ASSESSING LANDSLIDE VULNERABILITY AND DEVELOPING CLIMATIC TRIGGERING PREDICTORS FOR THRISSUR DISTRICT

By

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(2015-20-017)

THESIS

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2021

DECLARATION

I, hereby declare that this thesis entitled "**Assessing landslide vulnerability and developing climatic triggering predictors for Thrissur district**" is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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INTRODUCTION

CHAPTER 1: INTRODUCTION

Kerala, the Indian state renowned worldwide for its natural beauty located in the southern peninsula, enveloped by the Laccadive Sea and the mountain ranges of the Western Ghats, ranks the first among the Indian states in the SDG indices with outstanding achievements in human development comparable to developed economies. The State harbors three Ramsar sites of international significance in an ecologically strategic manner. One of the world's largest and highly endangered ecological hotspots is the Western Ghats. Kerala is highly prone to natural disasters, due to its proximity to the sea with a coastline of approximately 600 km, presence of several watersheds, rivers, and lakes, making a significant part of its area susceptible to the landslide.

Landslide refers to the down-slope movement of a mass of rock, rubble, soil, or earth under the direct control of gravity (Coates, 1981). Almost every landslide has multiple causes, rainfall and slope can be attributed as the major factors that trigger the landslide events. Landslides are catastrophic events impacting the economy, infrastructure, culture and heritage, and human injury that can extend to the loss of lives. Landslides are a serious geological hazard that is prevalent in almost every state. It usually happens across one or even more distinct boundary slip surfaces (Hutchinson, 1988). Geomorphological features, slope, climate, and human action all have a part in the initiation of slides. Every year, as the monsoon season approaches, reports of slope failures/landslides rush in from nearly all of the highland areas.

These frequent disasters in and around the districts necessitate a thorough investigation to pinpoint the most vulnerable places in terms of slope stability. Slope failures, more than any other natural hazard, are the most accessible to preventive solutions. Several studies have been presented, and a number of profiles near the geotechnical threshold have been discovered, proving that slope collapse in the Western Ghats and the occurrence of landslides are mainly confined to overburden.

(Sreekumar and Krishnanath, 2000; Thampi, 2006; Sreekumar et al., 2010; Abraham, 2011; Sajinkumar et al., 2011 and Sreekumar and Aslam, 2011).

During the monsoon season of 2018 from June to August the state received nearly 50 per cent more rain than the expected rainfall during this period. This torrential rain drenched almost the entire state. The government was forced to open the dam as the heavy rain continued, which further aggravated the situation. Numerous landslides of varying nature and severity occurred concurrently throughout the state. The aftermath was devastating, affecting almost one in every six persons in the state. Three-fourths of the villages were affected by the ravages and about 1.5 million residents were temporarily displaced. About five hundred people lost their lives and the gross loss and casualties were estimated to be worth INR 280 billion. In August 2019, another incessant rainfall triggered extreme flooding and landslides before revival from the shock of the 2018 catastrophic events. Sixty per cent of Northern Kerala villages were severely affected, particularly Wayanad, Malappuram, and Kozhikode. Finally, in 2020 a landslide occurred in Pettimudi, Munnar.

As Kerala experienced the worst floods in many decades, Madhav Gadgil, the author of a widely protested Western Ghats conservation report warned in 2011 about the coastal state's potential natural catastrophe unless critical actions were implemented to preserve the ecologically fragile Western Ghats. As the state faces monsoon fury with flooding and landslides killing hundreds across Kerala, Karnataka, and Maharashtra, the Gadgil commission recommended several suggestions that have been neglected by the state government are back in view. It was the intense rainfall and human intervention that played an immense role in 2018, 2019, and 2020 floods and landslides. But it is very certain that the state's developments in the past few years have dramatically undermined its ability to cope with incidents like this and have substantially intensified the severity of the misery. If the state government and local authority had adopted strict environmental regulations, the severity of the catastrophe may have been lower. Once again, this argument has taken the controversy – development vs environment – back to the forefront. There is an active debate between the environment and development; both are hard to reconcile without undermining the other. And all of us know, sustainable development is the need of the hour.

As people migrate into new areas of hilly or mountainous terrain, it is essential to understand the significance of the future susceptibility to landslide hazards. Cities and towns should plan for modern construction engineering, land use, and infrastructure that will minimize the cost of living with landslides. The physical causes of landslides cannot be checked; landslide risks can be minimized by geological studies, by sound engineering practices, and by productive land use management laws. The triggers, movement characteristics, soil properties, geology associated with them, and where they can occur are important to consider. Furthermore, mitigation measure estimates may decrease damages due to landslide to a greater degree and strong risk avoidance strategies can be applied to decrease hazard severity. Several studies have been attempted to understand how extreme climatic conditions can trigger the landslide. The purpose of the research outlined in this paper was to know and determine the highly vulnerable region for landslide and the climatic condition that may lead to the catastrophic event. In particular, understanding the climatic factor and vulnerable zone will help to reduce the impact of the disaster on people's lives, their economic situation and also help in planning mitigation measures.

The objective of the study

1. To assess causative factors for landslide events.
2. To develop climate threshold for predicting landslides in Thrissur district.
3. To prepare landslide hazard zonation map for Thrissur.

REVIEW OF LITERATURE

CHAPTER 2: REVIEW OF LITERATURE

2.1 General overview

Natural disasters are unpredictable, life-threatening phenomena that are beyond human influence (Alimohammadlou et al., 2013). Further, it is categorized into different types based on the frequency of hitting such as landslides, tornadoes, flash floods, tsunami and droughts. In addition, disasters with a fast onset like landslides, have a significant impact on the global ecological systems and they have a wide range of consequences on the socio-economic systems. However, the lack of advanced early weather warning systems will further enhance the severity of landslide. Moreover, it is considered the world's third most dangerous natural hazard (Zillman, 1999). The major problem associated with landslides are usually unpredictably triggered and less time for the proper evacuation (Christopher et al., 2016).

Landslides have wreaked havoc on people and their livestock causing injuries and death which also cause damage to infrastructure, farm fields, and housing (Schuster and Fleming, 1986; JRC, 2003; Bloechl and Braun, 2005; Guzzetti et al., 2012). Economic losses stimulated due to landslides have risen in recent decades (Petley et al., 2005; Guha-sapir et al., 2012; Guzzetti et al., 2012), which was further intensified due to increased development and investment in landslide-prone regions (Bandara et al., 2013; Petley et al., 2005).

Several attempts have been made to assess the impact of landslides on socioeconomic structures (Mertens et al., 2016). The socioeconomic consequences of landslides are yet to be thoroughly investigated. For Sri Lanka until the late twentieth century landslides were considered as a minor disaster (Rathnaweera and Nawagamuwa, 2013). Until 2002, the annual total number of landslides in Sri Lanka was less than 50. Since 2003, the number of landslides rose sharply. According to studies conducted by Sri Lanka's National Building Research Organization (NBRO), the number of landslides has increased as a result of increased human activity, such as unplanned planting, non-engineered construction, and deforestation.

Lack of data was a major limitation that arises during the socio-economic impact assessments on landslide (Deheragoda, 2008). A publication by Crosta and Frattini (2001) emphasized the importance of having accurate databases containing all the information needed to study rainfall events. It is equally important that the type of information used must be carefully defined in order to enable a comparison between data produced by researchers operating in very different geographic contexts.

The major factor for landslide triggering is the changes in intensity and frequency of precipitation caused by global warming (Fischer and Knutti, 2015), which is expected increase in the future leading to further occurrences of landslides (Crozier, 2010; Gariano and Guzzetti, 2016; Saez et al., 2013).

Employing physical and empirical methods in evaluating rainfall thresholds helps in predicting the possibility of slope failures that may occur in an area (Campbell, 1975). Empirically based thresholds are typically used in warning systems. Rainfall forecasts, real-time rainfall monitoring and rainfall–landslide thresholds are an important element of the warning systems.

Recently, many countries use geological hazard information and rainfall thresholds for developing early warning systems (EWSs) (Baum and Godt, 2010; Graziella et al., 2015; Osanai et al., 2010). A study was conducted in China by Wang et al., (2016) for developing a real-time EWS by combining the global rainfall threshold along with the landslide and debris flow susceptibility.

The infiltration of rainfall across the slope results in changes in the pore water pressure, which reduces the shear stress further extending it to a slope failure

(Iverson, 2000). Studies were conducted by Chung et al., (2017) and Wu et al., (2017) in which they analysed the physical processes and the critical value of rainfall. This required extensive data collection methods including high spatial resolution geological information which were not feasible for larger regional and global scales (Posner and Georgakakos, 2015). On the other hand, it is much easier to use statistical methods of rainfall information on historical landslide events to determine lower boundary that result in slope failure. Statistical approaches including bayesian statistics (Guzzetti et al., 2007), logistical regression (Giannecchini et al., 2015), confidence level (Segoni et al., 2014) and quantile regression (Rossi et al., 2017; Saito et al., 2010) are applied in calculating rainfall thresholds suitable for larger regional scales.

Antecedent rainfall can be a predisposing factor in the activation of soil slips, according to a study done by Wieczorek (1987). In low-permeability soils, antecedent rainfall can be a significant impact because it reduces soil suction and raises pore-water pressures. In contrary to this, a study conducted by Brand, (1992) pointed out that antecedent rainfall is not an important factor in tropical areas. Corominas and Moya (1999) found that debris flows can develop in slopes covered with coarse colluvium with wide interparticle gaps without significant antecedent rainfall. Similar responses were witnessed in pervious soil in the presence of preferential groundwater passageways (Corominas, 2000). The enumeration of the impact of antecedent rainfall is difficult as it depends on several factors, including the regional climate, strength and heterogeneity of soil, and permeability properties. A result obtained from the study of Aleotti, (2004) show that there is no significant correlation existing between antecedent and critical rainfall.

Recent studies have reduced the complexity in quantification of the landslides impact on the socio-economic system, with the advancement in technical aspect of remote sensing, field investigation and socio-economic survey (Mertens et al., 2016).

Thus, it become necessary for warning systems, which employ thresholds, to predict the climate system that can trigger the landslides.

In the San Francisco Bay area, the USGS created one of the first warning systems (Keefer et al., 1987; Wilson and Wieczorek, 1995) dependent on the National Weather Service's quantitative precipitation rainfall forecast (QPRF), with a network of about 40 real-time continuous rainfall gauges, along with rainfall threshold that is required for the initiation of landslide (Cannon, 1985). A warning message was sent out when actual real-time readings and expected values approached the threshold. Similar warning systems were described, developed and adopted in many regions namely Hong Kong, South Africa, Japan, Italy, New Zealand, and Virginia.

An automated computer system for landslip warning was introduced by the Geotechnical Engineering Office (GEO) in Hong Kong, which is the world first in landslide forecasting (Premchitt, 1997). Rain gauges, radar and satellite imagery were used to monitor the movement and growth of rain-bearing clouds in this landslide warning system. Areas prone to landslides caused by rainfall, a warning threshold is introduced ahead of the actual triggering threshold (RBMCJ, 1985), which, if crossed, triggers emergency procedures. These warnings are broadcasted through television and local radio to the public at regular intervals.

2.2 Global Climate Change

Climate change is the changes in the state of the climate that can be identified by the long-term variations of its physical properties that persists for an extended period of time (IPCC, 2013). Global warming and climate change are the major concern of mankind in the 21st century. Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased tremendously as a result of anthropogenic activities. The global concentration of carbon dioxide increased primarily due to the combustion of fossil fuels, changes in the land use pattern. The gases like methane and nitrous oxide are increases primarily due to agricultural activities. Carbon dioxide is the most important greenhouse gas (GHG). Changes in the atmospheric concentration of GHG and aerosols, solar radiation and land surface properties alter the energy balance of the earth climate system. In addition, these changes are clearly visible in terms of radiative forcing, which is used to compare the extend of human and natural factors driven changes on global climate. The understanding of anthropogenic warming and cooling influences on climate has improved since the Third Assessment Report (TAR), leading to very high confidence that the globally averaged net effect of human activities contributing to global warming and it is unequivocal. Further, it causes the increases in global average air and ocean temperatures, widespread melting of snow and ice glaciers, and rising global average sea level (IPCC, 2007). Over the last century, atmospheric concentrations of carbon dioxide increased from a pre-industrial value of 278 parts per million (ppm) to which now soar past the scary threshold 416.3 ppm, and the average global temperature rose by 0.8°C (NOAA, 2021) (IPCC, 2013). Indian monsoon shown vagaries due to increasing global temperature and associated climate change. It is reported that there was a decrease of 4.51 per cent of all India summer monsoon rainfall.

Climate change is a multifaceted phenomenon with many and far-reaching implications for the environment and sustenance. Global climate trends and their consequences have been well understood, but locally applicable analyses are far smaller and of lower quality (Gopakumar, 2011). Several studies denoted that, climate change is real whose ill effects spread across various sectors like agriculture, socio economy, health and so on. Frequency of extreme events like flood, drought, heat waves, cyclones, storm surges etc (Mishra, 2017; Barnett, 2011; Carleton and Hsiang, 2016; Franzke, 2017) are also increasing (UNFCCC, 2009). Under changing climatic scenarios crop failures, reduction in yields, reduction in quality and increasing pest and disease problems are common and they render the cultivation unprofitable (IPCC, 2007).

Traditional development indices all have the issue of ignoring the impact of human and economic activity on the natural environment. Growing research suggests that economic development at the expense of the ecosystem is unlikely to be sustainable. Natural disasters and climate change pose a significant threat to long-term sustainability (Fang et al., 2019). According to Lampietti and Dixon (1995), global deforestation produces an average of 100 tonnes of carbon emissions per hectare, with a huge environmental threat and economic loss per tonne of carbon emissions to the atmosphere. This becomes a severe threat to both land and aquatic ecosystems and impact on human health and food security (Fang et al., 2019). Moreover, deforestation affects many geographical landscapes along with their climate change implications (Escolano et al., 2018). The climate change impact on carbon sequestration (Ward et al., 2014), ecohydrology (Van Vliet et al., 2013), biodiversity (Bellard et al., 2012; Pauli et al., 2012), and ecosystem service provision (Elkin et al., 2013; Fuhrer et al., 2014; Schirpke et al., 2013; Leitinger et al., 2015) all have been subjects of scientific discussion in recent years.

Southeast Asia, with a population of over 600 million primarily depends on agriculture and forestry for their livelihoods, ranks high on the impact of climate change vulnerability. According to Finlyson (2016) the impacts of climate change extends from shifting seasons that affect planting and growing periods; extreme heat, erratic rainfall and droughts, that makes farm planning difficult if not impossible, increased aridity and water shortages that reduce or wipe out yields; storms, floods and landslides that destroy crops, livestock and homes; increased salinity of farmlands caused by the rising sea levels; increased human, plant and livestock diseases; to lowered productivity of livestock, including fisheries. Extreme weather conditions are becoming more frequent, intense, and long-lasting, posing a serious threat to global food security and rural livelihoods. Climate change has long been recognised as having an impact on agriculture, with negative consequences on food production being frequently reported (Lobell et al., 2008; Pautasso et al., 2012). Many long-term climatic shifts have been observed, including changes in Arctic temperatures and ice, widespread precipitation changes, ocean salinity, wind patterns and extreme weather events, including drought, heavy rainfall, heat waves and tropical cyclone strength (IPCC, 2007).

2.3 Natural Disasters and its Impacts on Ecosystem

Natural disasters have catastrophic consequences on environment and living things in its vicinity (Sivakumar 2005). When viewing through an economic perspective, these events cause a widespread distress to the functioning of the economic system, with significant negative impact on assets including buildings and natural resources, production factors such as agriculture, employment, output or consumption as they are directly exposed to natural disasters and their unwelcome consequences (Hallegatte and Przyluski, 2010). Natural events that usually occurs become disastrous when they potentially cause death and injury to the population along with the destruction of natural and physical capital on which their quality of life and livelihood depend on. Climate change pull the strings by increasing the frequency and intensity of weather-related natural disasters. As remarked by NRC (1999), not all natural disasters result in significant ecosystem impacts. In some cases, extreme events actually had positive impacts, while, many of these impacts were non-market related and were exceptionally difficult to quantify and monetize.

Variations in the natural cycle and patterns have undeniable evidence pointing towards the global climate change. These changes, however, are strikingly exceptional; the global average temperature has been rising for at least the previous 2000 years (Jones and Mann, 2004), indicating changes in specific extreme occurrences such as hurricanes, floods, and drought. It's difficult to comprehend the fundamental principles involved, as these extremes are uncommon in nature, making data collection and comparison unfeasible. (Anderson and Bausch, 2006).

Climate change poses serious consequences which can impact on different time frames, some of which take longer time to uncover while others have sudden impacts which can attributed to extreme weather events. It is also crucial to consider the secondary effects of climate events that have an indirect impact on the environment. Climate-related extreme weather can be divided into three categories: as more frequent and severe simple extremes; secondly involving complex extremes requiring a combination of factors to occur; and lastly involving large catastrophic climate events, including ceasing of the thermohaline circulation. In recent years, a number of headline incidents have sparked alarm about extreme weather hazards which has far reaching consequence that have record setting highs (EEA, 2004).

