan & Mahad

| **Case Study** | Ambeghar tarf Marali | Taliye |
|---|---|---|
| **Latitude** | 17.286469 | 18.111269 |
| **Longitude** | 73.829713 | 73.582583 |
| **Taluka** | Patan | Mahad |
| **District** | Satara | Raigad |
| **Region** | Paschim Maharashtra | Kokan |
| ***State*** | Paschim Maharashtra | Maharashtra |

Source: Authors.




(a) (b)

Figure 1- a) Landslide in Ambeghar b) Landslide in Taliye (Source: Google Earth).

### Site Investigation

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The site has a variety of large trees and bushes, and most of the land is used for agriculture. Landslides took place at this village, located in Patan tehsil, on the intervening night of Friday, July 23, 2021. Earlier, the administration had said a total of 30 people were missing and 16 were dead due to a landslide. The rescue operation is being carried out by local police, residents, and the National Disaster Response Force (NDRF). Due to heavy rainfall and a lack of proper road facilities for communication, the administration faced many obstacles in reaching the aid. As per the 2011 Census, the population of this village is 810, of which 389 are female and 421 are male.

In a little town named Taliye in the Raigad district of Maharashtra, 160 kilometres from the state's capital Mumbai, 84 people perished in a landslide, inflicting one of the state's biggest disasters in recent memory (AUTADE; PARDESHI, 2017). On Thursday, July 22, a sizable mound descended into the community, levelling 35–40 homes as it went. Most of the land is utilised for agriculture, and the area is home to a variety of huge trees and plants. On the night between Thursday, July 22, 2021, and Friday, July 23, 2021, there were landslides in this hamlet in the Mahad tehsil.

**Structure of Soil**

The manner in which individual sand, silt, and clay particles are put together determines the structure of the soil. Grade (degree of aggregation), class (average size), and kind of aggregates are the best categories to define soil structure (form). Some parts of Patan Tehsil are plains, while the majority are mountainous with steep valleys. There is a lot of rain. Common soil is red lateritic soil, which is red; cottony soil is black in plains; and basaltic and lateritic soil are found at altitudes.

Based on their texture, the soil types of Mahad Tehsil may be roughly divided into two groups: sandy soils and clayey soils. Sandy soils often have a loose, granular texture that allows water to travel through rapidly. They are also generally well-draining. Rice, coconut, and mango may all be grown on these soils, which are often found in coastal regions. Conversely, clayey soils have a finer texture and a propensity to hold onto water for longer. Typically found in inland regions, these soils are ideal for growing crops including vegetables and legumes. The Deccan Traps, a sizable igneous region in west-central India, have a significant impact on the local geology, which also affects the soil in Mahad tehsil. The basaltic lava flows of the Deccan Traps are well-known for having weathered through time to provide fertile soils that sustain local agriculture.

**Texture of Soil**

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In the study area, we found loamy soil. Loamy soils are mostly found in the Mahabaleshwar hills and Patan in Satara district. Due to their red colour, laterite soils are also known locally as "tambad mati". In certain areas, black soils and laterite or red soils have been blended (Figure 2).

The Konkan area, which is noted for its steep topography and abundant rains, is where Mahad Tehsil in Maharashtra State is situated. Its vulnerability to landslides is significantly influenced by the soil texture of this area. In general, sandy loam to clay loam, which is typically regarded as relatively stable soil, makes up the majority of the soil texture in Mahad tehsil. On the other hand, the region's abundant rainfall and steep hills might make landslides more likely. Because of their high water-holding capacity and poor permeability, clay soils are more prone to landslides and are often more stable.

Figure 2- Soil Texture of Taliye (Google Earth).

## Soil Exploration

To determine the engineering qualities of soils using laboratory tests and in-situ testing methods, soil samples must first be taken from the site and the profile of the natural soil deposits identified. We took three representative disturbed and undisturbed core soil samples from the top, middle, and bottom portions of the study area. Along with it, one disturbed and undisturbed core soil sample was taken from a non-landslide area, which is in the south-east direction of the landslide area.

## Type of landslide on case study

Mudflow occurred in the study area on July 23, 2021. Mudflow is a type of water flow that contains a lot of suspended particles and silt. It is denser and more viscous than streamflow and can deposit just the coarsest

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fraction of its load, resulting in irreversible sediment entrapment. Its high viscosity prevents it from flowing as far as water. Mudflows occur on steep slopes when vegetation is inadequate to prevent fast erosion, but they can also occur on gentle slopes if other requirements are satisfied (GAWALI et al., 2017). Other causes include intense precipitation in brief bursts and erodible source material. Mudflows may occur in any climate, although they are most prevalent in dry and semiarid regions. They may travel at rates of up to 100 km/h (60 miles/h) down a slope, causing significant destruction to life and property. Mudflows have displaced boulders the size of homes.

On July 22, 2021, there was a debris flow in the research area. A form of water flow known as debris flow has a lot of water content in it. Because it is denser and more viscous than stream flow and can only deposit the coarsest portion of its load, sediment is irreversibly trapped. It can flow as far as water because of its high viscosity. When vegetation is insufficient to stop rapid erosion, debris flow occurs on steep slopes, but they can also happen on moderate slopes if other conditions are met. Intense precipitation that occurs in short bursts and erodible source material are other factors. Although they can happen in any climate, debris flows are most common in dry and semiarid areas (GAWALI et al., 2017). Methodology adopted has been described in the Figure 3.

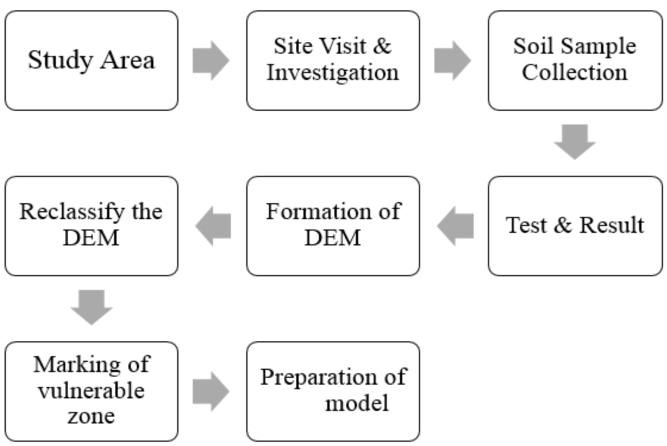


Figure 3- Methodology.

**Rainfall Analysis of Patan and Mahad Tehsil**

In order to understand the causes and patterns of landslides, rainfall analysis is essential (HOSENUZZAMAN; KIBRIA; SARKAR; ABEDIN, 2022) (Figure 4 and Figure 5). A rainfall study for the year 2021, concentrating on July in particular, might offer helpful insights into the probable landslide activity during that time in the context of the Satara and Raigad districts in Maharashtra, India. Maharashtra's Satara and Raigad

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districts, among other regions, had heavy rains in July 2021. Assessing the rainfall patterns and their relationship to the incidence of landslides may be done by carefully analyzing the rainfall data that was gathered from meteorological stations in these districts during the month of July. The study should take into account factors including the overall quantity of precipitation, the severity of the rain, and the length of the rain episodes.