2.3.1 Heat and Cold waves

Extreme temperature hazards such a heat and cold waves have serious impact on human and other living beings. The increased blood flow required by heat waves can be fatal for persons with failing hearts, as severe heat causes loss of water and salt in sweat leading to coronary and cerebral thrombosis. (Keatinge et al., 2000). Studies by Moberg and Jones (2005), showed that in Europe, daily high temperatures are rising more in summer than in winter, whereas Tank and Können, (2003), as well as Alexander et al., (2006) found that global temperatures are rising, and warm extreme temperatures are increasing twice as quickly as cold extremes. A study by Brunet et al., (2005) found that the rise in warm days is particularly pronounced towards the late twentieth century. Statistical studies indicate that increased risk of a severe heat wave is due to human influence (Brown et al. 2005) and is estimated that the risk possessed will be at least doubled (Stott et al. 2004). The extent of the rise in mean temperatures and the presence of strong extremes defy natural cycles, and climate change is the most likely explanation (IPCC, 2001; Schär, 2004). According to Beniston, (2004) occurrence of heat waves becomes three to ten times more likely by the end of the century. Heat waves that were formerly expected every 100 years could become ten times more common as a result of continued global warming. (Schär, 2004).

2.3.2 Windstorms and hurricanes

Temperature and precipitation trends are somewhat understood while the understanding on trends, characteristics and intensity of windstorm are still at its early phases and more information has to be delineated. Studies show that the results obtained on windstorm intensities and characteristics vary across different regions of the world (Ikelle, 2020). There is no clear pattern in windstorm frequency or magnitude, and there is enough ambiguity in time and geographic location to make a signal impossible to detect even if it occurs (Renggli et al., 2011). A study by Alexandersson et al., (2000) observed that intensity of storm was at peak during 1880s and has fallen and attained secondary peak at early 1990s.

Hurricanes are becoming significantly more intense, according to studies, and great progress has been made in identifying the impact of climate change on them. (Emanuel, 2020; Webster et al., 2005; Elsner et al., 2008). Scientists believe the increased frequency of storms is a result of natural cyclical fluctuations (Trenberth, 2005; WMO, 2005). It is widely discussed that increased frequency and intensity of hurricane is probably contributed by global warming. In spite of this, measurements show observable rise in the SST, which contribute to the strength of storm along with the convective available potential energy and column of water vapour above the sea surface (WMO, 2005; Trenberth, 2005). The projection on future storm trends is worrying and is obscure than temperature and precipitation trends. Even though studies reveal that climate change has a major impact on storm activity there is little consensus yet (IPCC 2001). Along with increased SST due to climate change and global temperature, more water vapour in the air offers more energy to storms and deepens low-pressure systems leading to high intensity storms (Frei et al., 1998; Emmanuel, 2005). In a scenario with twice current atmospheric CO2 concentrations, a simulation of hurricane intensity shows a threefold increase in the number of category 5 storms with catastrophic repercussions (Thomas and López, 2015).

2.3.3 Rainfall, and associated disasters

It is far more difficult to establish a relation between climate change and precipitation levels, as well as its influence to subsequent flooding and drought, than it is for heat waves (Wijngaard et al., 2003; Deque, 2003). Precipitation and floods are regular occurrences, whose variations in major weather are more difficult to detect and model by contrast drought can be clearly identified. Theoretically, an increase in temperature and ambient water vapour points to increased rainfall intensity in short periods of time, while in some places, this may lead to extended dry periods (McGregor et al., 2005). Climate modelling and observed precipitation changes are becoming more consistent (Tank et al., 2002), indicating a rise in average precipitation and an increasing tendency in the occurrence of high-intensity rainfall events (Tank and Können, 2003). Reports from UK (Osborn et al., 2000), the Alpine region (Frei and Schär, 2001) and Mediterranean were average amount of rainfall is declining, a rise in intense rainfall events are observed (Alpert et al., 2002), these patterns have been observed in other parts of the world as well (Alexander et al., 2006). Major disasters associated with rainfall includes floods, droughts and landslides, these all depends on the intensity, duration and intervals of rainfall events.

Flooding is the most common natural disaster, yet its patterns are difficult to determine since they are unpredictable. According to Milly et al., (2005), there is a probability that high-volume floods may increase in high-latitude locations in the future decades, however Rollerson et al., (2001) disagrees, claiming that there is no consensus among many global and regional researches. As noted by Frei and Schär, (2001), there is no evident increase in the frequency of floods because it is difficult to establish patterns in a limited data set of infrequent catastrophic events. According to models, winter precipitation will increase, making high rainfall winters two to five times more common than they are currently (Palmer and Räisänen, 2002), but summer precipitation would decrease. Floods, particularly flash floods, are becoming more likely as heavy rainfall increases. This is especially true in the winter, when more precipitation falls as rain rather than snow, posing a greater risk of runoff (EEA, 2004). Less rainfall but more intense precipitation in regions like the Mediterranean, resulting in a devastating combination of drought followed by high rainfall, resulting in destructive flash flooding. Desertification is caused by their combined effect, as well as forest fires and soil deterioration (EEA, 2003). Drought is highly likely due to a decrease in total summer precipitation combined with an increase in heat and surface drying (Parry and Carter, 1985; Tank et al., 2002). Drought has become much more common and severe and cyclical episodes may now be predicted every ten years, with highly intense events occurring every 40 years on average (Saunders et al., 2005). Changes in precipitation and the warmer temperature are also factors that contribute to this trend. According to a study by Dai et al., (2004), the global land area affected by severe drought has doubled since the early 1970s.

Usually rise in global average temperature and resulting extreme events and weather patterns are accounted to the rising GHG concentrations. However certain elements of global climate system changes abruptly, which has the potential to cause catastrophic changes that will come to light in a period of few years or decades. The well-known example of these catastrophic changes is cessation of the thermohaline circulation (THC) and disintegration of the West Antarctic ice sheet. The THC plays an important role in the global temperature distribution which get disrupted due to the changes in the temperature and salinity of the ocean water. Models suggest that the THC will be ceased completely and will be possibly irreversible by 2100 and would have serious consequence on global temperatures. The disintegration of West Antarctic ice sheet has severe consequences on global sea level rise. Over the next millennium the melting of these ice sheets yields to a three-metre rise in the global sea level.

2.3.4 Landslides and other hazards

A landslide is the movement of a mass of rock, debris, or earth down a slope, under the influence of gravity (WP/WLI, 1990; Cruden, 1991; Cruden and Varnes, 1996). Landslides are a serious hazard in many parts of the world and play an important role in the evolution of landforms. It causes more deaths and economic destruction than other natural disasters such as hurricanes, volcanic eruptions, and flooding. Because of the wide range of landslide occurrences, there is no single tool for identifying and mapping landslides, determining landslide risks, and assessing the risk associated with them (Guzzetti, 2006). Landslides are triggered by a number of factors, including heavy or prolonged rainfalls, earthquakes, rapid snow melting, and various human activities. It usually occurs as flowing, sliding, toppling, or falling movements, and many landslides show a mixture of two or more forms of movements (Varnes, 1978; Dikau et al., 1996; Cruden and Varnes, 1996). Landslides occur in wide range, making them one of the most diverse and complicated natural hazards it is observed both on land as well as seas and oceans. A landslide can range in size from a small soil slide of a few square metres to massive submarine landslides spanning hundreds of square kilometres of land and sea floor. Sub aerial and submarine landslides can generate tsunamis but are less frequent to occur when compared with earthquakes. Mapping and studies of submarine landslides suggested that only a few of them had potentially caused tsunamis and they were minor (Tappin, 2017).

The risk of a slope failure based on historical incidences of slope failures and their spatial distribution, as well as the effects of local topography factors on this distribution, is known as landslide susceptibility (Fell et al., 2008). This probability indicates how well a particular terrain can survive future slope movements (Guzzetti et al., 2005; Günther et al., 2013).

The influence of water causes oversaturation of soil mass on slope areas can be considered as one of the primary trigger off for landslides. This saturation can be facilitated from intense precipitation, rapid snowmelt, and changes in water levels along the coastlines, banks of lake, reservoirs, canals, rivers and ground water. Often debris flows and mudflows are mistaken as floods, as these events occurs simultaneously in the area under the influence of precipitation, runoff and saturation of ground in water.

Seismic and volcanic activity also have significant effect on the landslide. A moderate frequency earthquake itself make the mountainous areas vulnerable to landslides and avalanches. Volcanic activity on glacier covered mountain caps has a devastating effect as the volcanic lava melts the snow rapidly causing a deluge of soil, rock, ash and water to wash away anything on its way down the slope.

Landslides have irreplaceable effects on the natural environment. The mountain and valley morphologies both on the continents and beneath the oceans are most significantly affected by downslope movement of large landslide masses. The forests and grasslands that cover much of the continents and wildlife often are negatively affected by landslides, with forest and fish habitats being most easily damaged, temporarily or even rarely, destroyed (Balasubramanian, 2014).

Landslide Mitigation and Tools for Evaluation of Landslides

The site, type of human activity, use, and frequency of landslide events all influence landslide vulnerability (Paron et al., 2013). The impact of landslides on people and structures can be minimized by completely eliminating landslide danger zones or by restricting, prohibiting, or enforcing conditions on hazard-zone activities such as avoiding development and construction on steep slopes and existing landslides, or by stabilizing the slopes (Highland and Bobrowsky, 2008). Geologic, geomorphic, and hydrologic conditions play a key role in evaluating and analyzing landslides hazards and the future slope failures may occur as a result of the same conditions that caused past slope failures. Changes in natural topography or hydrologic conditions, can build and increase the vulnerability of the area to slope failures. Slope stability can be increased by construction of a retaining structure or placing the weight of a soil/rock at the toe of the landslide it can also be attained by preventing rise of ground water in the landslide mass by covering the landslide with an impermeable membrane and directing or draining surface water away from the landslide, and by minimizing surface irrigation (Highland and Bobrowsky, 2008).

Map analysis is one of the initial steps in landslide investigation, along with remote sensing, and monitoring are the major techniques for analyzing and evaluating the landslides (Scaioni et al., 2014). Map analysis involves analysis of different feature maps including geomorphology, topography, bedrock, soils and surficial geology (Metternicht et al., 2005). Conclusions concerning increased probability of landslide and susceptibility can be obtained by combining geological analyses of materials and process (Corominas et al., 2014) with knowledge of short- and long-term meteorological conditions (Kirschbaum and Stanley, 2018).

Analysis using aerial photography is essential method for the quick overview of the terrain, its geologic information and indicates human activities. (Rib and Liang, 1978; Barnett et al., 2004) Moreover, availability of aerial imagery from satellite images makes aerial investigation very versatile and cost effective (Vericat et al., 2009)

Land cover distribution of an area is another frequently used landslide inventory (Guzzetti et al., 2012; Bell et al., 2012; Reichenbach et al., 2014; Steger et al., 2016a). Major difficulty is faced during the mapping of landslides in forest regions using remotely sensed datasets (Brardinoni et al., 2003; Bell et al., 2012;

Petschko et al., 2016) due to difficulty in detection of small landslides and features in the woodlands through Aerial Photo Interpretation (API) thus, underestimating the apparent spatio-temporal landslide activity in forested areas.

Brardinoni et al. (2003) reported that portion of landslides which are visually not detectable in the rugged forest areas accounts for about 85 percent of the total number of landslides and the positional accuracy in this API based inventory depends strongly on the spatial resolution of the aerial image (Schwab, 1986; Rollerson et al., 2001). The usage of high-resolution Digital Terrain Models (DTMs) from Light Detection and Ranging (LiDAR) facilitated the identification by increasing the level of sophistication on landslide and terrain mapping (Petley, 2010) especially in forested areas (Van Den Eeckhaut et al., 2007; Bell, 2007; Anders and Seijmonsbergen, 2008; Petschko et al., 2016), thus, demarcating landslide areas and features of dense forest (Van den Eeckhaut et al., 2012; Chen et al., 2014), were ground truthing is literally impossible. Slope failures leave distinct features in the terrain, which are typically easy to see in hill shades from high-resolution LiDAR-DTMs. The appearance of various landslide characteristics such as scarp, rupture surface, and deposition area of the transported mass material can vary significantly.

Major limitations faced by maps and aerial photography is the difficulty in identifying subtle signs of slope movements. Moreover, it is difficult to identify major features in heavily forested or fully urbanized area and these features on an active slide, changes over time. Thus, field investigation is necessary to verify and detect these landslide features, to critically evaluate potential instability of vulnerable slopes and to identify past landslides using laboratory testing of soil and rock. Along with map analysis, aerial photography and field investigation, geophysical techniques can be used to determine the subsurface characteristics that can cause landslides. The geophysical techniques help to determine porosity, texture, geometry of units and consolidation of subsurface materials.

2.4 Factors Associated with the Root Cause for Landslide

Landslide movements and failure have significant social and economic implications that are potentially catastrophic. Diverse sources, including geological factors, morphological factors and physical and human activity, can trigger landslides (Cruden and Varnes, 1996; Griffiths, 1999). The triggers may be external disturbances like high rainfall, earthquake, rapid reclusion of reservoirs, which lead to increased shears along the failure surface or internal stimulation like progressive failure or weathering (Popescu, 1994; Terzaghi, 1950). The causes of landslides are of paramount importance and need to be acknowledged. It is only by correct diagnosis that the landslide dynamics and the development of preventive proposals can be understood (Popescu, 1994; Ma et al., 2017).

Landslide causal factors are divided according to their effect and origin, as ground conditions and geomorphological, physical or man-made processes. These factors are either preparatory or triggering function. Ground conditions includes the type and condition of material such as plastic, sensitive or collapsible material which are weathered, sheared, jointed or fissure typed oriented as mass or structural discontinuities with its effect on ground water and permeability. Ground conditions may not have a triggering function, while it may have a preparatory function. Geomorphological processes are based on physical feature or geological structure such as tectonic or volcanic uplift or formation by fluvial, wave, glacial or subterranean erosion or by loading of slope crest and vegetation removal. These processes usually have a triggering function. Physical processes such as intense short period rainfall, rapid snowmelt, prolonged high precipitation, rapid flood by high tide or breaching of natural dam or crater lake, earthquake, volcanic eruption and shrink and swell weathering of expansive soil are all triggering conditions for a landslide. Man-made processes including excavation of the slope, draw down of reservoirs, defective maintenance of drainage systems and irrigation, deforestation, mining and quarrying, creation of dumps of very loose waste, Artificial vibration of traffic, pile driving, heavy machinery (Popescu, 2002).

In all slopes there are forces that serve to improve downslope movement and to resist movement. The factor of safety F, of a slope is calculated by comparing the downslope shear stress with the soil's shear strength over an assumed or known rupture surface. Terzaghi, (1950) differentiated the landslide causes into external causes, which lead to increased shear stress and internal causes leading to decreased shear resistance by this factor of protection. While contrary to that Varnes, (1978) points out that there are a variety of external and internal factors that can both tend to increase or decrease shearing stress.

In most cases, landslides are the result of several factors that are interrelated. The process that leads to the formation of a slide originates with the rocks basic qualities being identified, along with subsequent processes such as crustal motion, erosion, and weathering. Ground conditions are important factors in the development of an unstable slope, and they are exacerbated by environmental factors such as stress, pore water pressure, temperature, and precipitation (Kadry and El Hami., 2015; Varnes, 1978). Thus, the strength of the ground barely matters and failure occurs as a result of the effective causal process which can be either natural or anthropogenic, that sufficiently changes the ground conditions adequate to adversely change the stability state and cause the slope failure (Popescu, 1984).

Physically, slopes can be characterised as stable, slightly stable, or actively unstable (Crozier, 1986). Marginally stable slopes will fail at some point in reaction to destabilising forces after reaching a certain degree of activity, whereas stable slopes have sufficient stability to survive all destabilising forces. Finally, actively unstable slopes are particularly sensitive to destabilising forces that cause continuous or intermittent movement. Destabilizing processes can be divided into two categories based on their temporal variability: slow-changing processes like weathering or erosion, and fast-changing activities like earthquakes and drawdown. Slow changes take long periods to overcome or diminish the shear resistance while fast changes can be recognised as having triggered movements.

2.4.1. Soil type and landslide

The particle size of the soil has a significant influence over, drainage, and cohesion of soil material. Soils with larger particle size drain water more readily due to its less attractive force and lack of binding make them highly vulnerable to stresses. Thus indicating soils with larger particles are very low in cohesion and very high in drainage (Wynn and Mostaghimi, 2006b) and are easier to erode. Another indirect measurement that can be aided determining cohesion and size of the sand particle is bulk density. Soils with smaller particles have high bulk density and it also behave variably under the influence of different factors like compaction.

Amount of soil that a root can anchor depends on the soil type and its soil particle. Smaller particles in the soil help roots to attach against more of the soil's surface area, reducing the number of roots pulled out (Wynn and Mostaghimi, 2006a). Clay has a natural ability to bind with itself, making it resistant to external forces.

The number of landslides was highest for negative or near-zero curvature when considering the land's curvature and topography. The number of landslides dropped as the curvature of the slope changed from convex to concave, indicating that landslides were focused on concave slopes. It is because there is a possibility that concave areas hold water better than convex areas, hence an increase in soil moisture content could cause a landslide.

Landslide potential can be indicated by stratification of soil components. Different strata erode at different rates, resulting in unstable circumstances that are exacerbated as water flows between layers, causing additional erosion and stress throughout the site (Shields et al., 2009). Other factors that increase the effect of stratification include soil type, height, and inundation. Erosion rates are higher on stream banks with stratified soil layers.

Low bulk density soils drain water quickly, resulting in dry conditions for plants whereas high bulk density soils have smaller particle sizes, which generate greater cohesion and attraction between particles. Moisture is needed for the roots to give stability and protect them from freezing damage (Pollen, 2007), as well as to maintain resistance to pulling out because there is more surface area for root hairs to connect to and anchor (Wynn and Mostaghimi, 2006b). Due to compaction and gravitational forces, deeper soils have a larger bulk density and fewer roots (Piercy and Wynn, 2008).

Percolating water is forced laterally out when a resistant layer of clay or bedrock obstructs its path to the water table (Pollen, 2007) thus surrounding soil particles become more unstable and stressed (Wynn et al., 2004).

2.4.2. Hydrological causes of reservoir landslide movements.

According to a study conducted by Ma et al., 2017, as a result of the Majiagou landslide in the Three Gorges Reservoir, there were more than two sliding surfaces, with the primary sliding occurring along a deep weak mudstone interlayer and the other sliding surfaces involving shallower deposits that developed progressively under the combined action of prolonged heavy rainfall and water level fluctuations. In fact, the water level in the reservoir was low and the slope was stable prior to the initial impoundment. Deformations occurred along the primary slip surface as the water level rose, followed by movement along the secondary slip surface. Second slip surface daylighting led to the formation of a tertiary slip surface. Rainfall is thought to be one of the causes of landslide movement in the Three Gorges Reservoir area.

Landslide instability is likely to be induced by variations in rainfall patterns, such as very short-lived high-intensity showers or long-duration less intense showers, combined with fast changes in water levels in case of reservoirs (Westra et al., 2014). As the ground is permeable, most of the water infiltrates into it after prolonged and strong rainfall. Rising water levels in the reservoir and seepage of water cause an increase in pore-water pressures, which causes softening of the materials on the slip surface, lowering shear resistance and effective normal stress, resulting in reduced stability and landslides (Yang et al., 2018; Igwe and Fukuoka, 2015). Furthermore, water may weaken the slip surface's mechanical strength, speeding up movement.

Slope modification, drainage, retention structures, and internal slope reinforcement can all be used to rectify or control landslides, as well as any combination of these four main strategies (Popescu, 2002).

2.4.3. Impact of Land Use Land Cover Changes on Landslide

Land use change is a mechanism by which human actions alter the natural environment, with a focus on the functional role of land for commercial activities. These changes are often nonlinear, and they can cause systemic feedback, stress living environments, and put people at risk (Paul and Rashid, 2017). It is also a matter of serious worry which is debatably the most pervasive socio-economic power, driving changes and degradation of ecosystems. On landslide susceptibility, there is still much to learn about the influence of LULC dynamics. The majority of the fundamental reasons of land use change, such as resource scarcity, increasing vulnerability, and changes in social organisation, are emergent. Changes in land use pattern affects both physical and chemical properties of soil, depending on the intensity and type of use. In addition to human activities, landscape transformation is strongly driven by land use and climate change. Changes in land use are typically discussed as secondary causes of landscape transition, functioning implicitly through their impact on climate change (Pielke, 2005). Advanced research is required to unravel the interactive effects of both the processes.

Climate change impacts are high in agriculture land use. For the normal growth of a crop there are normal temperature and rainfall pattern. If the temperature and rainfall pattern is deviated from the normal pattern for the normal growth of crops, crop production is decreased. Farmers usually change the land use by modification of agriculture, if the temperature increases continuously. Further, the farmers may migrate from the area as well if the production is not satisfied (IPCC, 2011). Deforestation alters the terrain mostly for the purpose of increasing land farmed areas or soil sealing for urban centers and infrastructure. Another challenge leading to landscape transformation is the fragmentation of land holdings due to population pressure, steering to land use intensification and declining of traditional agroforestry system for promoting monoculture with emphasis on commercial model of agriculture development (Jose and Shanmugaratnam, 1993).

Land-use transitions and changes have been addressed globally (Hertel, 2011; Lambin et al., 2001; Lambin et al., 2014; Vliet et al., 2015) as well as in the Indian context (Saikia et al., 2013; Islam et al., 2015), with the main focus on land-use and land-cover changes in agriculture-forest ecotones (Jose and Padmanabhan, 2016). Rainwater infiltration was found to be rather large due to unplanned tea planting on the upper slope, according to a study done in Sri Lanka. As a result of the intense, sustained rain, pore-water pressure built up, causing substantial destabilising forces on the slope (Matsuura et al., 2008). Mugagga et al. (2012), in contrast to this study, investigated deforestation and cultivation of steep slopes on Mount Elgon (Uganda) and found that tree roots stabilised the slopes. Changes in regional land use have an impact on the geographical and temporal probability of slope stability (Vanacker et al., 2003; Van Beek and Van Asch, 2004; Reichenbach et al., 2014).

LULC modifications have been shown to have a significant impact on slope stability in studies. Innovative approaches have been proposed to determine the abiotic and biotic drivers of future LULC changes, such as climate and topography, as well as biotic factors such as species dispersion and plant diversity (Shu et al., 2019). These methods use statistical techniques like binomial regression or machine learning techniques like neural networks to analyse observational datasets containing a variety of LULC categories (Hyandye et al., 2015; Khawaldah, 2016; Patil et al., 2017). This aids in the incorporation of spatial data from protected areas, road networks, and other land use categories into the research (Jiang et al., 2015; Yirsaw et al., 2017; Liping et al., 2018). Thus landscape managers and researchers can use the LULC models and high-quality landslide inventories to predict near and mid-term changes, which can be used to calibrate and validate landslide susceptibility models. It may be used to assess and advise decisions based on simulated scenarios and physical slope stability model performance (van den Eeckhaut et al., 2010; Petschko et al., 2016).

Vegetation has an important function in slope stabilisation against landslides and has been studied from a geotechnical standpoint (Mao et al., 2014; Liu et al., 2016). The accompanying land use and land cover can be connected to the variation in landslide density across slopes (McGuire et al., 2016). As a result, gathering information on land use and land cover patterns is crucial and must be taken into account in order to reduce the risk of slope failure. The Wu model (Wu et al., 1979) and the fiber-bundle model were used to quantify the reinforcement of slope stability by vegetation (Kun et al., 2006).

Studies have focussed on the hillslope reinforcement by forest dynamics on a spatio temporal scope (Rickli and Graf, 2009; Ghestem et al., 2011; PapathomaKöhle and Glade, 2013). When considering forest land use pattern trees has the ability to stabilise the hillslope using roots to anchor the underlying soil mantle. Additionally, roots help to lower the soil moisture by assimilation. When forest land use is changed by clear cutting the forest, it has far-reaching consequences because the removal of canopy cover allows infiltration of rainwater quickly, causing soil saturation to occur much faster. Cohesion force of the roots also decline reducing the slope stability (Sidle and Ochiai, 2006).

In areas where hillslopes are subject to agricultural and silvicultural activity, there is a periodic change of timber harvesting and afforestation practises (Marden and Rowan. 1993). Glade (2003) found that certain locations that are subjected to periodic anthropogenic change have a higher likelihood of landslide triggering events. When building a multitemporal landslide inventory for the goal of investigating potential land cover related effects on landslide incidence, these places are to be given special attention. Even though understanding the risk and danger lurks of agro forests and agricultural activities along the slope, its significant contribution to the socio-economic system and financial benefits to the engaged communities cannot be pretended as not seen, thus, accepting these high risks.

2.4.4. Effects of vegetation on combating landslide

Deforestation can play a significant role in the probability of landslide events. Persichillo et al. (2017) discovered that abandoning agricultural land increased the vulnerability of landslides in the northern Italian Apennines. There have been further studies on the influence of natural vegetation regeneration (Rickli & Graf 2009; Chen & Huang 2013) that have shown vegetation to be an important factor in decreasing the chance of shallow landslides, with forests having a particularly large impact due to their deeper roots. Schmaltz et al. (2017) used long-term landslide inventories in Austria to construct an empirical correlation between slope failures and forest cover. Forested areas are less susceptible to failure than other vegetation types, according to all of these research.

Plant roots improve soil stability by binding sediments, resulting in more stable soils (Wynn and Mostaghimi, 2006b). Soil particles will be bound together by the roots, providing higher cohesiveness (Edmaier et al., 2011). The amount of vegetation and its subterranean root networks, root structure, number, and depth, as well as the type of soil material that helps the soil bind together and improves resistance to outside shear pressures, all influence cohesive strength (Brooks et al., 2003; Wynn and Mostaghimi, 2006a).

Due to differences in the size and strength of their roots, herbaceous and woody plants give varied levels of stability. Trees have a greater maximum rooting depth than herbaceous plants (Canadell et al., 1996). Different species of vegetation help in preventing erosion, but the efficiency varies depending on root depth, root size, root density, and patterns, as well as plant species, site conditions, and a variety of other factors (Piercy and Wynn, 2008).It's crucial to understand how roots create stability in order to comprehend this process.

Roots offer mechanical stability; they actually hold the soil against erosive forces (Pollen and Simon, 2005), which is commonly recognised; yet, the precise processes that produce this stability are poorly understood. Soil buttressing, altering hydrology, and actual root reinforcement are all examples of these processes (Abernethy and Rutherfurd, 1998). Researchers and modellers employ tensile strength, or the force necessary to break apart a single root when tugged, to compute the failure point for a bulk of soil based on the suspected strength of the roots within that region. Root strength is influenced by a variety of factors making root reinforcing complicated and variable (Pollen and Simon, 2005). Depending on their size, density, and other characteristics, each root has a distinct tensile strength (Pollen, 2007).

Major factor that has to be put into consideration when estimating a soils failing point using tensile strength is the chronological breaking and root differences. Old roots which get weaker with time break easily when subjected to stress while comparing with that of younger roots. The tensile strength of larger and denser roots is higher thus they are more difficult to break when pulled. When weaker roots break, the tension is redistributed to all other roots (Pollen and Simon, 2005). Stress is extensively concentrated in a few regions rather than being uniformly dispersed throughout the region. As a result when subjected to the same forces, not all roots will respond the same and will reach their maximum strain before breaking due to these variances. It is not necessary that roots will straighten before breaking (Pollen and Simon, 2005) if so happen it can redistribute the stress and absorb more force which increase the strength of the soil than expected from the tensile models (Pollen, 2007). Other conditions, such as flooding, might cause a root's tensile strength to deteriorate. When the section where the root breaks is weaker than the rest of the root, tensile strength might be deceiving.

When compared to small plants and roots, longer roots are more favourable because they have a larger surface area that interacts with the soil, enhancing resistance to uprooting (Edmaier et al., 2011). Soil moisture plays a significant influence in lowering soil cohesive strength, which means there's a higher likelihood of uprooting, which means the soil is less stable.

Human-caused erosion can be reduced through the development of restoration efforts and conservation strategies. Plant and root qualities can help to support the soil and reduce erosion (Wynn and Mostaghimi, 2006b). However, because there is limited information on root patterns and density, prescribing natural solutions to erosion and landslips is challenging. As a result, it is critical to prioritise a study to determine the use of vegetation for restoration and conservation of locations with significant erosion and infiltration rates. A research conducted by Underhill (2013), aims to give insight into erosion, restoration and conservation aspects of environment. The observations from his studies ascertained the need for understanding and acquiring more information about the root density across diversified environment, quantifying differences in erodibility using erosion predicting tools by using known plant and root properties and also provided insight for further restoration and conservation activities.

Usually, in root studies, trenches are dug to analyse plant root immediate to their natural environment. A study on roots by Weaver (1968) in a prairie environment observed that the roots grew quickly to depths more than 30 inches within a year of its growth. This was achieved due to water-scarce environment with very deep water tables. When considering riparian environments, roots need not run deep for water and nutrients as they are copious and shallow (Abernethy and Rutherfurd, 1998). Thus, it becomes evident that, abundant nutrients, nitrogen fertilizer and excess moisture impedes the growth and promotes branching of roots laterally instead of deeper reducing the root strength to anchor the soil (Weaver, 1968). However, root depth in riparian areas is substantially lower than predicted by prior studies in other habitats.

The root density and depth determine the amount of protection and stability supplied by a plant root. Deeper roots would be able to stabilise the soil more effectively and reduce erosion. An increased root density provides greater stability and strength for the soil (Wynn et al., 2004). Long, infrequent roots indicate good value of root depth, and low value for root density.

There are two basic consequences of soil saturation and flooding on roots. In the first place, roots that are saturated with water cannot take in oxygen. Oxygen diffuses slowly through water, limiting the amount of oxygen available in the soil while preventing oxygen replenishment. As the root loses oxygen, its strength deteriorates (Pollen, 2007). Second, soil saturation decreases its stability. As water, decreases the friction between soil and root it become difficult to grip the soil (Wynn and Mostaghimi, 2006b). Roots, on the other hand, can provide additional benefits by removing excess water from the soil and therefore strengthening its stability (Shields et al., 2009).

2.5 Advancement in Early warning system to predict landslide

Climate change is accelerated by human actions, despite the fact that it is a natural phenomenon. Climate change disaster policy is influenced by a number of factors, including ability to accept climate change as a reality and institutions capacity and willingness to integrate climate change risk assessment and management into development goals. These circumstances aren't uniformly present yet. An approach that ignores the importance of building capacity and resilience as a prerequisite for managing climate change risks is unlikely to lessen vulnerability to such risks. A crucial part of decreasing climate change risk is reducing vulnerability. This necessitates the need of changes in institutional structures and relationships along with novel approaches to combat the risk of climate change (O'Brien et al., 2006).

Recent landslides and debris flows have impacted natural resources. Every year, these events result in the deaths of people, the damage of property, economic losses, and severe environmental consequences. Intense rainfall has caused the majority of landslides and debris flows (Kubota, 2009). The relationship between rainfall and landslides has been studied in several places of the world by analysing landslide-triggering rainfall. Cumulative rainfall, antecedent rainfall, rainfall intensity, and rainfall duration are the most extensively studied rainfall characteristics in connection to landslide initiation. Various combinations of these parameters have been used to try to define thresholds. As extreme rainfall causes the majority of slope failures, a number of studies (Crozier, 1999; Glade et al., 2000; Wieczorek et al., 2000; Aleotti, 2004; Guzzetti et al., 2004; Hong et al., 2005; Giannecchini, 2006) have sought to develop rainfall intensity thresholds so that accurate slope failure predictions may be generated. Rainfall threshold defined in these studies were developed in terms of rainfall intensity, cumulative rainfall, ratio of antecedent-daily rainfall and duration-intensity ratio. Caine (1980) was the first to define landslide rainfall thresholds over the world. Similar threshold values were adopted in several studies across the world namely in California (Wieczorek et al., 2000), the Southern European Alps (Ceriani et al., 1992), pre-Alpine and Piedmont regions of Italy (Aleotti, 2004; Guzzetti, 2004), Japan (Hiura, 2005). A study in the Nepal Himalayas, Dahal and Hasegawa (2008) examined representative rainfall thresholds for landslides. A comprehensive characterization of the rainfall condition that generates landslides and debris flows is required in order to design a warning system. As a result, empirical rainfall intensity-duration limits for landslides and debris flows are critical.

There are two kinds of rainfall thresholds that can be defined in general: empirical and physical thresholds (Aleotti, 2004). The empirical thresholds are relational values derived from a statistical investigation of the rainfall-landslide relationship (Crozier, 1999; Guzzetti, 2004). Physical thresholds are typically characterised and defined using hydrologic and stability models. It takes into account a variety of factors, including rain and pore water pressure correlations as well as suction and infiltration along with bedrock structures and slope morphology (Crosta and Frattini, 2001; Jakob and Weatherly, 2003). Antecedent rainfall is also crucial in determining rainfall thresholds (Crozier, 1999; Rahardjo et al., 2001). Critical precipitation is defined as the amount of rain that falls between the moment ("zero point") when a sharp rise in rainfall intensity is recorded and the first landslide occurs. The slope of the rainfall's cumulative curve is significantly broken as a result of this rise.

Linear regression analysis was used to determine empirical rainfall intensity-duration thresholds for landslides and debris flows. Rainfall intensity grows exponentially as duration decreases, according to the regression analysis. According to study of the Mt. Bawakaraeng caldera indicated that the regression value of rainfall intensity duration before a large-scale landslide was higher than after the landslide. This result was obtained due to the geomorphology of the Mt. Bawakaraeng caldera that has changed since the large-scale landslide. In comparison to the scenario before the large-scale landslide, the caldera has become more vulnerable to debris flows and landslides even in less intense rainfall. Before and after the large-scale landslide, the area's sensitivity to the occurrence of landslides or debris flows was considerably different. The rainfall intensity-duration regression value was higher when compared with scenario prior to large-scale landslide. Thus, if the threshold after the large-scale landslide is applied, the rainfall warning will be more effective. The regression curve can be regarded as a dependable rainfall intensity-duration threshold, above which landslide or debris flow occurrences are possible (Hasnawir, 2013)**.**

MATERIALS AND METHODS

CHAPTER 3: MATERIALS AND METHODS

3.1 Study area

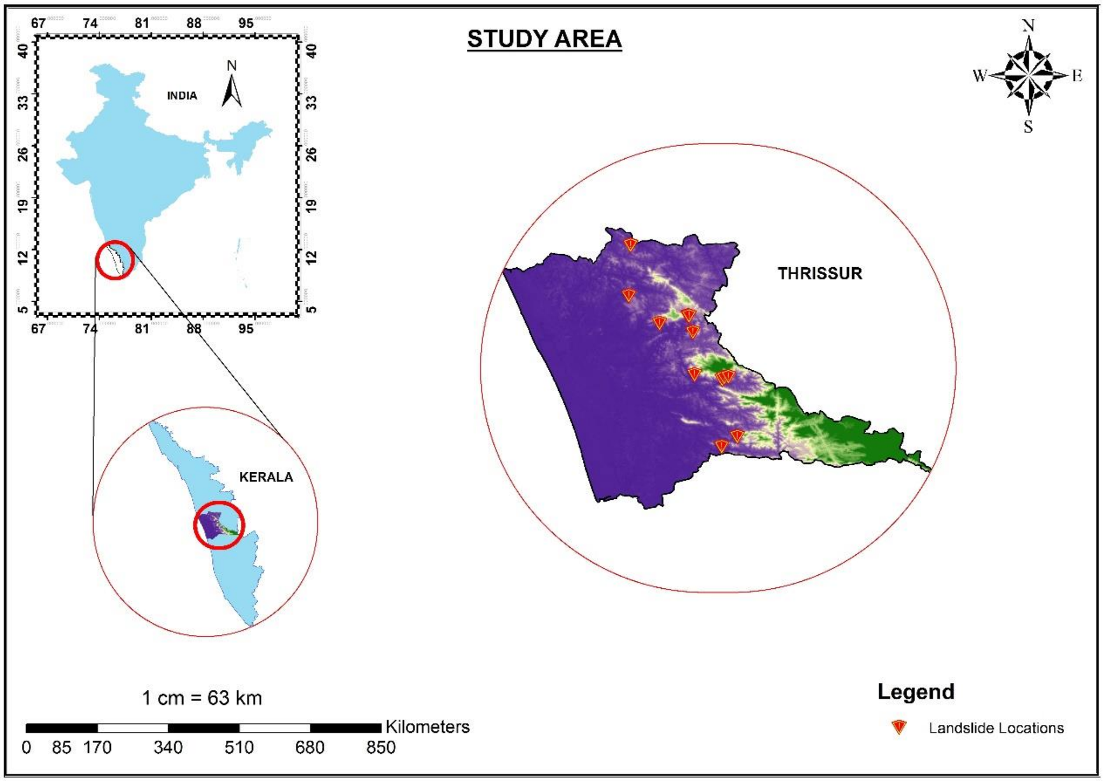

Figure 1. Location of study area.