This technique may be used to better understand regional slope stability and the temporal and geographical distribution of rainfall (HOSENUZZAMAN et al., 2022). The results of the study of rainfall can help the area's early warning systems, land use policies, and disaster management plans. In order to reduce landslide risks and strengthen the resilience of the affected regions, policymakers, local governments, and communities can use the knowledge gathered to direct the implementation of suitable solutions (KAUR; GUPTA; PARKASH, 2017)

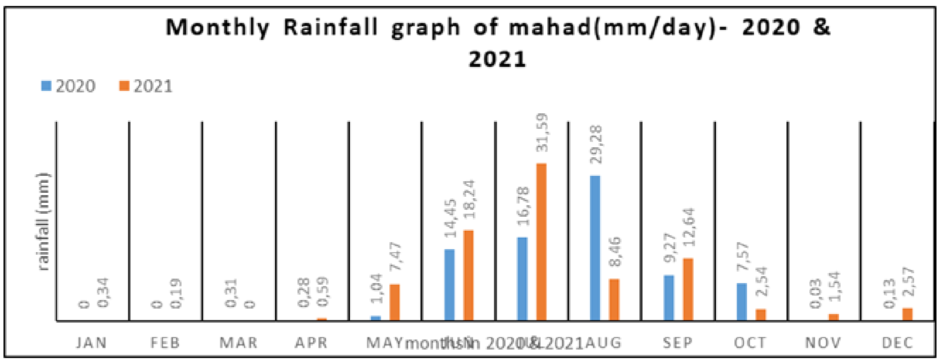


Figure 4- Monthly Rainfall graph of 2020 & 2021 of Patan in mm/day.

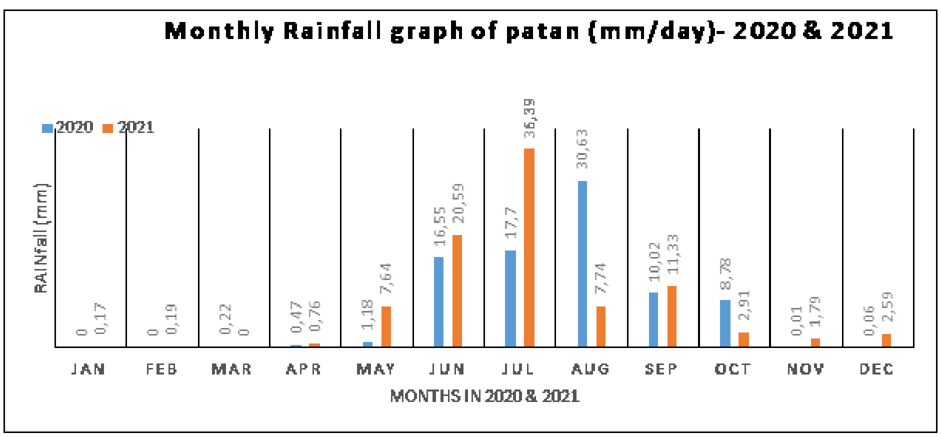


Figure 5- Monthly Rainfall graph of 2020 & 2021 of Mahad in mm/day.

Finally, the Figure 4 and 5 illustrates the soil and rainfall data of the Patan and Mahad tehsils show that there are hotspots in the region that are prone to landslides. The properties of the soil, including its composition, cohesion, and permeability, are critical in determining how susceptible a region is to landslides. Slope collapses are more likely when soils with loose, poor consolidation, including clay and silt, are present. A crucial factor in

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the creation of landslide hotspots is also the local rainfall pattern. When the soil is saturated, it loses its stability and is more susceptible to landslides. In locations with steep slopes, the Patan and Mahad tehsils, which frequently get heavy rains, are particularly susceptible to soil saturation (PERERA; JAYAWARDANA; JAYASINGHE; RANAGALAGE, 2019). In select spots within Patan and Mahad tehsils, the existence of sensitive soil types and severe rainfall combine to provide favorable circumstances for landslides to occur. Therefore, it is essential to carry out thorough environmental vulnerability assessments, taking into account other criteria including slope angle, land-use patterns, and infrastructure proximity, in order to detect and reduce the hazards associated with landslide hotspots in these locations (BIGNAMI; DRAGONI; MENDUNI, 2018). Such evaluations can help in the creation of focused measures to reduce the possible effect on communities and infrastructure.

## Vulnerability Analysis by using Analytical Hierarchy Process (AHP)

The pairwise comparison technique comprises assigning numbers to the relative weights of each criterion (Table 2 and Table 3). A matrix with rows and columns is used to structure the criteria (GEBRU et al., 2020). The diagonal matrix entries are assigned the value 1, as a criterion is always equal to itself. The remaining cells in the matrix are filled in by scoring each criterion from 1 to 9 in order of relative importance and comparing it to every other criterion. The matrix's values are then normalized by dividing each row by the total of its components. "Normalized decision matrix" is the term used to describe the final matrix. Next, the eigenvalue and eigenvector of the normalized decision matrix are calculated to determine the weights of each criterion. The eigenvector represents the weights of the criteria, and the eigenvalue assesses the general consistency of the pairwise comparisons. The consistency ratio (CR), which checks the consistency of paired comparisons, is then computed. If the CR is less than 0.1, pairwise comparisons are considered legitimate, and the weights may be utilized to decide how the alternatives will ultimately be ranked (UZIELLI; NADIM; LACASSE; KAYNIA, 2008). If the CR is larger than 0.1, the pairwise comparisons may be altered in order to improve consistency. When the number of parameters is less and the value of CR is greater than 0.1, it is acceptable.

Table 2- Saaty's Scale of Relative Importance (Saaty, 2005)

| Intensity Importance | Linguistic Variable |
|---|---|
| 1 | Equal Importance |
| 2 | Equal to moderate Importance |
| 3 | Moderate Importance |
| 4 | Moderate to the strong Importance |
| 5 | Strong Importance |
| 6 | Strong to the very strong Importance |
| 7 | Very Strong Importance |

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| | |
|---|---|
| 8 | Very Strong to the extremely strong Importance |
| 9 | Extremely Strong Importance |

Source: Authors.

AHP calculation of the Patan Tehsil's (Table 3) total value of LULC is 2.083, rainfall is in the value of 7.167, wherein the value of the flow direction is 10.833, slope is 12.583, aspect is 15.333 and the value of the hill shade is 18.000. On the other side AHP calculation of the Mahad Tehsil's total value of LULC is 2.176, value of the rainfall is 9.117, value of the flow direction is 11.700, whereas the slope is 14.667, aspect is 15.333 and value of the hill shade is 17.000.

Table 3- Factors considered for AHP calculation for Patan and Mahad Tehsil.

| Category | Factor | Datatype | Scale | Source |
|---|---|---|---|---|
| Topographic Factors | Slope | Grid | 1:10,000 | Bhuvan |
| | Aspect | | | |
| | Hill shade | | | |
| Hydrological Factor | Flow Direction | Grid | 1:10,000 | Bhuvan |
| Land cover Factor | LULC | Polygon | 1:10,000 | ESRI |
| Precipitation | Rainfall | Polygon | 1:10,000 | CRU Data |

Source: Authors.

I) In the preliminary stage, it is important to take into account the traits that make up landslide-triggering factors. Assign intensity importance in line with the aforementioned table. Following a division of the parameter by intensity significance, the sum of the entire table must be determined.

II) Next, we must calculate the normalised index using the formulas below. The next step is to identify the eigenvector using the formula described (KAUR et al., 2017).

$$Vp = \sqrt[n]{W1 \times W2 \times \ldots \times Wn} \quad \text{(i)}$$

III) Following the computation of the eigenvectors, the weighting coefficient (Cp) has to be found. This computation must then be followed by the determination of the eigenvalue using the technique below.

$$Cp = \frac{Vp}{\Sigma Vp} \quad \text{(ii)}$$

$$D = A \times Cp \quad \text{(iii)}$$

$$E = \frac{D}{Cp} \quad \text{(iv)}$$

$$\lambda max = \frac{\Sigma E}{n} \quad \text{(v)}$$

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IV) Next, we must calculate the consistency index (CI) using the algorithm below. Finally, by dividing CI and RI, we must compute the consistency ratio (CR). Saaty (1980) mentions the principles of RI.

$CI =$ ..................(GEBRU et al., 2020; IBRAHIM; HARAHAP; BALOGUN; USMAN, 2020) (vi)

$CR = \frac{CI}{RI}$ ............................................... (AKGUN, 2012)(vii)

Table 4- Values of RI as per Saaty (1980).

| **n** | 2 | 3 | 4 | 5 | **6** | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| **RI** | 0 | 0.58 | 0.9 | 1.12 | **1.24** | 1.32 | 1.41 | 1.45 | 1.49 |

Source: Authors.