The study area is located in Thrissur (Figure 1). The district of Thrissur is situated in the southern Indian state of Kerala, bordered on the north by the districts of Malappuram and Palakkad, on the east by the Palakkad district and Coimbatore district of Tamil Nadu, on the south by the district of Ernakulam, and on the west by the Lakshadweep Sea. The city is located between 10°10' - 10°47' N latitude and 75°57' - 76°55' E longitude with an area of 3032 sq. km and the highest elevation of 1218 m and a coastal line of 54 km. The geography of the study area changes from the hillock towards the midland and to the lowland where Thrissur Kole Wetlands is located. The Kole Wetlands serve as a major natural drainage for the region where the water flows to the river and from there to the Laccadive Sea, thereby keeping the town of Thrissur protected from the floods that threaten most of the other cities in Kerala. The major rivers that drain through the district are Periyar, Chalakudy, Karuvannur, and Bharathapuzha. Geologically, the region is made up of archaeans gneisses, charnockites, basic dykes, and crystalline schist. Major parts of the study area are composed of archaean rocks, and the biotite granite gneiss is the major rock type among the archaeans. The area lies in the center of the Indian tectonic plate and is prone to very little seismic activity.

Thrissur has a humid tropical climate under the Köppen climate classification, with a very hot summer and a heavy monsoon. Summer is the hottest period of the year between March and May. Due to high levels of heat coupled with excessive humidity, the summer months are unpleasant with daytime temperatures reaching 36 to 38 °C. Summer is accompanied by the South-west monsoon, from June to September. The region receives Northeast monsoon from October to December. Due to winds from the Western Ghats, winter is cooler and windier from December to February. Weather conditions throughout the winter are usually drier and less humid than other times of year. The mornings are cool, while the daytime temperatures are nearly reaches 30 °C.

Heavy rains deluge the region during the monsoon season. The annual rainfall is estimated to be around 300 cm. The South-west monsoon usually arrives in the last week of May, and rainfall diminishes by July. Each year, there are 124 rainy days on average. The maximum average temperature in the summer is 36 °C, while the lowest recorded temperature is 27 °C. A maximum temperature of 31 °C and a minimum average temperature of 20 °C are recorded during the winter season.

3.2 Selection of sample

Soils collected from the landslide inflicted regions in Thrissur were used in this study. The major landslide regions, was given the primary focus in this study and those were Chalakudy, Vadakkanchery, Pattikad, and Chimmony. All of these regions had multiple landslide incidents and some of them almost occurred annually. The most devastating landslides occurred during the monsoon season of 2018 & 2019.

3.3 Data collection

3.3.1 Primary Data collection

Soil samples were collected from the cut-of and exposed sides of the landslides using iron core by hammering horizontally into the soil profile. At Landslide sites with no exposed sides, pits were dug and soil was collected at various height across the profile.

From the collected soil, soil parameters such as soil texture, pH, organic carbon (OC), cation exchange capacity (CEC), and base saturation were determined in the laboratory. Appropriate methods were used for each of the parameters and procedures were strictly followed.

i. Soil Texture Analysis

Using the Bouyoucous-hydrometer method 50g of soil sieved in a 2mm sieve and 50ml of 6% hydrogen peroxide (H_2O_2) were mixed and kept in a water bath for half an hour at 70°C. Soil was pre-treated with H_2O_2 to eliminate the organic content from the sample. After the water bath treatment, 100ml of 5% calgon solution (sodium hexametaphosphate) was added to the sample. The sample was then stirred for 5 minutes in a mechanical stirrer and the sample was emptied into a measuring flask and made up to 1L and then manually stirred for another 1 minute. Four minutes after stirring the density of the sample was taken using a hygrometer. Similarly, after 2 hours the density was again noted.

From the values noted at the end of 4th minute and 2 hours, the percentage of sand, silt, and clay was obtained using the formula,

$$Clay\ \% = \frac{C_v + R_{2hour}}{W_{soil}} * 100$$

$$Silt\ \% = \frac{(C_v + R_{4min}) - (C_v + R_{2hour})}{W_{soil}} * 100$$

$$Sand\ \% = 100 - (\ Silt\ \% + Clay\ \%)$$

where,

R_{2hour} = Reading at 2hour, R_{4min} = Reading at 4th minute, W_{soil} = Weight of soil.

ii. pH Analysis

For the analysis of Soil pH, 10g of soil sieved through a 2mm sieve was used. 25ml of water was added and agitated for half an hour and tested in pH meter.

iii. Organic Carbon Estimation

For the estimation of soil organic carbon, the Walkley-Black wet digestion method was used. For this method, soil samples sieved in 0.2mm were used. In a conical flask, 0.5g of the soil sample was taken and 5ml of potassium dichromate ($K_2Cr_2O_7$) and 10ml of sulphuric acid (H2SO4) was added and kept for 30 minutes. 20ml of distilled water was added into the conical flask and kept for another 10 minutes. A few drops of ferroin indicator was added and titrated against freshly prepared Ferrous Ammonium Sulphate (FAS). The endpoint of the reaction was taken as colour change from green to wine red.

The percentage of organic carbon was determined using the formula,

$$Organic\ Carbon\ \% = \frac{(T_0 - T_v) * N_{FAS} * C_{eq.K_2Cr_2O_7}}{W_{soil}} * 100$$

where,

T_0 = Blank value, T_v = Titre value, $C_{eq.K2Cr2O7}$ = Carbon equivalent of 1ml 1N $K_2Cr_2O_7$, N_{FAS} = Normality of FAS, W_{soil} = Weight of soil.

iv. Cation Exchange Capacity (CEC)

For the estimation of CEC amount of readily exchangeable cation in the soil like Calcium (Ca), Magnesium (Mg), Sodium (Na), and Potassium (K) were extracted using Ammonium acetate (NH_4OAc) and estimated.

Soil sieved in a 2mm sieve was used. 5g of soil was mixed with 25mL of neutral ammonium acetate, shaken for 5 minutes and filtered immediately using a filter paper. The same filtrate was used for the estimation of Ca, Mg, Na, and K. Ca and Mg was estimated in AAS, and Na and K in a flame photometer.

3.3.2 Secondary Data

i. Rainfall data

Past ten-year rainfall data from 2010-2019 were used in the study. The rainfall data of landslide affected regions of Chalakudy, Thrissur, and Wadakkancherry were taken into account. Rainfall data of these locations from 2010-2014 were obtained from ACCER, KAU, Vellanikkara. Rainfall data from 2015-2019 of Chalakudy, Thrissur, and Wadakkancherry were obtained from RARs Chalakudy, KAU Agromet Observatory Vellanikara, and Wadakkancherry respectively.

ii. Satellite Image and Digital Elevation Model

Satellite Image with 10m resolution of the study area was obtained from SENTINEL 2A satellite from USGS Earth Explorer. The Satellite image was used for determining the vegetation, Land Use Land Cover (LULC). A 30m resolution Digital Elevation Model (DEM) of the study area was obtained using the satellite, ASTER from the NASA website EARTHDATA. Drainage map, slope, flow direction was delineated from DEM, and geology and soil type were digitized and processed in ArcGIS 10.6 version. ArcGIS was also used for the hazard zonation mapping of Thrissur.

3.4 Fragility Index

The methodology of hazard zonation involved assigning weights for the potential causes of landslide and ranked the terrain into various categories of fragility according to its total weightage. Terrain fragility was evaluated by considering all the parameters obtained from the study area. All the maps created from the study area were converted into 30 m x 30 m resolution and divided into grids (total 32721 grids for an area of 2944.9 sq. km). These grids were superimposed over each factor map and the corresponding weight of each factor was allocated to all grids. The overall weight value for each grid of the study area was determined after the procedure was repeated for all of the factor maps. The grids were classed into highly fragile, fragile, moderately fragile, and stable based on the cumulative weight value of all parameters, resulting in the creation of a fragility (zonation) map. In addition to providing a general picture of the segment's fragility, the output provides particular hot spots. Fragility index was used to calculate the segment's total terrain fragility:

Fragility Index (FI) = Total weight value of grids (W) /Total no. of grids (G).

Climatic threshold for predicting landslide

The empirical rainfall thresholds model was used in this study (Figure 2).

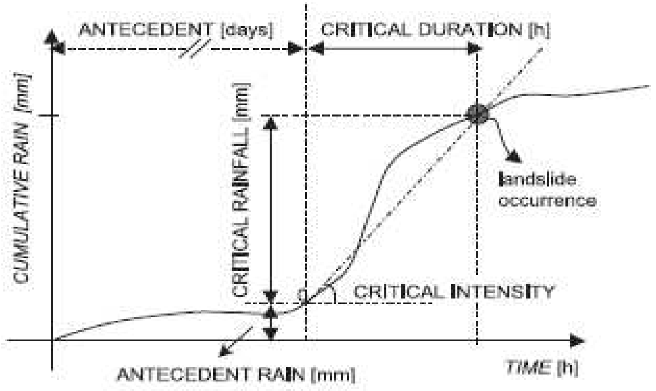

Figure 2. Schematic diagram of Antecedent rain, Critical intensity and duration leading to landslide occurrence.

The linear regression analysis that coupled rainfall intensity and duration was used to generate empirical rainfall intensity-duration thresholds for landslides and debris flows. Before the large-scale landslide, the rainfall intensity-duration regression equation was $I = 41.85D^{-0.85}$, and the latter was $I = 37.71D^{-0.90}$, where I denotes rainfall intensity (mm/hr) and D denotes rainfall duration (hr) (Hasnawir, 2013).

RESULT AND DISCUSSION

CHAPTER 4: RESULT AND DISCUSSION

The results of the study titled “Assessing landslide vulnerability and developing climatic triggering predictors for Thrissur district” are outlined and discussed hereunder.

4.1 Distribution of landslide

Table 1. Landslide affected regions of 2018 & 2019 included in the study.

Sl. No.	Local Name	Location	Range	Year
1	Choolakadavu	Pariyaram	Pariyaram	2018
2	Thumboormuzhi	Konnakuzhy	Pariyaram	2018
3	Kottambathoor	Deshamangalam	Wadakancherry	2018
4	Kurancheri	Minalur	Wadakancherry	2018
5	Cheeni	Chimmoni	Chimmoni	2018
6	Ayyappankundu	Chimmoni	Chimmoni	2018
7	Poothode	Chimmoni	Chimmoni	2018
8	Goshmukku	Mannamangalam	Pattikkad	2018
9	Thonnickal	Pattikkad	Pattikkad	2018
10	Poovanchira 1	Vazhukumpara	Pattikkad	2018
11	Poovanchira 2	Vazhukumpara	Pattikkad	2019
12	Chirakkakode	Vellanikara	-	2018

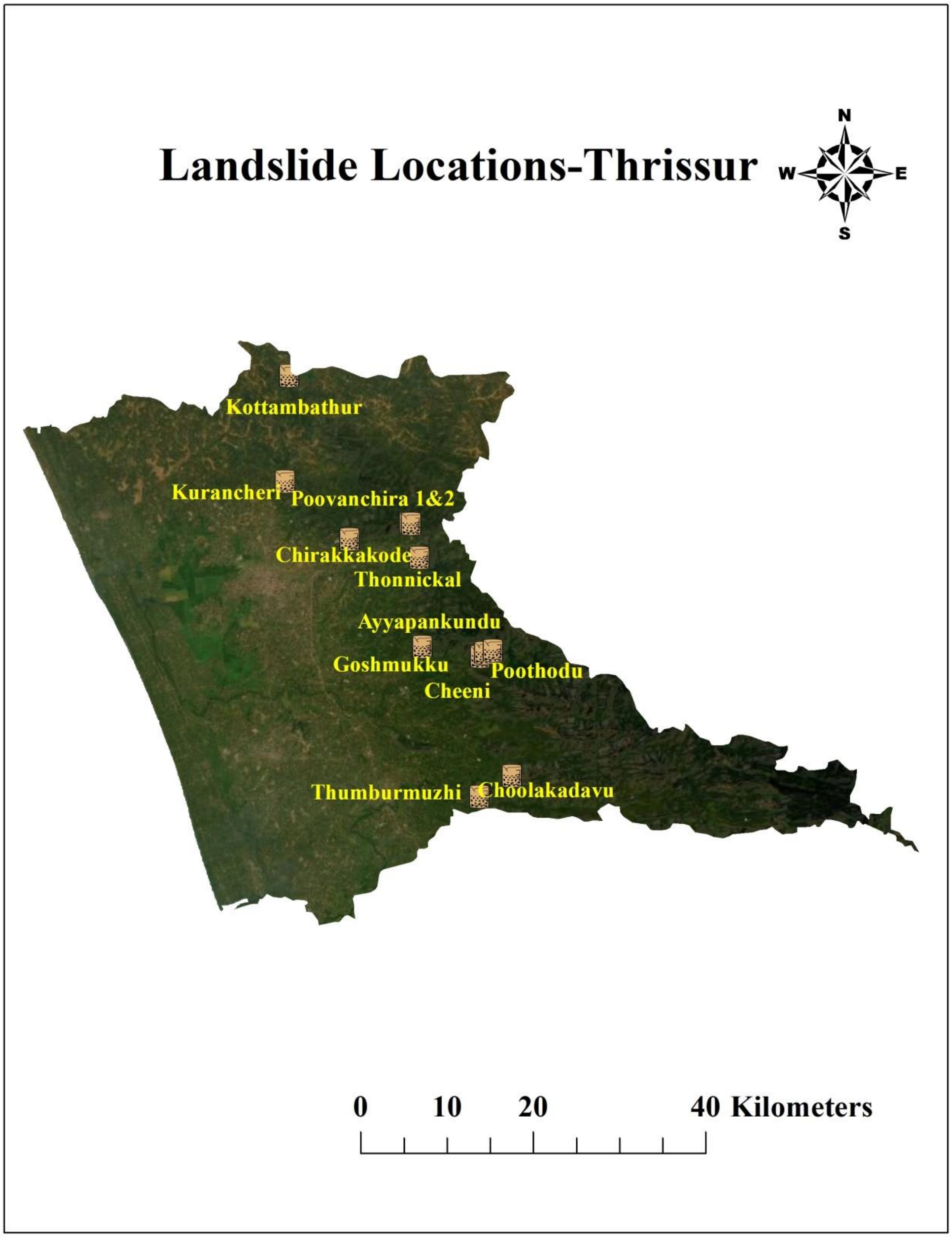

Figure 3. Major landslide locations in the study area.

The monsoon season of 2018 and 2019 devastated Thrissur district with a number of landslides. Major five landslide-affected regions of Thrissur were selected for the study. These landslide events occurred both in human settlements and in forest areas. The locations selected for the study were Chalakudy, Wadakkancherry, Chimmoni, and Pattikkad (Table 1.). Each of these locations had more than one landslide incident.

A total of 18 samples from the surface and sub-surface layers were collected from the landslide-affected regions. Due to the prevalence of rocks in the subsurface layers, soil samples were only collected from the surface layers of Choolakadavu, Thumboormuzhi, Ayyapankundu, Poothode, Thonnickal, and Poovanchira 1. The majority of the landslides occurred in the study area during 2018.

Plate 1. Location of Landslide: Vazhukumpara

Plate 2. Location of Landslide: Chimmoni

Plate 3. Location of Landslide:
Mannamangalam

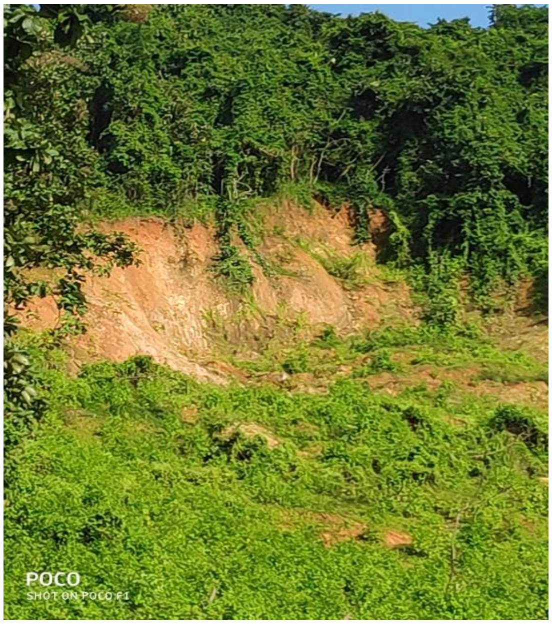

Plate 4. Location of Landslide:
Kurancheri

Plate 5. Location of Landslide:
Chirakkakode

Plate 6. Location of Landslide:
Thumboormuzhi

4.2 Soil properties

4.2.1 Soil Texture

The amount of sand, silt, and clay size particles that make up the soil's mineral fraction is referred to as soil texture. The USDA soil taxonomy classification system distinguishes soil into 12 textural classes based on the percentage of soil particles. Soils collected from the landslide-affected study area were analysed and identified as shown in Table 2. The soil texture triangle was aided for the determination of soil type.