Table 5- CR calculation of Patan Tehsil.

| **Vp** | **Cp** | **D=A*Cp** | **E=D/Cp** | **λ max** | **CI** | **CR** |
|---|---|---|---|---|---|---|
| 3.260 | 0.435 | 2.986 | 6.858 | **7.159** | **0.232** | **0.187** |
| 1.390 | 0.186 | 1.548 | 8.341 | | | |
| 1.157 | 0.155 | 1.138 | 7.364 | | | |
| 0.794 | 0.106 | 0.720 | 6.791 | | | |
| 0.525 | 0.070 | 0.460 | 6.573 | | | |
| 0.364 | 0.049 | 0.341 | 7.030 | | | |
| **7.489** | **1.000** | **7.193** | **42.956** | | | |

Source: Authors.

Table 6- CR calculation of Mahad Tehsil.

| **Vp** | **Cp** | **D=A*Cp** | **E=D/Cp** | **λ max** | **CI** | **CR** |
|---|---|---|---|---|---|---|
| 3.448 | 0.432 | 3.454 | 7.995 | **7.524** | **0.233** | **0.188** |
| 1.718 | 0.215 | 1.726 | 8.020 | | | |
| 1.214 | 0.152 | 1.171 | 7.699 | | | |
| 0.695 | 0.087 | 0.620 | 7.121 | | | |
| 0.525 | 0.066 | 0.456 | 6.937 | | | |
| 0.382 | 0.048 | 0.353 | 7.373 | | | |
| **7.981** | **1.000** | **7.780** | **45.145** | | | |

Source: Authors.

In Patan tehsil, Normal weight calculation is 1.000, value of the total weight is 6.000 and the percentage of 100. In Mahad tehsil, Normal weight weight calculation is 1.000, value of the total weight is 6.000 and the percentage of 100.

## Vulnerability Analysis maps of Patan and Mahad Tehsil

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ArcGIS 10.8 provides the integration of several data sources, such as remote sensing data, geological data, and socio-economic data, in order to provide a full analysis of landslide susceptibility (AUSTIN; MULLER; GONG; ZHANG, 2013). The research has evaluated six factors from three data sources for this study.

**(a) Study Area Map: Patan & Mahad**

In the Maharashtra state's Satara District, Patan is both a town and a tehsil (Figure 6). A tehsil in India is a subdivision of a district that oversees overseeing and collecting taxes for a specific region within the district. It is a fundamental component of the local governance system and is essential to the growth and management of the neighbourhood. The census statistics from 2011 show that Patan Block (CD sub-district)'s code is 04264. The Patan Tehsil has a total area of 1,386 $km^2$, of which 5.77 $km^2$ is urban and 1,380.05 $km^2$ is rural. A total of 2, 99,509 people live in Patan tehsil, of which 13,779 live in the city and 2, 85,730 live in the countryside. The population density of Patan Tehsil is 216.1 people per square kilometre. The sub-district has 64,465 rural homes and 3,052 urban homes for a total of 67,517 dwellings.77.89% of the men and 60.41% of the females in Patan Tehsil are literate, making up the 68.88% of the population who are. You may look through the list of villages in Patan Tehsil, which has around 333 settlements.

In the Indian state of Maharashtra, the Mahad tehsil is situated in the Raigad district. It is a coastal tehsil that is bordered to the west by the Arabian Sea and is located on the banks of the Savitri River. According to the 2011 Indian Census, the tehsil has a population of around 130,000 people and a total area of about 314.5 square kilometres. The tehsil is renowned for its significant historical past and rich cultural heritage. It is the location of a number of significant sites, notably the Raigad Fort, which served as the Maratha Empire's administrative centre under Chhatrapati Shivaji Maharaj. The Mahad Ganpati Temple, one of the eight Ashtavinayak Temples in Maharashtra, is one of the several religious attractions that can be found in the tehsil. The Mahad Tehsil is a significant hub for fishing and farming. Rice, coconuts, and mangoes are the main crops farmed in the region, and fishing is a significant source of income for many coastal towns (MANDAL; DHARANIRAJAN; MEENA; JAMAN; RANA, 2023). In addition, the tehsil is vulnerable to landslides and floods, especially during the monsoon season(MANDAL et al., 2023). In order to lessen the effects of such occurrences on the local people and infrastructure, appropriate disaster management and mitigation methods are required (ANDERSON et al., 2014).

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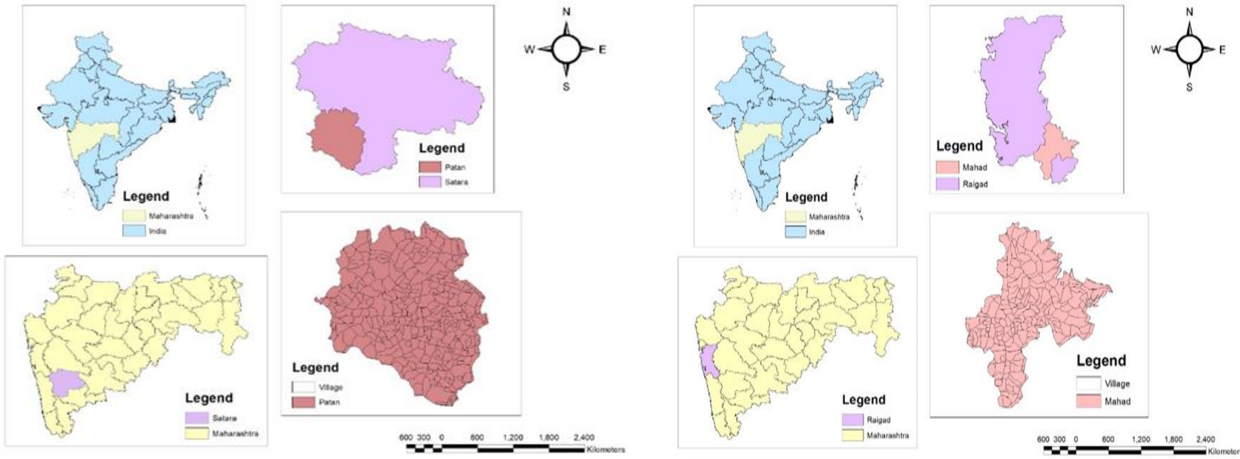


A B

Figure 6- Study Area: A) Patan B) Mahad.

**(b) DEM of Study Area**

A three-dimensional digital depiction of the topography or surface of the Earth is called a DEM. The Patan and Mahad tehsil's DEM, which has a resolution of 30 metres, gives thorough details on the terrain's elevation in these locations. Since the DEM has a resolution of 30 metres, each cell in the DEM represents a 30 by 30 metre region on the ground. Numerous applications, including as geological investigations, hydrological modelling, and the evaluation of natural hazards, benefit from this degree of information. A landslide vulnerability study requires a number of topographic factors, including slope, aspect, and curvature, which may be generated using the DEM (BANERJEE; GHOSE; PRADHAN, 2018). It may also be used to spot steep slopes and high relief regions that are more likely to have landslides. Additionally, land use planning, soil conservation, and forest management may be done using the DEM of Patan and Mahad tehsil. It gives a thorough image of the landscape, making it easier to pinpoint locations that might be good for different endeavours including forestry, agriculture, and infrastructure development. In conclusion, the DEM of Patan and Mahad tehsil with a resolution of 30 metres offers useful information about the topography and may be used for a variety of purposes, such as assessing natural hazards, planning land uses, and managing the environment.