Plate 7. Soil texture analysis using Bouyoucous method.

Sandy clay loam, sandy loam, and loamy sand were the main soil types identified from the study area. Clay content was more in the soils from Thumboormuzhi, Kottambathoor, and Kurancheri. The clay content varied from 10.16 in Chirakkakode (subsurface) to 32.16 in Kottambathoor (surface). The sand and silts contents were maximum in Poovanchira 2 (87.87%) and Chirakkakode (8%), respectively.

Water movements in soil is primarily influenced by soil texture. Fine soil particles like silt and clay have large surface area while compared with larger sand particles. Large surface area helps to hold more water. Coarse sandy soils can be recharged with soil moiture quickly while it is unable to hold water. Silt and clay has fine texture and narrow pore spaces which hold water more tightly than soils with wide pore spacing. Hydraulic conductivity of silt and clay are low due to small pore space and large frictional resistance. The increased resistance to percolation of water causes the saturation of soil leading to increased pore water pressure which inturn affect the soil stability.

Table 2. Percentage of Clay, Sand, and Silt and Soil texture of samples collected.

Location	**Depth**	**Sand%**	**Silt%**	**Clay%**	**Soil Type**
Choolakadavu	Surface	83.84	2	14.16	Sandy Loam
Thumboormuzhi	Surface	75.84	2	22.16	Sandy Clay Loam
Kottambathoor	Surface	63.84	4	32.16	Sandy Clay Loam
Kottambathoor	Sub-Surface	71.84	2	26.16	Sandy Clay Loam
Kurancheri	Surface	65.84	4	30.16	Sandy Clay Loam
Kurancheri	Sub-Surface	71.84	2	26.16	Sandy Clay Loam
Cheeni	Surface	81.84	2	16.16	Sandy Loam
Cheeni	Sub-Surface	83.84	1	15.16	Sandy Loam
Ayyapankundu	Surface	81.84	4	14.16	Sandy Loam
Poothode	Surface	79.84	4	16.16	Sandy Loam
Goshmukku	Surface	79.84	6	14.16	Sandy Loam
Goshmukku	Sub-Surface	77.84	4	18.16	Sandy Loam
Thonnickal	Surface	82.84	1	16.16	Sandy Loam
Poovanchira 1	Surface	77.84	4	18.16	Sandy Loam
Poovanchira 2	Surface	85.84	4	10.16	Loamy Sand
Poovanchira 2	Sub-Surface	87.84	2	10.16	Loamy Sand
Chirakkakode	Surface	75.84	8	16.16	Sandy Loam
Chirakkakode	Sub-Surface	85.84	4	10.16	Loamy Sand

4.2.2 Soil pH

Table 3. Soil pH of the samples.

Location	Depth	pH Reading
Choolakadavu	Surface	5.97
Thumboormuzhi	Surface	5.7
Kottambathoor	Surface	5.67
Kottambathoor	Sub-Surface	5.32
Kurancheri	Surface	5.8
Kurancheri	Sub-Surface	5.6
Cheeni	Surface	5.03
Cheeni	Sub-Surface	5.26
Ayyapankundu	Surface	5.05
Poothode	Surface	4.9
Goshmukku	Surface	5.9
Goshmukku	Sub-Surface	5.59
Thonnickal	Surface	5.76
Poovanchira 1	Surface	6.25
Poovanchira 2	Surface	6.7
Poovanchira 2	Sub-Surface	6.7
Chirakkakode	Surface	5.5
Chirakkakode	Sub-Surface	5.8

The table above depicts the measure of acidity or basicity of a soil. The soil pH of the samples from the study area indicates the acidic nature of the soil. The pH generally ranged from slightly acidic to nearly neutral.

4.2.3 Soil Organic Carbon

Table 4 depicts the percentage of soil organic carbon (SOC) content of the samples from the landslide affected regions. SOC was more in the dense forest region and least near the settlement regions. The highest SOC content in the dense forest region was found to be at Goshmukku (7.65%) and Cheeni (7.5%) in Pattikkad and Chimmony forest ranges respectively. The least SOC content was at Chirakkakode (0.18%) and Kurancheri (0.3%).

Organic matter enhances soil aggregate and structural stability, which, along with porosity, is vital for soil aeration and water infiltration. Downstream flooding and landslide threats are reduced by a stable, well-aggregated soil structure that resists surface sealing and continues to infiltrate water during heavy rain events. (Lefèvre et al., 2017).

Plate 8. Estimation of soil organic carbon.

Table 4. Organic carbon content of the soil sample.

Location	Depth	Organic Carbon%
Choolakadavu	Surface	5.85
Thumboormuzhi	Surface	3.3
Kottambathoor	Surface	2.01
Kottambathoor	Sub-Surface	0.81
Kurancheri	Surface	0.3
Kurancheri	Sub-Surface	0.45
Cheeni	Surface	7.5
Cheeni	Sub-Surface	1.02
Ayyapankundu	Surface	6.75
Poothode	Surface	2.43
Goshmukku	Surface	7.65
Goshmukku	Sub-Surface	2.46
Thonnickal	Surface	5.55
Poovanchira 1	Surface	3
Poovanchira 2	Surface	1.05
Poovanchira 2	Sub-Surface	0.42
Chirakkakode	Surface	0.57
Chirakkakode	Sub-Surface	0.18

4.2.4 Cation Exchange Capacity

Cation Exchange Capacity (CEC) is a vital soil property that is hard to alter significantly which has a considerable impact on soil structure, strength, pH and nutrient supply including the soil's response to fertiliser and other ameliorants (Hazleton and Murphy, 2016). It is a measure for the soil's ability to hold essential nutrients and functions as a buffer against acidification. The CEC of organic matter is very high and tends to be higher in soils with a higher clay fraction and thus high water holding capacity. Higher CEC value points to the greater capacity to hold cation and low CEC soils are high in sand content and contain fewer nutrients and are more prone to anion nutrient leaching. The strength of stabilised soil is determined by the effect of soil CEC. Soil cation exchange was discovered to decrease the calcium hydroxide saturation in the soil sample. If the CEC of the soil is too high, the calcium hydroxide in the pore solution is unable to reach saturation, and further cation exchange consumes the Ca^{2+} ions that should have been used to produce calcium silicate hydrate, thus resulting in the poor strength of the soil (Yu et al., 2014). Base saturation refers to a measurement, of the percent of the soil CEC that is occupied by the sum of a group of nutrients.

It was determined by estimating the amount of cations from the study area (Table 5) that the concentration of cations in the soil varied in the order Ca > Mg > K > Na. CEC was found to be highest in Poovanchira 2 (25.64 cmols(p^+)/kg) and minimum at Poothode (2.80 cmols(p^+)/kg). The base saturation of the study sites varied from 93.5 to 99.8 (Table 6).

Table 5. Estimation of minerals present in the soil collected from study area (cmols(p^+)/kg).

Location	**Depth**	**Ca**	**Mg**	**K**	**Na**	**Cu**	**Fe**	**Mn**	**Zn**
Choolakadavu	Surface	9.50	4.27	1.78	0.03	BDL	0.002	0.05	BDL
Thumboormuzhi	Surface	8.71	3.49	1.30	0.06	BDL	0.0001	0.01	0.04
Kottambathoor	Surface	6.42	5.72	2.26	0.13	0.0003	BDL	0.03	0.44
Kottambathoor	Sub-Surface	5.34	4.33	1.88	0.30	0.003	BDL	0.1	0.73
Kurancheri	Surface	6.38	5.97	1.21	0.17	0.007	BDL	0.02	0.18
Kurancheri	Sub-Surface	9.71	5.95	1.95	0.09	BDL	BDL	0.11	BDL
Cheeni	Surface	11.06	3.19	1.85	BDL	BDL	0.002	0.04	BDL
Cheeni	Sub-Surface	5.58	2.05	1.14	0.03	0.002	0.0003	0.02	0.006
Ayyapankundu	Surface	12.85	2.57	1.10	0.11	BDL	0.0005	0.01	BDL
Poothode	Surface	1.57	0.50	0.63	0.09	0.005	0.0003	0.006	BDL
Goshmukku	Surface	2.55	1.85	2.61	0.08	0.004	0.0008	0.02	0.009
Goshmukku	Sub-Surface	1.86	2.28	2.49	0.05	0.004	0.0004	0.01	0.04
Thonnickal	Surface	11.13	3.87	1.56	BDL	BDL	0.001	0.04	BDL
Poovanchira 1	Surface	9.35	4.38	4.38	BDL	BDL	0.0003	0.06	BDL
Poovanchira 2	Surface	18.73	5.26	1.59	0.01	BDL	0.001	0.04	BDL
Poovanchira 2	Sub-Surface	9.08	4.97	2.15	0.10	0.002	BDL	0.17	BDL
Chirakkakode	Surface	6.21	6.38	2.00	0.26	0.008	0.0003	0.03	0.08
Chirakkakode	Sub-Surface	3.18	1.68	1.05	0.02	0.005	BDL	0.05	0.004

Table 6. CEC and Percentage base saturation.

Location	**Depth**	**CEC** (cmols(p^+)/kg)	**% Base Saturation**
Choolakadavu	Surface	15.63	99.6
Thumboormuzhi	Surface	13.60	99.6
Kottambathoor	Surface	15.00	96.8
Kottambathoor	Sub-Surface	12.69	93.5
Kurancheri	Surface	13.93	98.5
Kurancheri	Sub-Surface	17.80	99.4
Cheeni	Surface	16.14	99.7
Cheeni	Sub-Surface	8.83	99.7
Ayyapankundu	Surface	16.65	99.9
Poothode	Surface	2.80	99.6
Goshmukku	Surface	7.12	99.5
Goshmukku	Sub-Surface	6.74	99.2
Thonnickal	Surface	16.59	99.8
Poovanchira 1	Surface	18.16	99.7
Poovanchira 2	Surface	25.64	99.8
Poovanchira 2	Sub-Surface	16.47	99.0
Chirakkakode	Surface	14.97	99.2
Chirakkakode	Sub-Surface	5.99	99.0

4.3 Rainfall

According to IMD, rainfall from 64.5 - 124.4 mm is considered as heavy rainfall, 124.5 - 244.4 mm as very heavy rainfall, and rainfall above 244.4 mm as extremely heavy rainfall (IMD, 2013). Analysis of the past 10-year data from 2010 - 2019 of Thrissur district showed that there were only a few instances during which the daily rainfall had been greater than 100mm. The annual rainfall of Thrissur during the years 2018 and 2019 were 3490.8mm and 3128.3mm respectively. Table 7 depicts the rainfall data of the summer monsoon of 2018 and 2019. The monsoon season of 2018 and 2019 had more than 4 consecutive days with heavy rain. During the monsoon season of 2018, from June to August, there were six days that recorded heavy rainfall and three days recorded very heavy rainfall, and one day recorded extremely heavy rainfall of 253.6mm. While comparing with the rainfall of 2018, the year 2019 had six heavy rainfall and one very heavy rainfall incident. In both the years, the heavy to extremely heavy rainfall had occurred in close proximity within a span of 4 consecutive days leading to landslides. These consecutive high-intensity rains would have created immense pressure over the soil which in turn led to landslides. As the rainfall infiltration starts and moves across the pedological horizons the soil become saturated from below resulting in pore water pressure build up and percolation controls the moisture supply for the removal of soluble minerals and the leaching of rocks leading to transient loss of shear strength across the slope which burst out inducing soil and underlying finer less permeable bedrock and region around it to liquefy and flow downslope (Lumb, I975; Wilson and Wieczorek, 1995).

The graph (Figure 4) shows three (June, July, August) month cumulative rainfall of 2018 and 2019, and 29-year average cumulative rainfall of Thrissur. There was a steep rise in the rainfall during the month of August. From the graph, it is evident that the rainfall of 2018 was higher when compared with that of the 29-year average rainfall from 1991-2019.

Table 7. Rainfall (mm) data of 2018 & 2019.

Day	**2018**			**2019**		
	Jun	Jul	Aug	Jun	Jul	Aug
1	0.0	0.2	14.3	0.0	0.2	2.8
2	0.4	0.5	3.5	0.0	3.5	0.2
3	0.4	2.2	13.1	0.0	1.0	0.2
4	22.0	0.0	0.0	0.5	39.6	0.0
5	4.7	0.0	14.0	0.0	37.3	17.2
6	0.0	9.0	0.6	0.8	34.1	51.9
7	23.3	0.2	33.6	0.0	11.4	51.7
8	39.7	53.6	110.6	0.0	23.6	81.3
9	85.9	40.2	29.5	0.0	7.6	145.7
10	55.2	49.0	6.7	51.2	45.4	77.8
11	25.8	87.8	13.5	51.9	0.2	113.1
12	41.8	48.1	14.1	41.0	0.0	10.5
13	29.1	12.1	26.5	12.8	0.0	28.0
14	128.2	32.1	8.3	36.0	3.5	90.8
15	10.2	34.9	140.6	2.6	31.5	48.5
16	0.2	95.2	253.6	8.4	34.6	0.3
17	0.7	34.6	148.4	0.4	12.0	4.2
18	7.1	70.7	23.6	0.0	0.3	0.5
19	46.7	13.9	28.0	19.8	78.3	0.2
20	66.2	26.7	2.6	9.0	90.6	0.0
21	30.5	12.5	1.7	7.9	56.9	19.9
22	5.3	0.5	7.1	38.7	52.0	31.3
23	12.5	14.9	1.5	25.6	49.6	21.2
24	1.4	39.2	0.0	10.2	16.0	16.3
25	3.1	23.6	0.0	2.8	13.7	15.4
26	15.3	22.7	0.0	1.3	5.5	16.7
27	3.5	1.8	0.0	0.0	0.0	45.0
28	40.4	1.9	9.7	0.0	4.2	33.7
29	26.0	6.4	22.4	3.3	0.0	4.1
30	4.5	17.3	0.2	0.2	1.8	46.2
31		41.4	0.3		0.0	2.8
Total	**730.1**	**793.2**	**928.0**	**324.4**	**654.4**	**977.5**

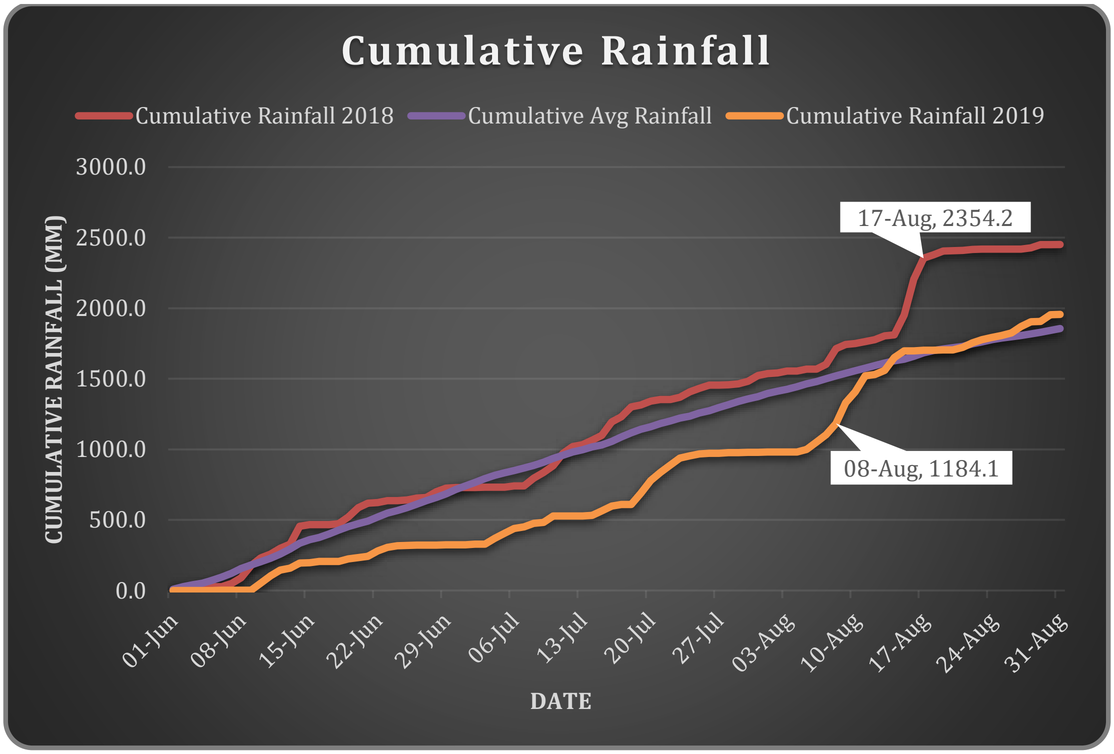

Figure 4. Cumulative monsoon rainfall of Thrissur during 2018, 2019 & 29-year average.

The climatic threshold for predicting landslide

During the prediction of a climatic threshold for a landslide the major challenge encountered was the limited availability of rainfall data immediate to the landslide affected regions. To meet this challenge Chirakkakode was selected as a representative region where both KAU Agromet observatory and the landslide regions were near to each other.