**(c) Slope and Reclassified Slope map of Study Area**

For the investigation and visualisation of geographical data, ArcGIS 10.8 is a potent tool. Slope is one of the important terrain characteristics that can be obtained from a Digital Elevation Model (DEM) by utilising

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ArcGIS. In many geospatial applications, the slope, which is the rate at which elevation changes over a specified distance, is a crucial topographical feature (ADHIKARI, 2017). Using ArcGIS 10.8, we can use the Slope tool to create a slope map for Patan and Mahad Tehsil (Figure 7. (a) and (b)). This tool determines the slope at each pixel based on elevation information from the DEM. The result is a raster layer that displays the slope values in either degrees or percentages for each individual pixel (UZIELLI et al., 2008). The Reclassify tool in ArcGIS 10.8 may be used to reclassify the slope map into equal slope categories. Using user-defined ranges or classes, the Reclassify tool enables us to assign new values to the slope values in (Figure 7 (c) and (d)). For instance, we may categorize various ranges of slope values as low slope, moderate slope, or high slope.

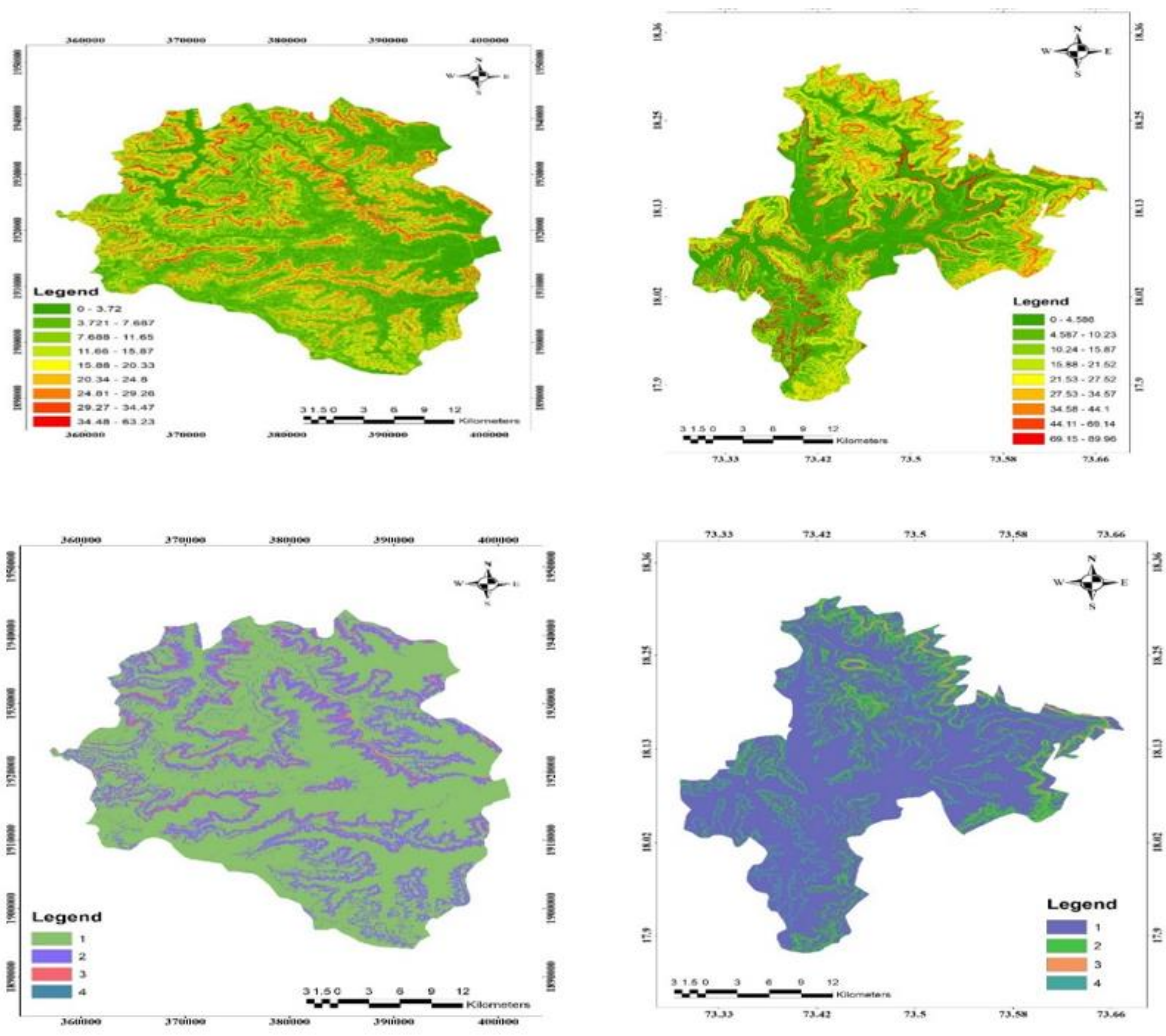


Figure 7- (a) and (b): Slope map of Patan and Mahad: (c) and (d): reclassified slope Map of Patan and Mahad.

**(d) Aspect and map of Study Area**

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A terrain feature called aspect gauges how the slope is oriented in relation to the cardinal directions (Figure 8). Using the Aspect tool in ArcGIS 10.8, the aspect of Patan and Mahad Tehsil may be obtained from a Digital Elevation Model (DEM). The Patan and Mahad Tehsils aspect map that is produced can then be divided into groups according to how they are facing (e.g., north, south, east, or west) (Figure 8. (a) and (b)). The Reclassify tool, which enables the user to give new values to each class, may be used to do this. Applications for the reclassified Patan and Mahad Tehsils aspect map include locating regions that are more vulnerable to erosion, vegetation growth, and sun radiation (Figure 8. (c) and (d)). For instance, slopes facing north have a tendency to be colder and more humid, whereas slopes facing south have a tendency to be drier and warmer. Planning for land use, agriculture, and environmental management in the area can all benefit from this knowledge (LI; JIANG; WANG; CHEN, 2011).

In conclusion, ArcGIS 10.8 offers tools for obtaining aspect and reclassification aspect maps of Patan Tehsil, which can offer useful details on the orientation of the terrain and its consequences for different application

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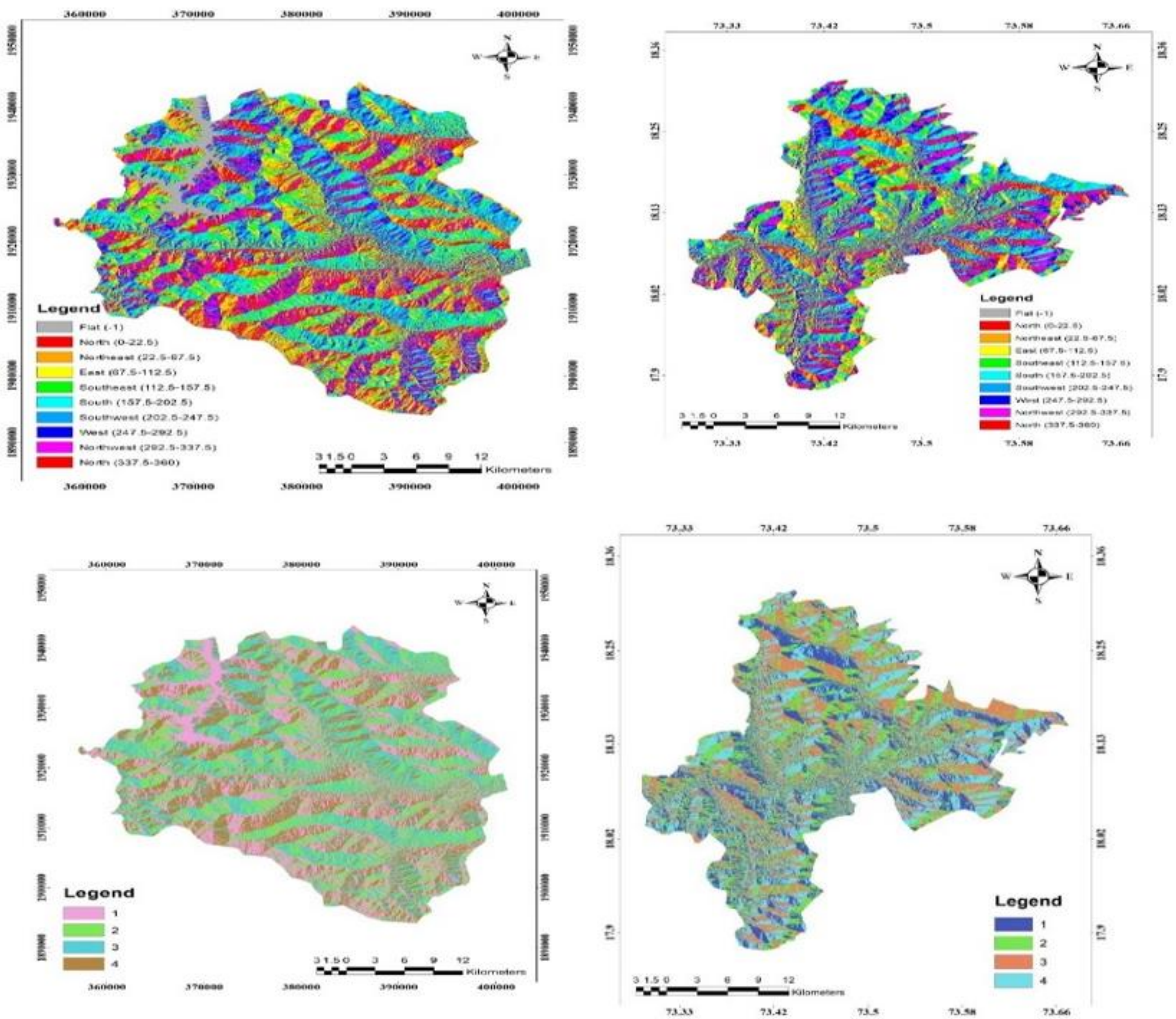


Figure 8- (a) and (b): Aspect map of Patan and Mahad: (c) and (d): reclassified Aspect Map of Patan and Mahad.

## (e) LULC and Reclassified LULC map of Study Area

Understanding the patterns of land use and land cover in a region is essential for a number of purposes, including environmental monitoring, land-use planning, and natural resource management (MANDAL; MONDAL, MANDAL; MONDAL, 2019). This is accomplished through the process of land use and land cover (LULC) mapping. In the Indian state of Maharashtra's Satara district is the territory known as Patan Tehsil and Raigad district is the territory known as Mahad Tehsil (Figure 9. (a) and (b)). ArcGIS 10.8 has a number of tools for LULC mapping, including tools for picture categorization and reclassification. By examining satellite images and applying land cover classes to various regions of the area, ArcGIS 10.8 may be used to create a LULC map of

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Patan and Mahad Tehsils (Figure 9. (c) and (d)). By classifying the original land cover classes into more general groups based on their traits and attributes, the reclassified LULC map is created. This may be used for a variety of purposes, including urban planning, soil conservation, and forest management, and can be helpful for recognising patterns and trends in land use and land cover.

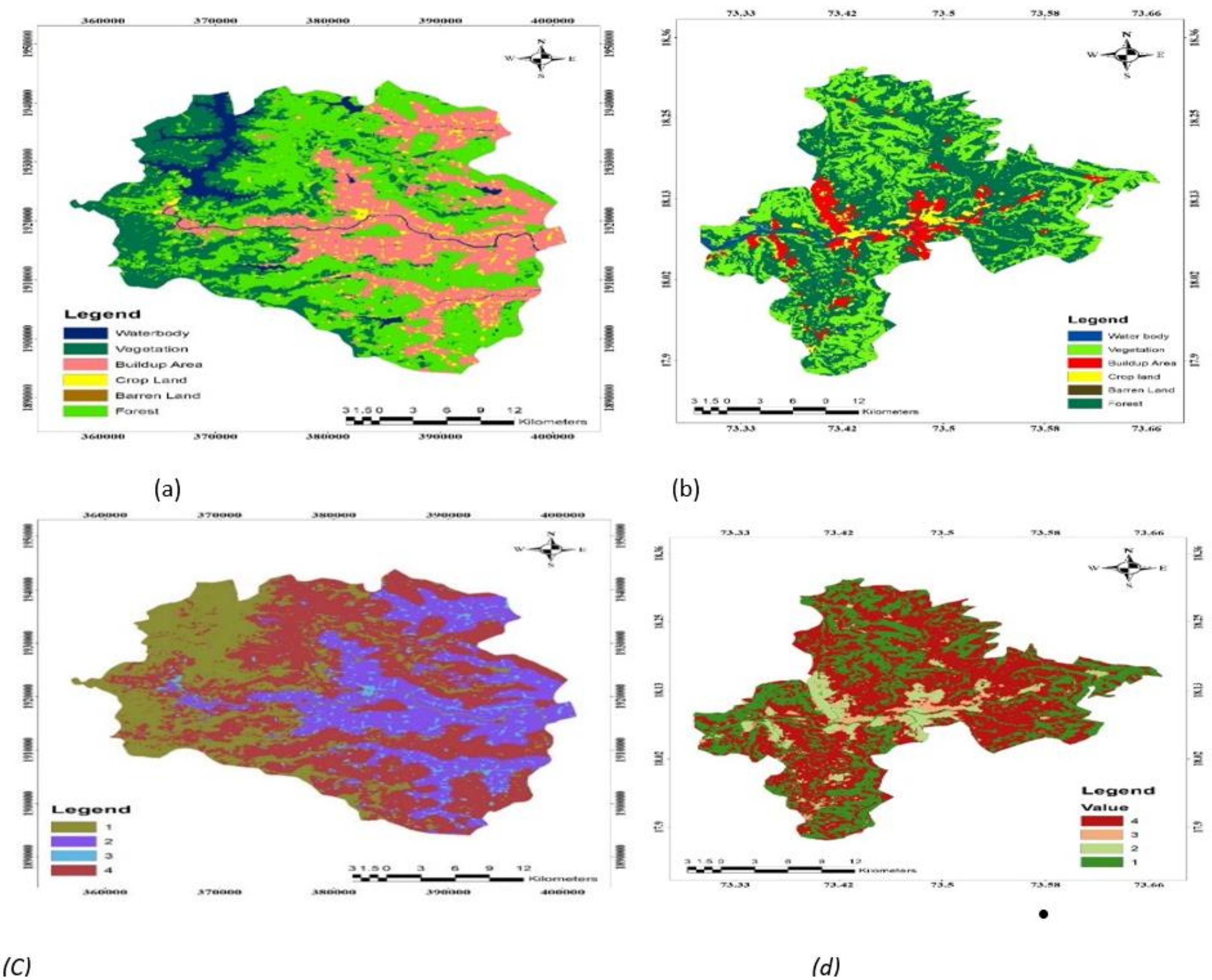


Figure 9- (a) and (b): LULC map of Patan and Mahad; (c) and (d): reclassified LULC Map of Patan and Mahad.

**(f) Hill shade and Reclassified Hill shade map of Study Area**

For landslide vulnerability studies, land-use planning, and disaster management, hill shade mapping is a crucial tool. Maps of Patan and Mahad Tehsil's hill shade (Figure 10. (a) and (b)) and reclassified hill shade may be made using the effective tool ArcGIS 10.8 (Figure 10. (c) and (d)). The hill shade map of the area may be

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created using ArcGIS 10.8, which can be used to apply different terrain analysis techniques to identify the places with steep slopes and high elevation. Landslides and other natural disasters are more likely to occur in certain places. The hill shade map may also be categorized based on slope and elevation to produce the classed hill shade map (LI et al., 2011). This map can assist to identify regions with varied degrees of vulnerability to landslides and other hazards and can give a more thorough knowledge of the topography. In conclusion, the hill shade mapping of Patan and Mahad Tehsil using ArcGIS 10.8 is a useful tool for understanding the topography and locating places that are more vulnerable to landslides and other dangers. The generated maps can be applied to regional disaster management, infrastructure development, and land use planning (DING; MIAO, 2015).