Linear regression analysis was used to determine empirical rainfall intensity-duration thresholds for landslides and debris flows. It was determined that the rainfall intensity duration prior to the landslide was found to be significantly higher than the region's capacity to withstand. During the month of August 2018 (15 to 17 August, 2018), the region experienced continuous rains for 24hours with a rainfall intensity of 2.8 mm/hr. It was found that the region had received rainfall intensities much greater than this threshold values thereby triggering landslides (Table 7). The threshold refer to the relational values based on statistical analysis of the relationship between rainfall and landslide occurrences. The rainfall intensities exceeding the threshold limit is an indication of increasing soil moisture causing excess pore water pressure. The excessive pore water pressure and soil moisture liquefy the soil and become unable to withstand and flows down gravitationally influenced.

After the large-scale landslide, the geomorphology, strength, and properties of the region will be changed. This renders the region more vulnerable to debris flows and landslides in the future, even with less severe rainfall than before the large-scale landslide. Thus the rainfall intensity that the region can withstand in future was calculated to be 2.15 mm/hr for 24hr duration.

4.4 Preparation of thematic layers

Depending upon the factors inducing landslide and its severity, degree of fragility can be assessed, which help in predicting geographical landslide hotspots. During the fragility analysis main factor which collectively influence the landslide were only considered. The preparation of this hazard zonation map needed several thematic layers to be overlaid.

For the fragility estimation study, the following parameters were analysed and theme maps were created: (1) slope; (2) land use land cover; (3) geomorphology; (4) lineament density; (5) geology; (6) drainage density and (7) soil. Considering the ease and accuracy of the hazard map preparation and to eliminate the regions where chances of landslide are least to occur, the coastal regions of Thrissur were neglected.

Seven factors were considered for the thematic maps and were ranked according to the protocols of GSI. The major force that act on a landslide is the effect of gravity and this effect increases with the slope angle of the terrain. Thus, highest ranking (56) is given to slope as the slope stability is largely related to slope angle. LULC change is given second highest ranking (10) as it greatly influence landslide susceptibility due to infrastructure development and rapid economic activities. It is followed by drainage density (9), lineament density (7) and the least ranking (6) is given to geology, geomorphology and soil parameters. Similar terrain conditions were adopted in several studies (Thampi, 2006: Mathai, 2009). Table 8 shows the ranks assigned to each parameter

Table 8. Ranking allotted for various parameters

Parameter	Ranking
Slope	56
Land Use Land Cover	10
Drainage density	9
Lineament density	7
Geology	6
Geomorphology	6
Soil	6
Total	**100**

To calculate the terrain's fragility at the micro level, all of the parameters (Table 8) were further subdivided. The individual terrain factors are explained in further detail below

4.4.1 Slope

The amount of inclination of a physical feature's surface to the horizontal is referred to as its slope and it is a key component in determining the risk of landslides. The study area's slope ranged from 0 to 72.45 degrees, and it was divided into three classes: 0–7.67, 7.68–19.03, and 19.04–72.45 degrees. With a steeper slope, there is a greater chance of rapid runoff and erosion. The slope has an inverse relation with infiltration, thus weightages were applied appropriately.

Table 9. Slope magnitude and weightage allotted.

Slope	**Slope angle**	**Weightage**
High	19.04 - 72.45°	9
Medium	7.68 - 19.03°	8
Low	<7.67°	1

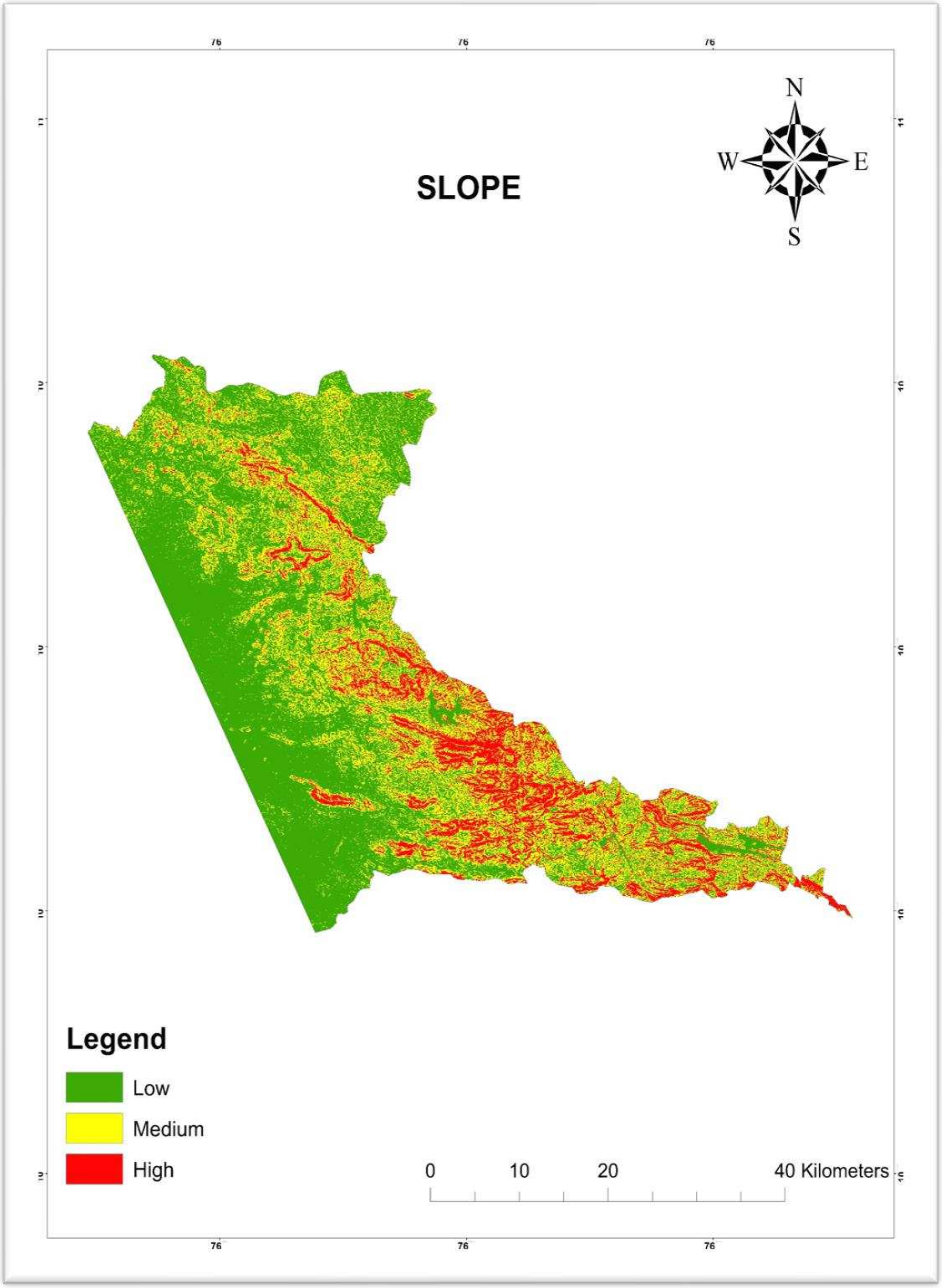

Figure 5. Map depicting the slope of the study area.

4.4.2 Land Use Land Cover

Land use map of the study area was prepared based on Sentinel 2A satellite data and google imagery, with limited ground truthing. The land-use map (Figure 6) depicts all the land-use patterns based on vegetation signatures. Table 10 shows the nine major land-use types that have been identified, as well as the weights that have been assigned to each of them. Slope failures are more likely to occur in degraded forest, plantations, and mining.

The vegetation cover was the key determinant feature evaluated while examining the land use of the study area. The major part of the study area is covered by forest (563.55 sq. km), followed by agriculture (461.65 sq. km), settlement (323.46 sq. km), dense forest region (212.86 sq. km) and plantation (156.35 sq. km). According to studies conducted in the Western Ghats region, slope failures are most common in degraded forest areas on the upper slopes and in wasteland without vegetation (Roy and Parkash, 2016). High susceptibility zones include the discontinuous soil-covered areas between rock outcrops creating plateau borders, as well as natural degraded forests and grasslands. Slope collapses have not been observed in undisturbed forest, natural grasslands, or forest plantations. Slope failures are likely to occur in rubber, palm, etc. owing to poor land management methods and the growth of seasonal crops in sensitive zones. The most vulnerable moment for slope failures in plantations is when the older plants are removed for replanting (Abraham and Shaji, 2013).

Studies have shown that mining and active quarries are a major threat that reduces the strength and binding of the soil. Mining and quarrying across the ecologically fragile regions of the Western Ghats have a serious impact on both biotic and abiotic factors (Ramachandra, et al., 2018; Vandana, et al., 2020).

Table 10. Weightage allotted for Land use.

Land use category	**Weightage**	**Area (*sq. km*)**
Dense Forest	4	212.86
Forest	8	563.55
Grassland	5	24.48
Agriculture	1	461.65
Plantation	9	156.35
Settlement	7	323.46
Waterbody	1	72.07
Sand	1	16.32
Mining	9	6.31

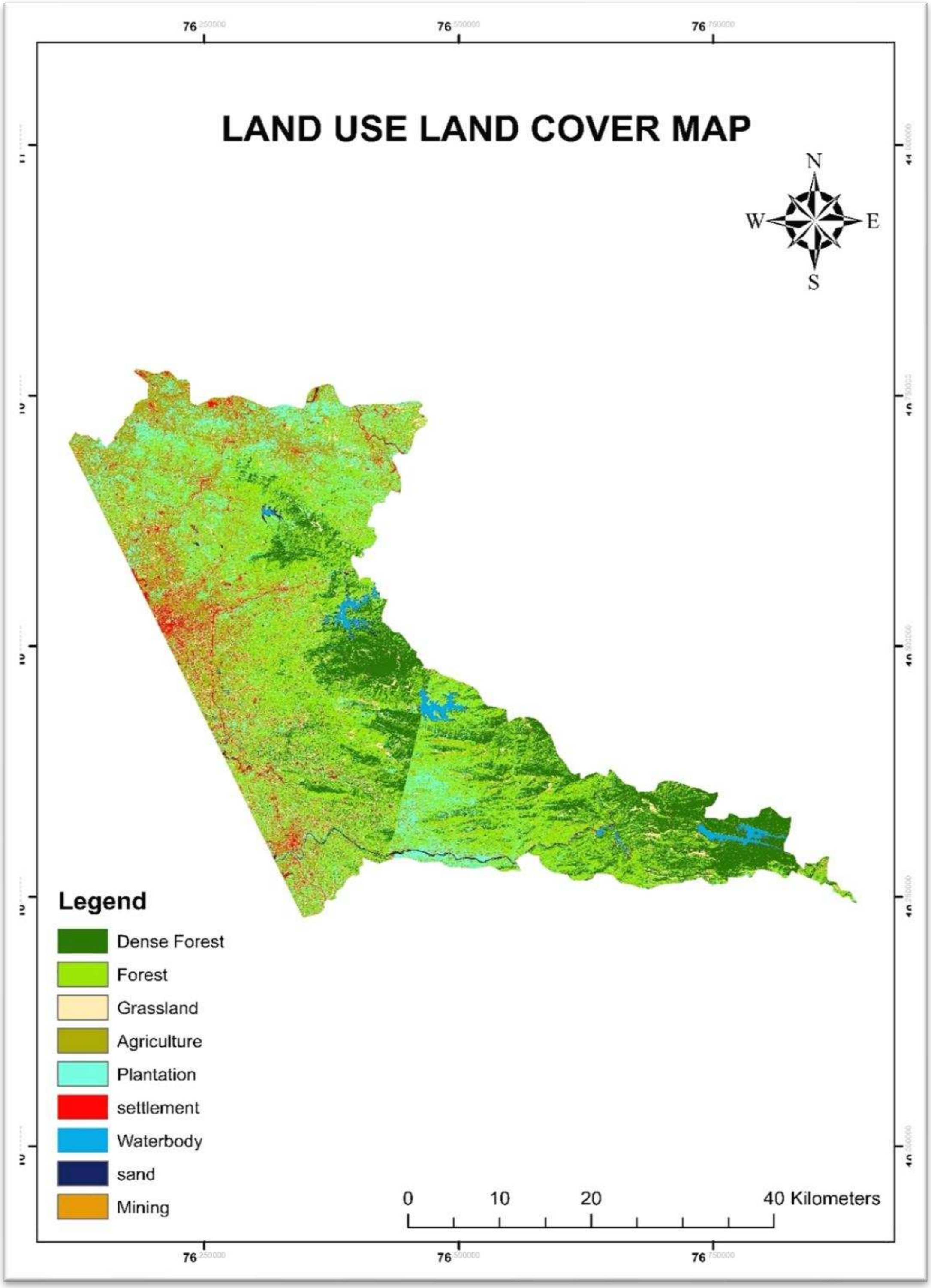

Figure 6. Land use and land cover map of the study area

4.4.3 Drainage pattern and drainage density

The kind of vegetation, the rainfall absorption capacity of soils, infiltration, and slope gradient all influence the drainage system of a given location (Manap et al., 2013). A low drainage-density area has more infiltration and less surface runoff (Kumar et al., 2007; Magesh et al., 2012). The drainage density is defined as the ratio of the sum of the stream lengths to the size of the grid area under consideration. (Adiat et al., 2012; Mogaji et al., 2015).

In view of slope stability, drainage pattern is important as it suggests high slopes. Further, the first order stream patterns are formed across the watershed basins source drainage region. These are regions where there is a significant erosion and slope retreat. Figure 7 depicts the drainage pattern of the study area.

Table 11. Area and weightage allotted for drainage density.

Drainage Density	**Area (*sq. km*)**	**Weightage**
Very High	903.12	6
High	215.67	4
Medium	155	2
Low	141.53	1
Very Low	303.29	1

Heavy drainage densities indicate impermeable layers, high rainfall, less vegetation, and active stream incision, all of which can be attributed to mass movements. (Figure 8). According to drainage density, the study area was divided into five classes: 11.18–314.47, 314.48–456.01, 456.02–611.02, 611.03–826.70, and 826.71–1729.83 km/km^2. Table 11 shows the distribution of drainage density across the study area, as well as the weights allotted. It was found that major portion of Thrissur falls under high drainage density. About 903.12 sq. km (29.78%) of the study area has very high drainage density.

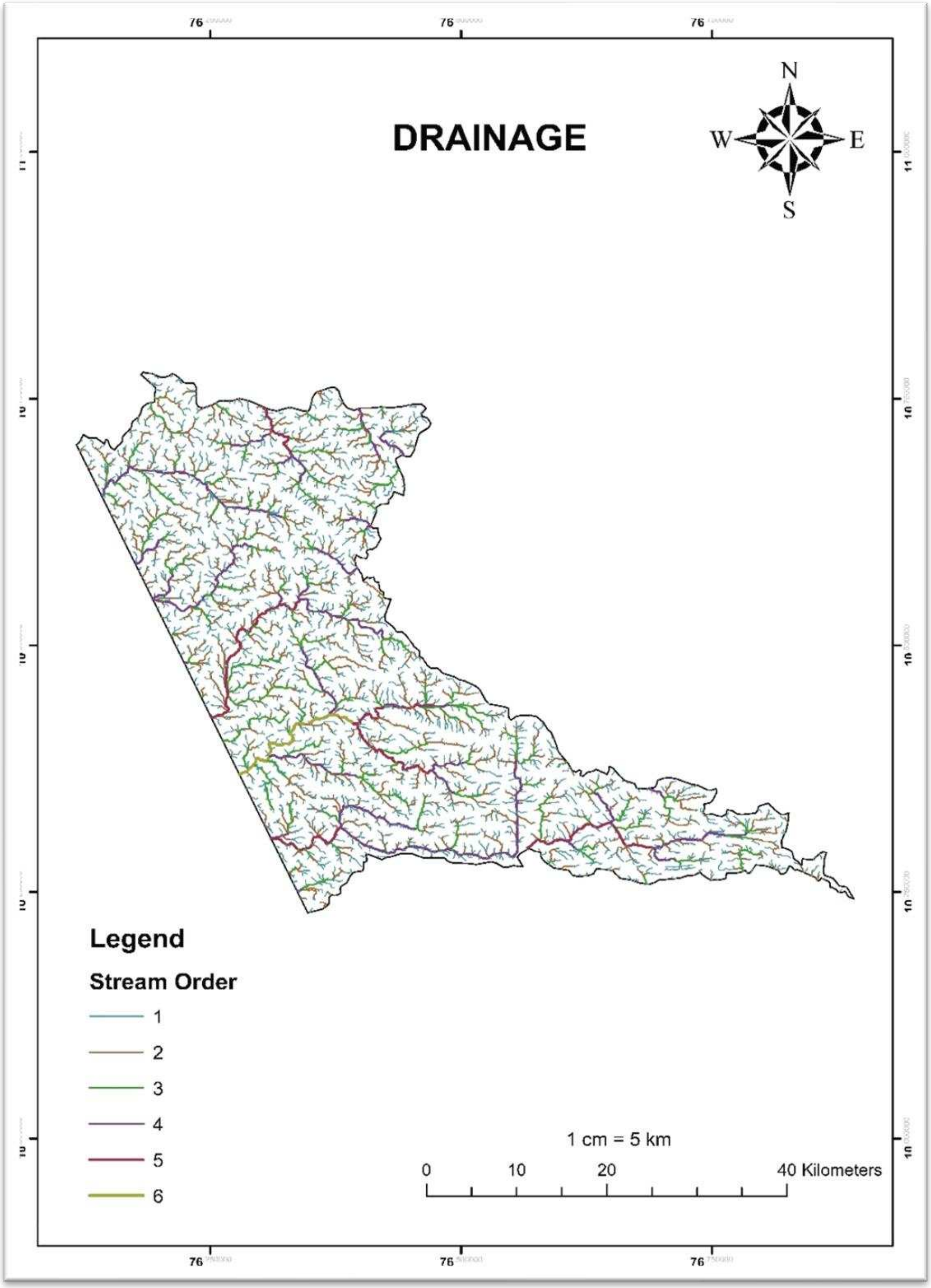

Figure 7. Drainage pattern and stream order of the study area.