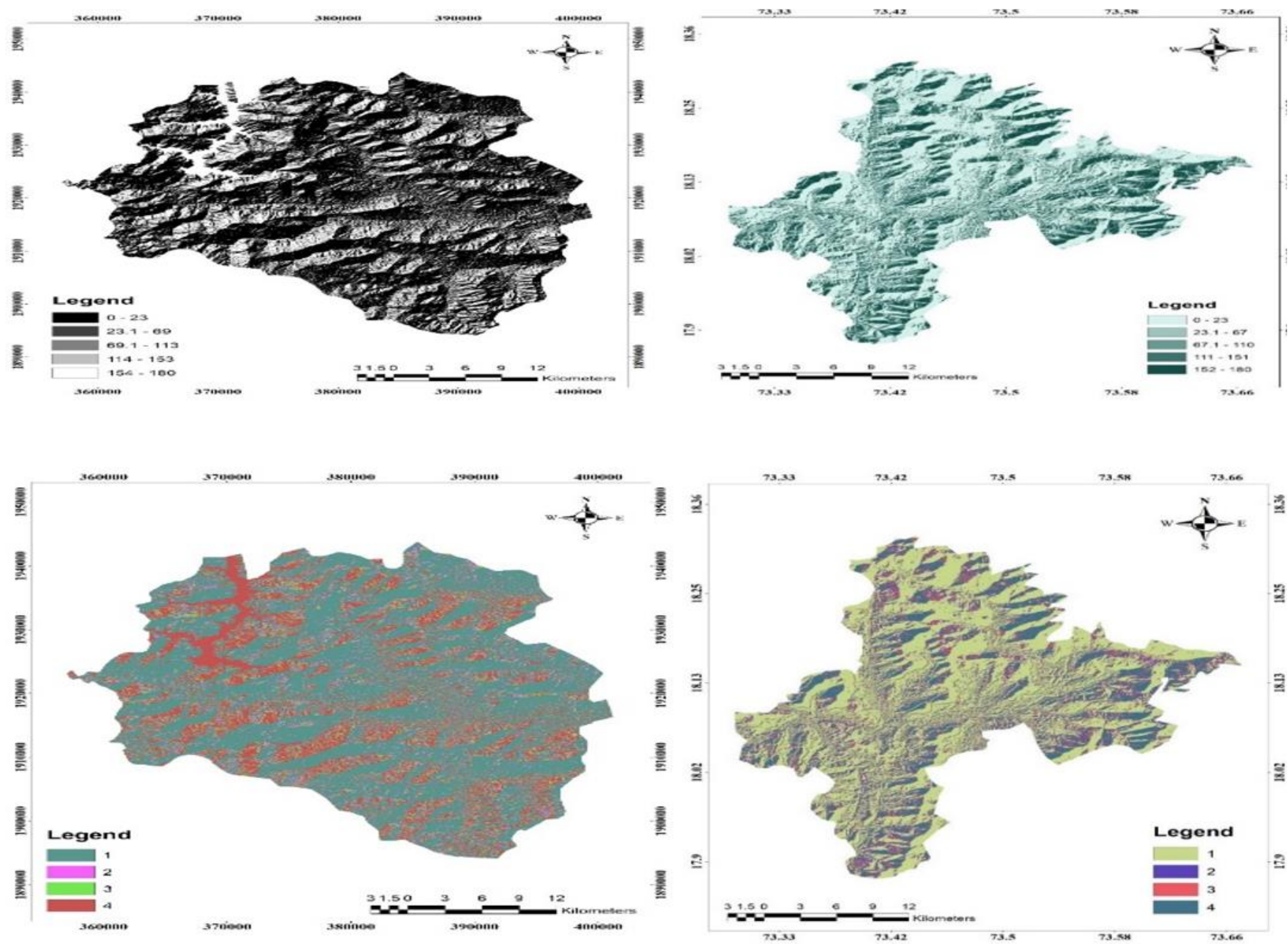


Figure 10- (a) and (b): Hill shade map of Patan and Mahad; (c) and (d): reclassified Hill shade Map of Patan and Mahad.

**(g) Flow Direction and Reclassified Flow Direction map of Study Area**

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Hydrological modelling and watershed management both heavily rely on flow direction and reclassification flow direction maps to analyse how water moves over the terrain. A digital elevation model (DEM) of the area may be processed using ArcGIS 10.8 to find the flow direction of Patan and Mahad Tehsil (Figure 11. (a) and (b)). In order to determine the direction of water flow over the terrain, it is necessary to determine the direction of the steepest slope for each cell in the DEM. In order to give useful information for hydrological modelling and watershed management, the flow direction map may then be categorised to display the direction of water flow in several classes, such as north, south, east, and west (LI et al., 2011). The Patan and Mahad Tehsil's reclassified flow direction map may be used to pinpoint locations that are most susceptible to floods and landslides, as well as places that are expected to see significant amounts of runoff or erosion (Figure 11. (c) and (d)). Planning for land use, building infrastructure, and disaster management in the area can all benefit from this knowledge.

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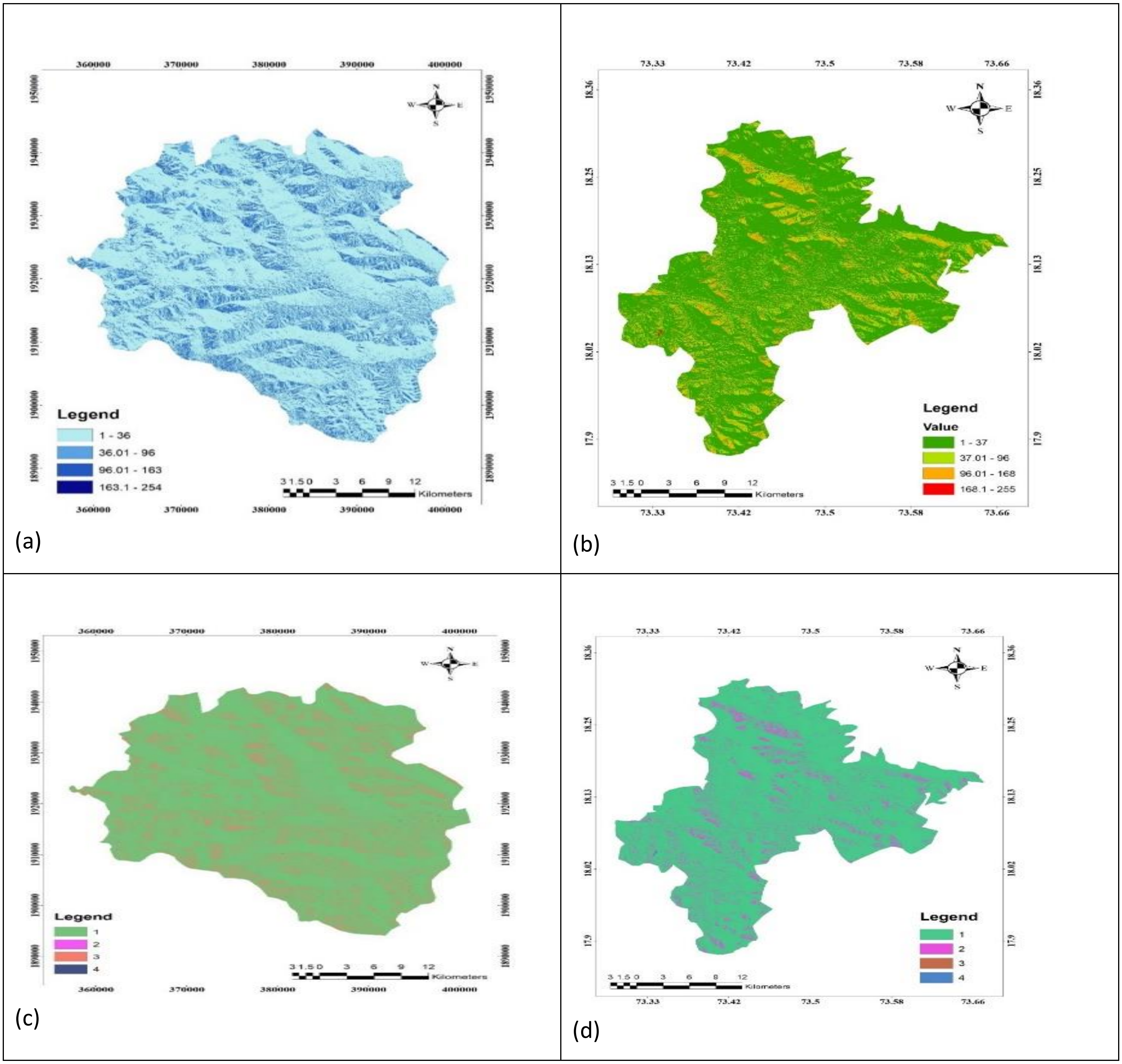


Figure 11- (a) and (b): Flow direction map of Patan and Mahad; (c) and (d): reclassified Flow direction Map of Patan and Mahad.

## (h) Rainfall and Reclassified Rainfall map of Study Area

ArcGIS 10.8 is a capable programme for handling and analysing geographical data, including statistics on rainfall. A rainfall map of Patan and Mahad Tehsil may be created using ArcGIS 10.8 using rainfall data that has been processed and classed (Figure 12. (a) and (b)). This map can be used for a variety of purposes, including hydrological modelling, crop management, and disaster management. There are several ways to get information

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on rainfall, including using weather stations or satellite-based data (RAM; GUPTA, 2022). The information may then be uploaded into ArcGIS 10.8 and categorised according to the severity of the rainfall. This may be accomplished by utilising the Reclassify tool in ArcGIS 10.8, which enables users to choose various criteria for various categories of rainfall intensity (Figure 12. (c) and (d)). A Patan Tehsil rainfall map may be produced utilising the classed rainfall data when it has been done. The rainfall map can be helpful for planning and managing water resources as well as for locating places that are vulnerable to flooding, erosion, and landslides. In conclusion, rainfall data may be classed and utilised to create a Patan Tehsil rainfall map using ArcGIS 10.8.

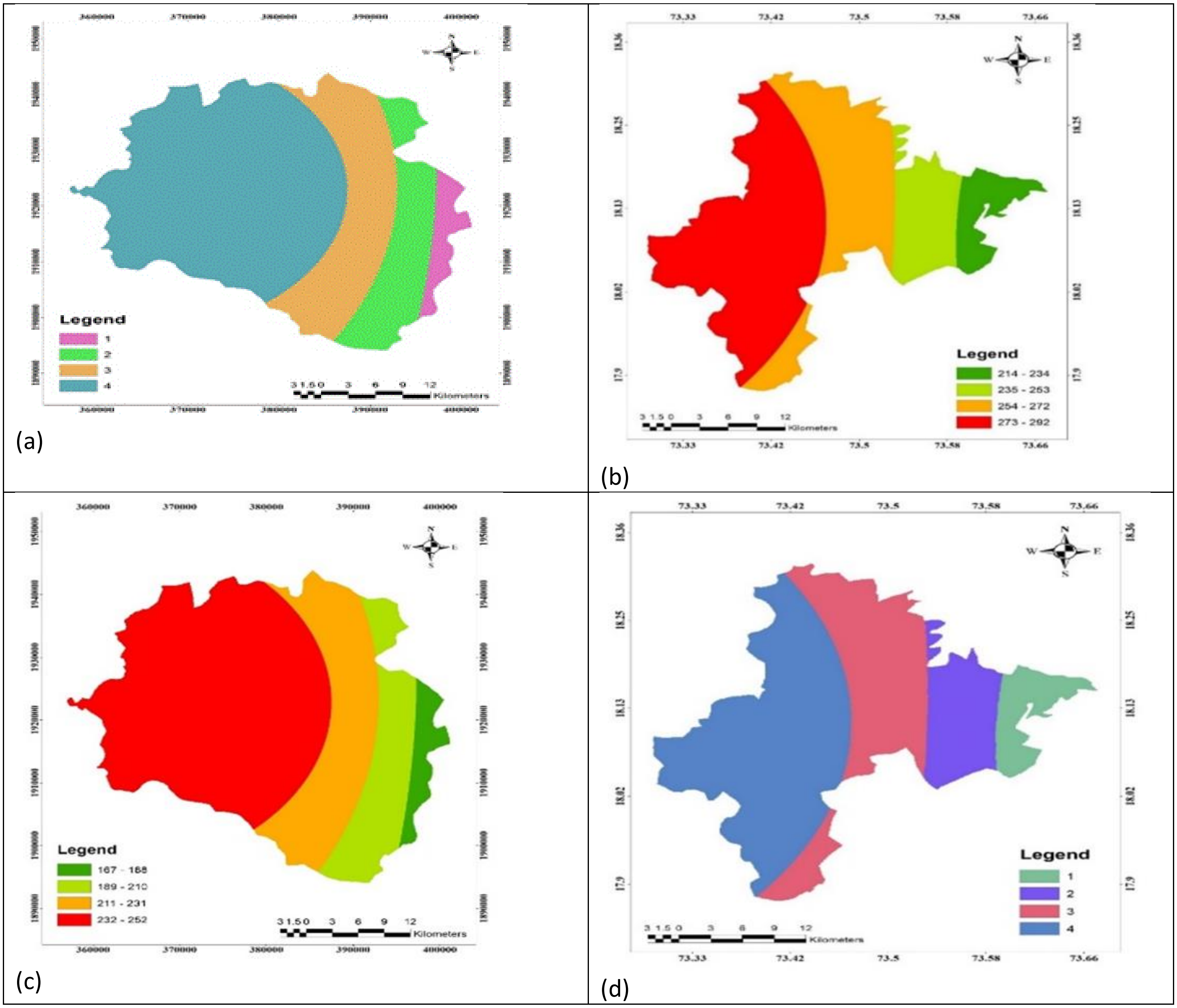

Figure 12- (a) and (b): Rainfall map of Patan and Mahad; (c) and (d): reclassified Rainfall Map of Patan and Mahad.

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## IV. RESULTS AND DISCUSSION

**Landslide Vulnerability map of Patan Tehsil:**

Zones that are high, medium, low, or not at all landslide-vulnerable are shown on the weighted overlay map for Patan Tehsil (Figure 13). For the analysis, the following factors were taken into account: LULC, slope, aspect, hill shade, flow direction, and rainfall According to the data, locations with steep slopes, more rainfall, and particular types of land use and land cover (LULC) (MANDAL; MAITI; MANDAL; MAITI, 2015), such as agricultural land and bare ground, are more prone to landslides. The landslide vulnerability of these locations was classified as high or medium. Areas with moderate slopes, reduced rainfall, and forest cover, on the other hand, were categorized as low-landslide-vulnerable zones. Lower landslide danger exists in certain places. In order to effectively plan land use and implement targeted mitigation measures, the weighted overlay analysis assists in identifying regions that are more vulnerable to landslides.

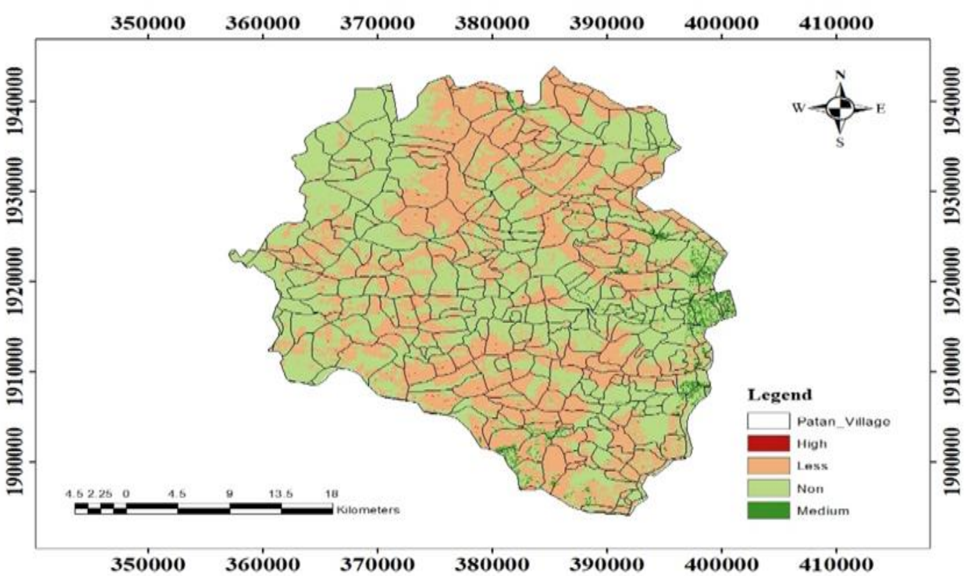


Figure 13- Weighted Overlay Map: Patan.