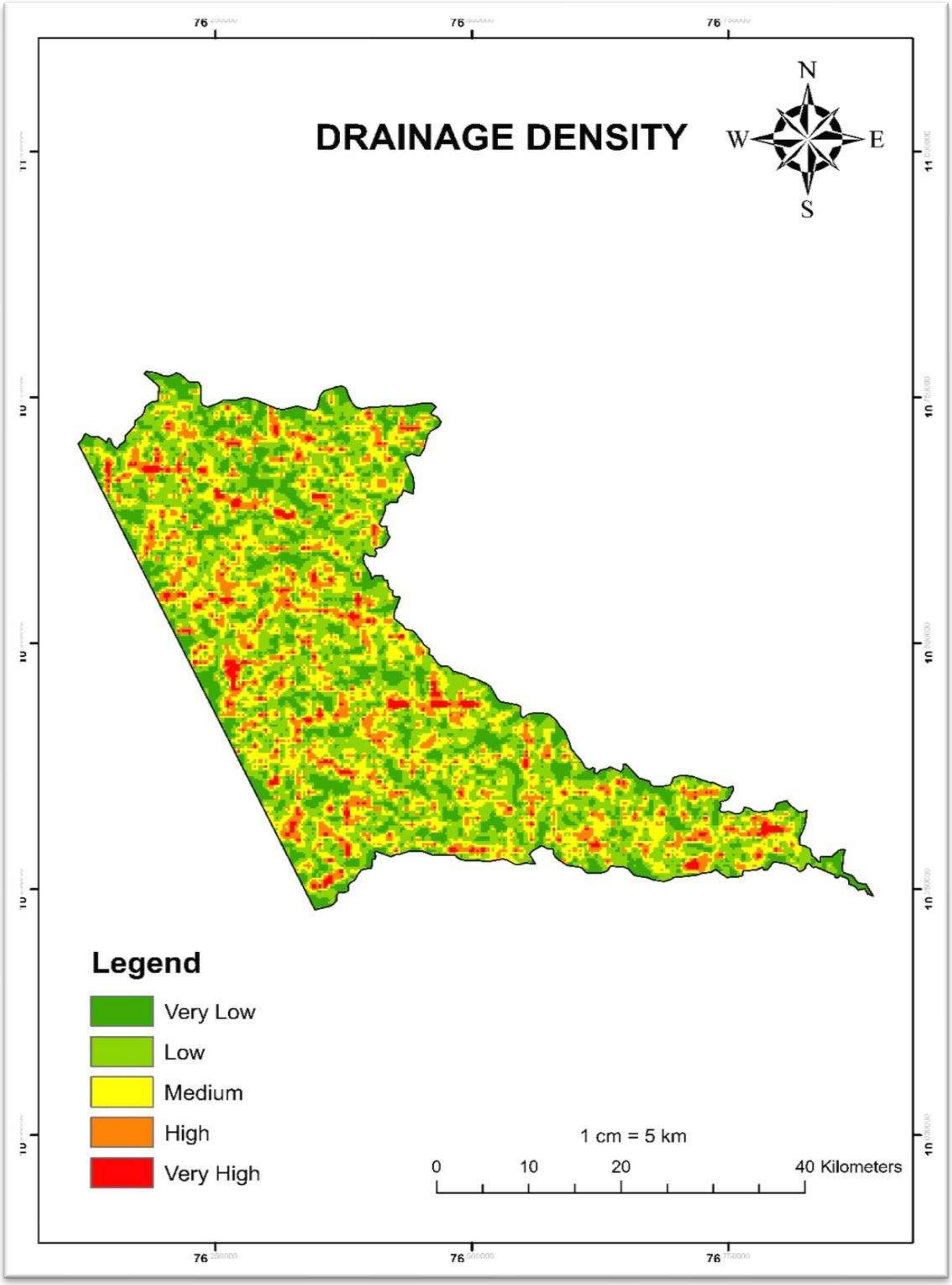

Figure 8. Drainage Density of the study area.

4.4.4 Lineament Density

Lineaments are geological characteristics in a landscape that are important lines in the landscape created by joints and faults, attributed to the rock's basic architecture. (Pradhan and Youssef, 2010; Muthumaniraja et.al, 2019; Pradhan et al., 2006). These faults aid in the permeation of surface runoff into the subsurface layers and are critical for groundwater storage and flow (Devi et al., 2001).

Table 12. Lineament and weightage allotted

Lineament Category	**Weightage**	**Area (*sq. km*)**
Very High	6	81.1
High	5	39.37
Medium	2	31.5
Low	1	25.99
Very Low	1	22.83

The total length of all recorded lineaments was divided by the region under consideration to get the lineament density (Edet et al., 1998; Rejith et al., 2019). The study area was classified into five classes based on the lineament density: 0.015–22.85, 22.86–48.85, 48.86–80.36, 80.37–119.74, and 119.75–200.85 km/km^2. Table 12 shows the weightage allotted to the lineament categories. It was found that an area of 81.1 sq. km falls under very high lineament density. Greater lineament density indicates more joints and faults in a given area pointing to increased chances of slope failures and the weightages were assigned accordingly.

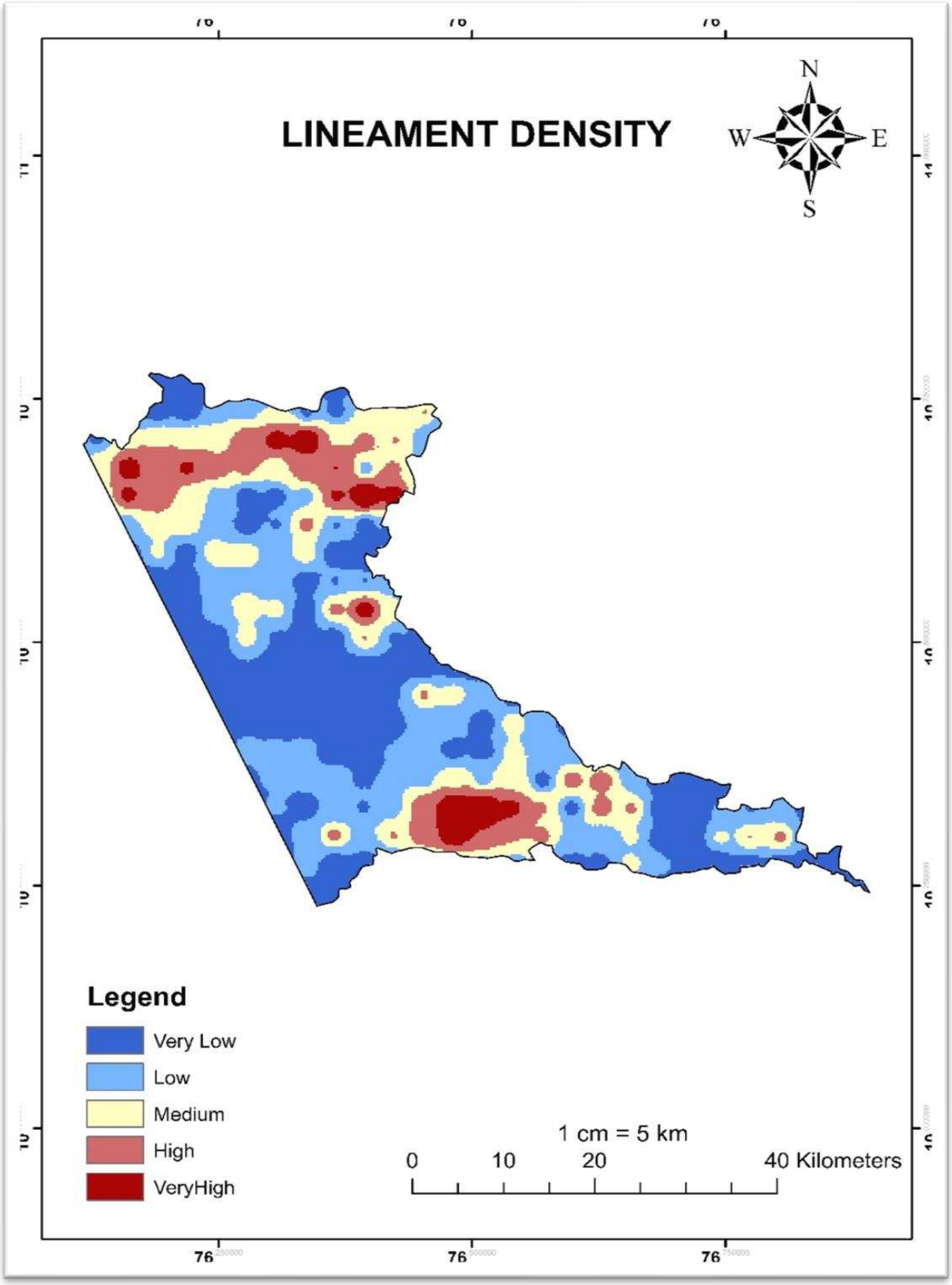

Figure 9. Lineament Density of the study area

4.4.5 Geology

The geological base map of Thrissur was obtained from the map published by the Geological Survey of India (GSI), 1995. The map was georeferenced and digitized and stored as various geological types in shape format. A major part of the study area is comprised of hornblende gneiss, laterite, and charnokite gneiss which are transversed by pink granite, calc granulite, gabbro, dolerite, pyroxene granulite, quartz vein, and magnetite quartzite.

Table 13. Weightage of geological characteristics

Geological Characteristics	Weightage
Calc Granulite	1
Dolerite	1
Gabbro	1
Granophyre	1
Hornblende biotite, Quartz Mica Gneiss	6
Laterite	2
Magnetite Quartzite	1
Pegmatite and Quartz vein	1
Pink granite gneiss	6
Pyroxene granulite	1
Quartz feldspar hypersthene granulite, charnokitic gneiss	4
Syenite	1

Areas where the landslide occurred was composed of charnokitic gneiss and quartz feldspar hypersthene granulite which was intercalated with laterite and pink granite gneiss (Figure 10). Table 13 gives details about the geological characteristics and weights allotted for each characteristic based on its contribution to the landslide. Several studies show that hornblende gneiss and granite gneiss show significant weathering conditions which show increased chances of landslides (Lindsay et al. 2001; Sajinkumar, et al., 2011) and thus it was allotted the highest weightage of 6, followed by quartz feldspar hypersthene granulite (4), and laterite (2). All other geological characteristics was given weightage of 1.

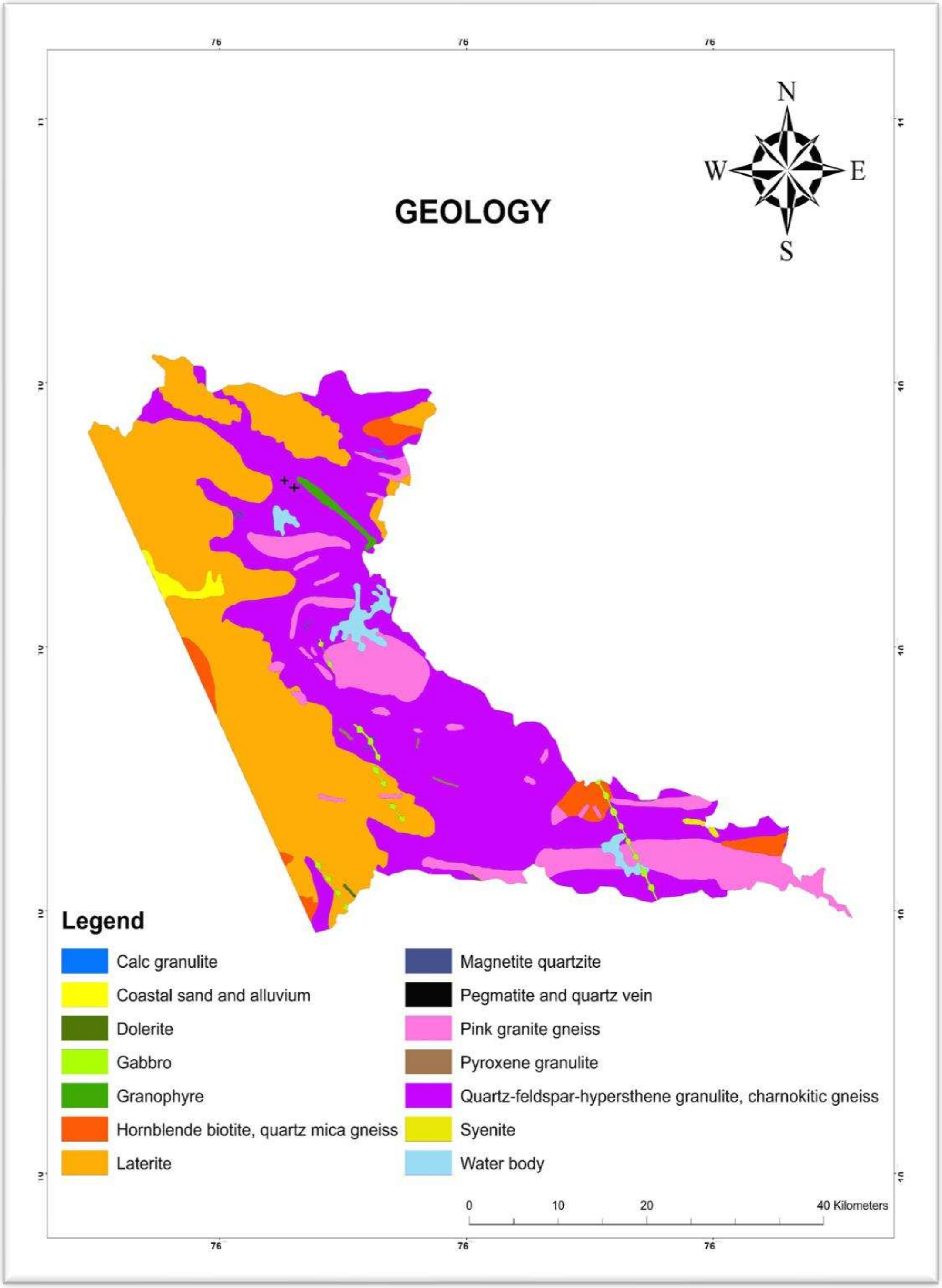

Figure 10. Geology map of the study area.

4.4.6 Geomorphology

The nature of landslide occurrence in a terrain is shown by a geomorphologic map exhibiting major geomorphic units and land-form characteristics, since these features are developed over a significant period of surface processes impacting the different lithology and underlying structures. The study area is geologically made up of pediment-pediplain complex, coastal and deltaic plain, structural and denundational hills, along with waterbodies including, dams and reservoir, active flood plains, and active quarries. It was found that about 29.07% of the study area was pediment pediplain complex (881.52 sq.km) followed by moderately dissected (409.87 sq. km), and highly dissected (193.41 sq. km) structural hills and valleys (Figure 10).

Mountain peaks or ridges formed mostly by slope retreat are known as denudational hills. These hill slopes are fundamentally weathering limited slopes, meaning that in situ weathering product rarely occurs, leaving bare rocks on the tops of the hills and debris of various sizes on the slopes.

The highest weightage among the geomorphological characters is assigned to active quarry (9) as the regions around them become less stable and reduce strength due to quarrying. Moderately and highly dissected structural hills and valleys are given a weightage of 6 and 7 respectively, followed by moderately and highly dissected denundational hills and valleys with weightage of 4 and 5 respectively. Pediment pediplain complex and pond is given the least weightage of 1 as landslide susceptibility is low in these regions (Table 14).