According to the classification (Table 8), 55.314% of the region is classified as having low susceptibility, followed by 42.990% as having medium vulnerability. Only 0.094% of the whole region is designated as having high vulnerability, whereas 1.602% is not. According to these results, the bulk of Patan Tehsil in Satara District is moderately to lightly vulnerable to landslides, underscoring the significance of taking proactive steps to preserve this advantageous scenario.

Table 8- Landslide Vulnerable Area of Patan (in sq.km).

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| Category | Area | % |
|---|---|---|
| High | 1.294 | 0.094 |
| Medium | 589.269 | 42.990 |
| Low | 758.189 | 55.314 |
| Non | 21.952 | 1.602 |
| **Total** | **1370.704** | **100.000** |

Source: Authors.

## Landslide Vulnerability map of Mahad Tehsil

The area is quite prone to landslides, as shown by the weighted overlay map for landslide-sensitive zones in Mahad Tehsil (Figure 14). Land use and land cover (LULC), slope, aspect, hill shade, flow direction, and rainfall were all included in the analysis, and each was given a weight depending on how significant a role it played in generating landslides (KAUR et al., 2022). As a result of the research, the territory was divided into high, medium, low, and non-landslide-prone zones, with the bulk of the area lying within the high and medium landslide-vulnerable zones. To lessen the impact of landslides, the region may plan and prioritize land-use activities, infrastructure development, and disaster management using the analyses' findings (RAHMAN; HUQ; AHMED; RAHMAN; AL-HUSSAINI, 2022).

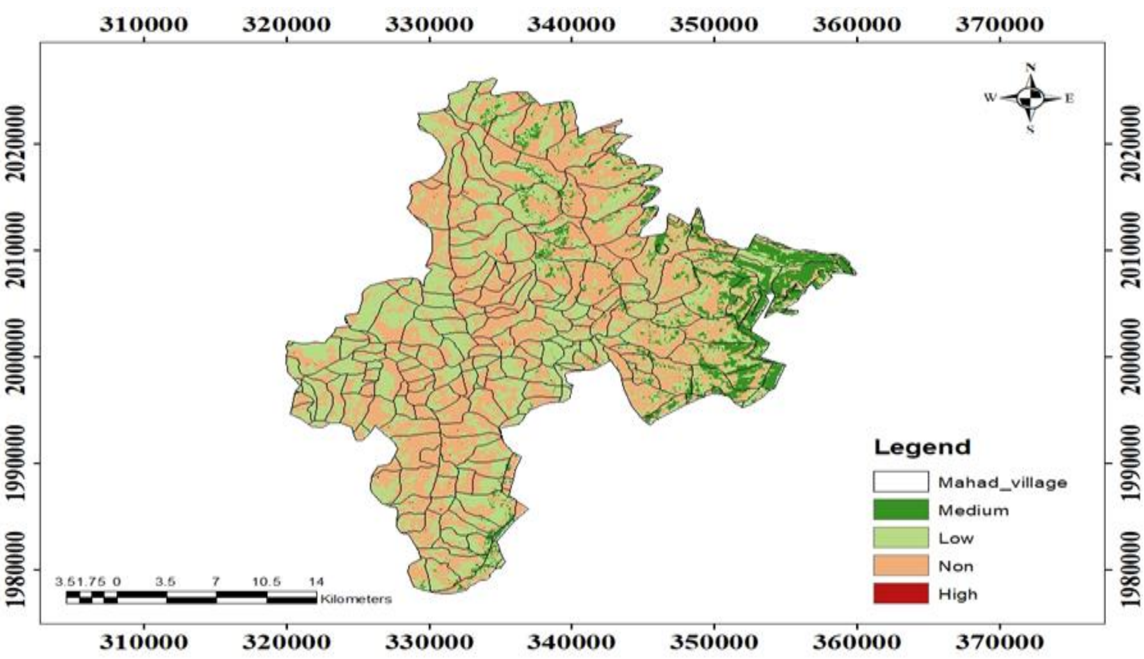


Figure 14- Weighted Overlay Map: Mahad.

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The investigation divided the places into four groups depending on their level of physical vulnerability. A total of 0.059% of the area is in high-risk zones, while 49.336% is in medium-risk areas. 41.462% of the land was in low-risk zones, while 9.143% was in no-risk zones. These findings demonstrate the importance of focused preparedness and mitigation initiatives, especially in high- and medium-risk regions.

Table 9- Landslide Vulnerable Area of Mahad (in sq.km)

| **Category** | **Area** | **%** |
|---|---|---|
| High | 0.474 | 0.059 |
| Medium | 398.862 | 49.336 |
| Low | 335.204 | 41.462 |
| Non | 73.916 | 9.143 |
| **Total** | **808.455** | **100.000** |

Source: Authors.

**Limitation of the study**

Every study will have its own limitations. In the similar perception, the present study is also having few limitations based on the acquired results for the research's objective. The contemporary research has limited its emphasis on the specific region of Satara and Raigad District. The study might have focused on the other regions of India. Landslide zonation maps can be created on a large scale, which may limit the ability to identify smaller areas that are prone to landslides. This scale may not capture all the complexities of the local terrain and geology, leading to oversimplified assessments of landslide risks in certain regions.

The efficiency of landslide susceptibility mapping relies heavily on the availability and accuracy of historical landslide data, geological surveys, and weather records. In regions where data is scarce or inconsistent, the reliability of the zoning maps might be compromised. Furthermore, relying on remote sensing data may result in uncertainties associated with the interpretation of satellite images. The assessment may fail to adequately consider socio-economic factors that affect vulnerability, such as population density, land use practices, and community preparedness. Not taking into account these factors could lead to a lack of understanding of the impacts of landslides on nearby communities and infrastructure.

## V. CONCLUSION

Landslides are the most common geological hazards in the world that causes damage to natural environment, human properties, infrastructures and large number of resources. It is a major problem worldwide in which the combined impact of man and natural processes lead for increasing landslide risks (BERHANE; TADESSE, 2021). Landslide can induce economic, ecological and social damage. Resource of the agriculture and

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forest are vanished, substructures and the places of heritage are found to be destroyed. Even it can completely block the waterways and augment the sedimentation of the downstream. Zone with intermediate slopes, declined rainfall, forest cover on the contrary side it is entitled as the least vulnerable areas of Patan. In Mahad, 059 % of the region is in greater risk, whereas the 49.336% is in the midway risk, then 41.462% is in slightest risk and 9% is of no risk. The contemporary research has focused on the vulnerability of the landslide regions that are at risk; atmospheric, global climatic change factors and the hazardous mapping regions; impact of the rainfall and soil's viscosity and the landslides that is associated with topographical, land-cover transformation, hydrogeological in the specified regions. Hence, the forthcoming study will emphasis on the preventive measures of landslides and the rehabilitation of the victims of landslides. Moreover, the study has not analyzed the other regions of India, so the forthcoming study could emphasis on the other parts of India. Hence the prospective research will suggest procedure for preventing the landslides and the convalescence of the victims of the landslides.

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