Table 14. Geomorphology and weightage allotted

Geomorphology	**Weightage**	**Area (*sq. km*)**
Pond	1	5.87
River	3	32.28
Active Quarry	9	6.76
Dams and reservoir	2	35.45
Active Flood plain	2	26.63
Low dissected denudational hills and valleys	3	44.54
Moderately dissected denudational hills and valleys	4	6.65
Highly dissected denudational hills and valleys	5	62.54
Low dissected structural hills and valleys	3	131.53
Moderately dissected structural hills and valleys	6	409.87
Highly dissected structural hills and valleys	7	193.41
Pediment Pediplain Complex	1	881.52

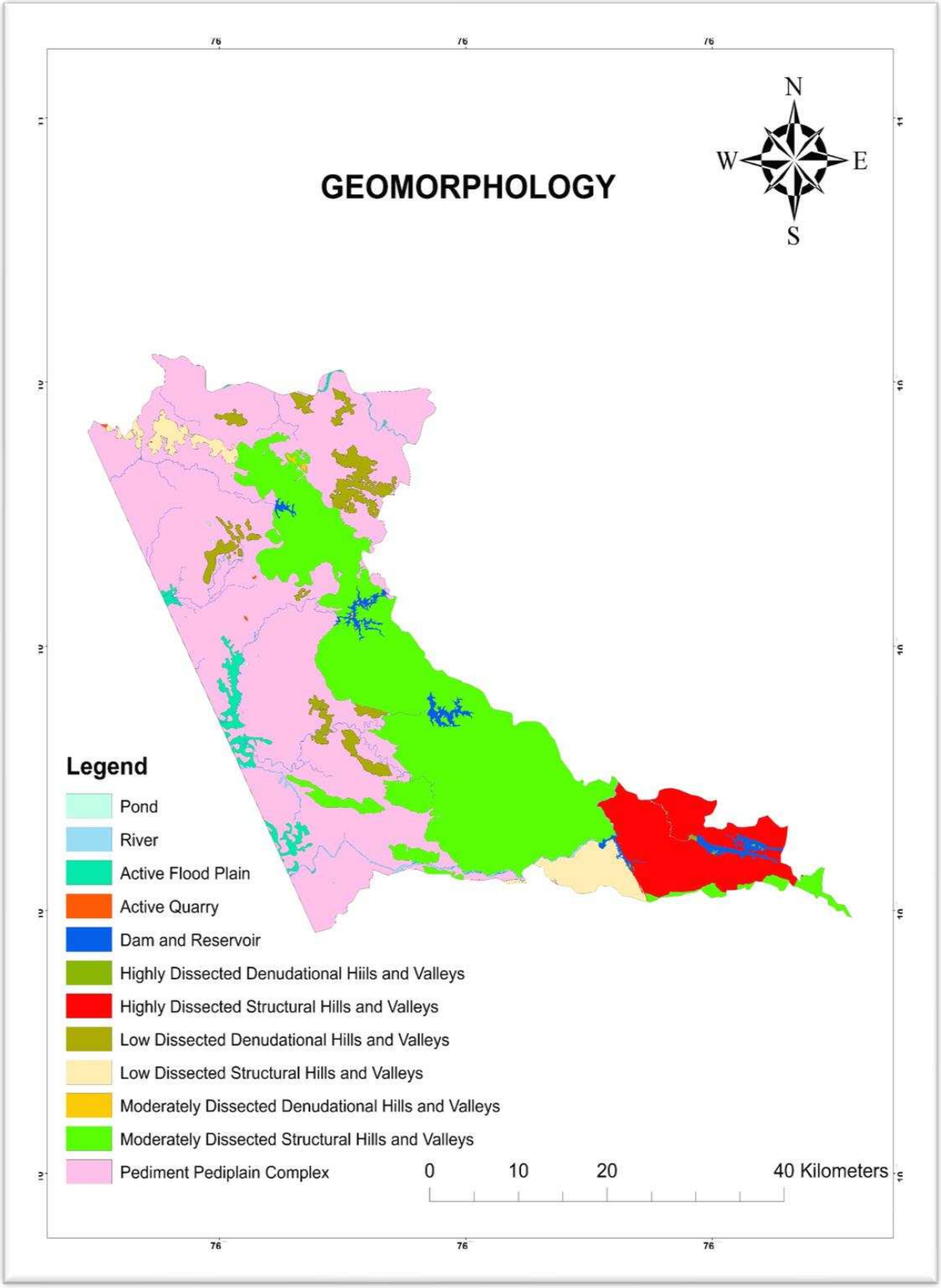

Figure 11. Geomorphology map of the study area

4.4.7 Soil

The soil is the ultimate weathering product and a significant conditioning element in landslide events. Major soil types in the study area included gravelly clay, gravelly sandy clay, gravelly sandy clay loam and sandy clay loam. The highest weightage among the soil type was 6 given to gravelly clay. Followed by gravelly sandy clay with weightage of 4 and both gravelly sandy clay loam and sandy clay loam with weightage of 2 (Table 15).

The soil loses its strength due to a rise in moisture content. Soils, however, often tend to flow when saturated with water due to increase in pore-water pressure resulting in the lack of shear strength. The pore water pressure is more in soils with high clay content and these fine clay particles migrate to void regions leading to strength reduction and causes blockage of pores. Thus, the gravelly clay is given the highest weightage. Soil sampling may provide more accurate information about an environment, vulnerable to landslides. (Anbazhagan et al. 2011; Liang, et al. 2020).

Table 15. Soil type and weightage allotted.

Soil type	**Weightage**
Gravelly clay	6
Gravelly sandy clay	4
Gravelly sandy clay loam	2
Sandy clay loam	2

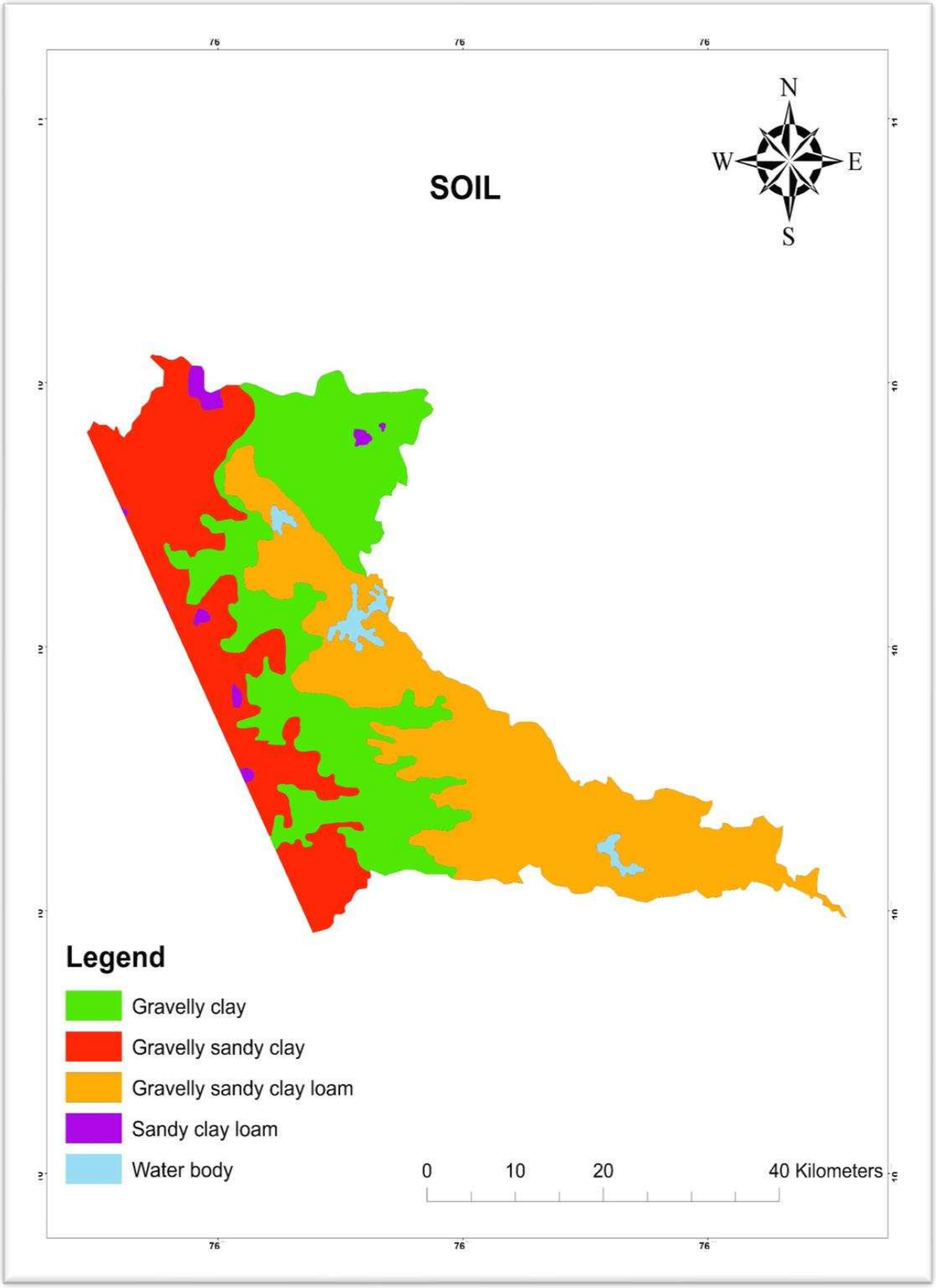

Figure 12. Soil map of the study area.

4.5 Hazard zonation

The fragility of the terrain was prepared using the summation of the seven characteristics obtained by terrain evaluation, and the overall terrain fragility of a segment was determined. (Table 16). The grids were classified as highly fragile, fragile, moderately fragile, and stable based on the total weight value of all factors. (Figure 13). An area of about 262.62 sq. km falls under a highly fragile zone which cover 8.66% of the total area of Thrissur. The selected landslide sites (2018 & 2019) of Thrissur fall in the highly fragile and fragile zones indicating the feasibility in predicting landslide prone areas of Thrissur.

Table 16. Fragility classification

Hazard Zonation	Total weight	Area (sq. km)
Highly fragile	>42	262.62
Fragile	21-42	560.69
Moderately Fragile	7-21	875.86
Stable	<7	137.88

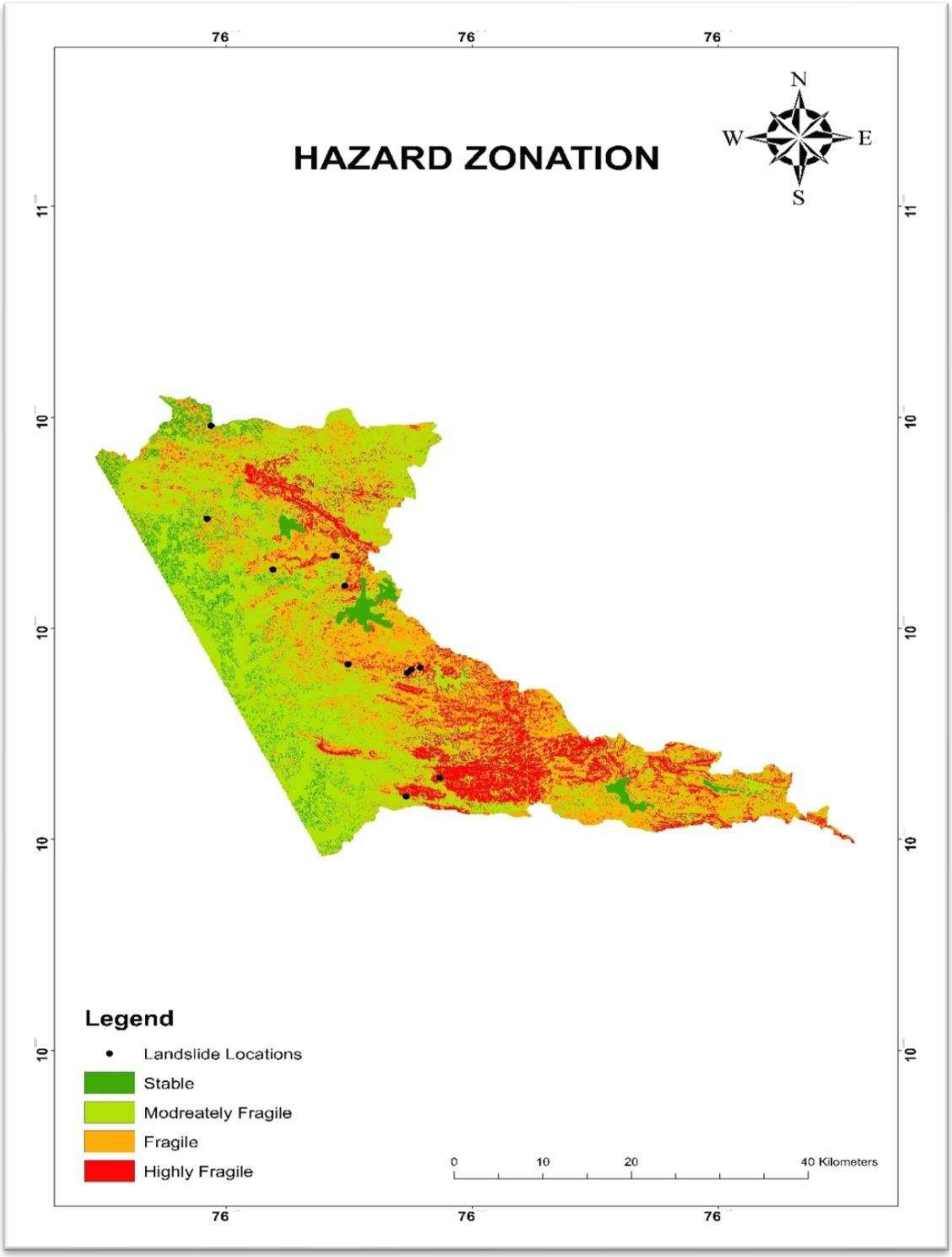

Figure 13. Hazard Zonation Map of the study area and Landslide affected locations of 2018 & 2019.

SUMMARY AND CONCLUSION

CHAPTER 5: SUMMARY AND CONCLUSION

The study conducted in the landslide sites of Thrissur district helped to identify different factors that have led to the occurrences of landslide. The study revealed that the major cause of the landslide during 2018 and 2019 was due to the high intensity of rainfall over short duration of time in these sites. The soil in these regions would have become saturated under the influence of heavy rainfall thereby reducing the cohesive and binding forces triggering the slide. Even though the landslide occurred regions had vegetation cover, they couldn't provide the resistance to anchor the soil against the slope failure.

Empirical methods of prediction of rainfall intensity and duration, show that a rainfall intensity of 2.8 mm/hr for 24hr duration could trigger landslide in the region. Further, the rainfall intensity that the region can withstand for another landslide event in the same site was estimated to be 2.15 mm/hr for 24hr duration.

A landslide hazard zonation map of Thrissur was prepared by using and overlaying seven thematic maps of the study area. The different thematic maps included soil type, geology, geomorphology, slope, drainage density, lineament density, LULC. The landslide hazard zonation map revealed that about 262.62 sq.km falls under highly fragile zone and the south eastern part of the Thrissur District is highly vulnerable to landslides.

Thus, from the study it can be summarised that in future the increase in extreme rainfall events with intensity of 67.2mm/day (2.8 mm/hr) and slopes above 19.03° are highly vulnerable to landslides. Along with change in land use pattern, exploitation of the environment by activities such as quarrying and deforestation would negatively affect the strength and stability of the soil leading to the increased probability of landslide.

Future line of work-

- Commissioning and setting up of hourly rainfall data collection points can help to accurately predict the rainfall thresholds that cause landslides.
- Incorporating the root density and root characteristics of trees in the study can provide better bio restoration options to mitigate the landslide.
- Innovative methods that help to monitor the rainfall and actively provide warning about the saturation conditions of soil and the maximum amount of water that the soil can withstand can help people and authorities to be prepared for the hazard.
- Assessing landslides across the state and developing site specific rainfall intensity duration predictions would help alarm people about possible landslide events.

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Appendix

SYMBOLS AND ABBREVATIONS

°C	Degree Celsius
API	Aerial Photo Interpretation
BDL	Below Determination Level
Ca	Calcium
CEC	Cation Exchange Capacity
Cu	Copper
D	Duration
DEM	Digital Elevation Model
DTM	Digital Terrain Model
EBT	Erichrome Black T
EDTA	Ethylene diamine tetra acetate
EWS	Early Warning System
FAS	Ferrous Ammonium Sulphate
Fe	Iron
g	Gram
GEO	Geotechnical Engineering Office
GHG	Green House Gas
GSI	Geological Survey of India
hr	Hour
I	Intensity
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
Km	Kilometer
LiDAR	Light Detection and Ranging
LULC	Land Use Land Cover

meq.	milliequvalent
Mg	Magnesium
min	Minute
mm	millimeter
Mn	Manganese
Na	Sodium
NBRO	National Building Research Organization
NOAA	National Oceanic and Atmospheric Administration
OC	Organic Carbon
ppm	Parts per million
QPRF	Quantitative Precipitation Rainfall Forecast
SDG	Sustainable Development Goal
SOC	Soil Organic Carbon
sq.km.	square kilometer
sq.m.	square meter
SST	Sea Surface Temperature
TAR	Third Assessment Report
THC	Thermo Haline Circulation
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
USGS	United States Geological Survey
Zn	Zinc

ASSESSING LANDSLIDE VULNERABILITY AND DEVELOPING CLIMATIC TRIGGERING PREDICTORS FOR THRISSUR DISTRICT

By

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THESIS

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ABSTRACT

Landslide refers to the down-slope movement of a mass of rock, rubble, soil, or earth under the direct control of gravity. Rainfall and slope can be attributed as the major factors among the multiple causes that trigger almost every landslide event. Landslides are catastrophic events impacting the economy, infrastructure, culture and heritage, and human injury that can extend to the loss of lives. During the monsoon season of 2018 from June to August Kerala received nearly 50 percent more rain than the expected rainfall during this period. The aftermath was devastating, affecting almost one in every six persons in the state. In August 2019, another incessant rainfall triggered extreme flooding and landslides before revival from the shock of the 2018 catastrophic events. As people migrate into new areas of hilly or mountainous terrain, it is essential to understand the significance of the future susceptibility to landslide hazards. Cities and towns can plan for modern construction engineering, land use, and infrastructure that will minimize the cost of living with landslides. The physical causes of landslides cannot be checked; landslide risks can be minimized by geological studies, by sound engineering practices, and by productive land use management laws. The triggers, movement characteristics, soil properties, geology associated with them, and where they can occur are important to consider. Furthermore, mitigation measure estimates may decrease damages due to landslide to a greater degree and strong risk avoidance strategies can be applied to decrease hazard severity. Thrissur was one of the mostly affected regions in the 2018 and 2019 landslide. In this context, it is very important to understand and analyse the causative and triggering factors of the landslide and to delineate location which are highly susceptible to landslide. This study aims to analyse thee causative factor including soil properties and rainfall. Also, identify climatic thresholds that can trigger the landslide. Hazard zonation map for the region was prepared which can be looked upon if the landslide trigger is activated in future.