A geospatial framework for rain shadow effect on land degradation: a case study of Attappady Western Ghats region, Kerala

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Abstract
Land is the complex of soil, water and the flora and fauna in a landscape, above and below the soil surfaces and is one of the most important resources for all organisms. Land conversion is a type of land use land cover change and it leads to land degradation. Land degradation affects both on-site and off-site soil productivity and poses a threat to human and animal health, water quality and soil resources caused by factors such as climate change, urbanization, population growth, industrialization, land use land cover change and desertification. Rain deficit also plays a significant role in contributing to land degradation in various regions. The Western Ghats in India, especially the eastern Attappady region, are facing significant land degradation.

The objective of the present research is to identify the land degradation expansion and its impact on the landscape of Attappady. To achieve this Landsat series multispectral data, IMD data, ASTER DEM, geospatial tools and multi-influencing factor (MIF) techniques have been employed to analyze land use and land cover changes and land degradation.

Keywords: Western Ghats, Rain shadow, Land Degradation, Climate Change.

Introduction

Land degradation refers to the quantitative or qualitative change in the properties of soil that reduces its potential for production. It is caused by human pressures and poor land use, disrupting the natural balance of soil components formed over geologic ages[33]. Land degradation is occurring in almost all terrestrial ecologies, impacting the livelihoods of the poor who heavily depend on natural resources[2]. Land degradation poses a critical threat to the lives of hundreds of millions of people.

Moreover, it can have devastating consequences in terms of social and economic costs[23]. The interplay of socio-economic and biophysical factors varies over space and time, leading to a decline in land productivity[8]. The majority of land degradation issues are anthropogenic, earning mankind the designation of "the prime maker of desert." Causes of land degradation can be both intentional and unintentional[22]. Other causes include deforestation, removal of natural vegetation, overgrazing, cultivation of marginal lands and overexploitation of vegetation[1].

Human-induced processes like land use transformation, overexploitation of natural resources, population enhancement and economic development also contribute to land degradation[25]. Additionally, ineffective laws, insecure tenure and lack of agreements further exacerbate the problem[16]. Pollution from agrochemicals and industrial emissions also leads to degradation of agricultural lands[52]. Rain shadow regions are also prone to land degradation due to reduced rainfall, impacting soil erosion and vegetation cover. The relationship between rainfall and land degradation is evident in tropical regions where soil structure and high rainfall potential directly contribute to erosion and crop yield fluctuations[36].

Orographic rain shadows are a primary feature of Earth's surface climatology. The rain shadow development is the function of both topography and atmospheric state. In Attappady, Western Ghats have a predominant influence on the atmosphere and they alter the flow of air and disturb the vertical stratification of the atmosphere by acting as physical barriers. The interactions between Western Ghats and the atmosphere produce precipitation with varying spatial scales enhanced in some regions and decreased in others. Depending on the Ghats magnitude and the efficiency of the condensation and release processes, precipitation will decrease on the leeward side (Eastern Part). A region of low precipitation in the lee of topography is "rain-shadow".

Rain shadow climate type exerts a strong influence over leeward vegetation type, biomass and diversity. Loss of vegetation or land use / land cover change can propagate further land degradation via land surface atmosphere feedback. This occurs when a decrease in vegetation reduces evaporation and increases the radiation reflected back to the atmosphere (albedo), consequently reducing cloud formation leading to rainfall deficit. As the rainfall decreases, the greenery gets sparser and less continuous. Plants and animals in dry areas have had to adapt all sorts of ways to cope with the challenges of fluctuating temperatures, sporadic rainfall and dry soil. Because it is generally hot and dry in these areas, not a lot of organic matter is being produced.

With less organic matter, the soil does not hold together as well, making it more prone to erosion from wind and water. How much erosion happens, can change depending on how much it rains and how strong the winds are. Even short-term changes in weather and climate could shake things up by altering what kinds of plants grow where, especially in the semi-arid regions of Attappady. These causes result in the loss of soil fertility, depletion of water resources and changes in species diversity and abundance, ultimately impacting the overall ecosystem integrity. Inappropriate land use types and conversions have the potential to expand desertified areas and amplify the degree of land desertification[10,48].

The intensification of land degradation heightens competition for land, as it diminishes the availability of land suitable for various uses such as food production[42]. To identify the intricate relationship between factors which are responsible for the land degradation, is complex especially in the hetrogenous characteristic landscape like Attppady. In this context, geospatial technology plays a crucial role in addressing land degradation as it provides operational tools for identifying problems, defining causes and finding solutions. It enables the evaluation of the state and impact of land degradation in different territories, supporting land planning and management[30].

Geospatial tools have also been developed to spatially identify and prioritize areas for implementing actions to avoid, reduce and reverse land degradation, integrating biophysical and socio-economic dimensions[38]. These tools provide quantitative and spatially explicit information, enabling evidence-based approaches in restoring degraded landscapes[21].

Objectives:
1. To analyse the driving forces of land degradation in the Attappady region of Western Ghats.
2. To identify the Land Degradation zone in the Attappady.

Data Available:
1) 1970 – Survey of India Toposheet (1: 50,000)
2) 1991- Landsat:5 - Thematic Mapper
3) 2005 – Landsat:7- Enhanced Thematic Mapper
4) 2021-Landsat: 8 – Operational Land Imagery and Google Earth Imagery
5) https://www.imdpune.gov.in/lrfindex.php Indian Meteorological Data (1951 – 2023)

Material and Methods

To demarcate land degradation map, Multi-Influencing Factor Technique were applied. The present study adopted a modified version of the land use classification proposed by the National Remote Sensing Centre (NRSC). This modification was necessary because not all land use types defined in various classification schemes are found uniformly across all areas. Therefore, it became essential to develop a classification scheme suitable to the specific characteristics of Attappady. Land use maps for the year 1991, 2005 and 2021 were prepared using data from the Landsat 5, 7 and 8 satellite program, which was downloaded from www.earthexplorer.com[50]. This source provides open-access satellite imagery with a relatively high resolution of 15 meters (by applying resolution merge with 15 meter PAN data), which is valuable for addressing various environmental issues. In this study, a Supervised Classification-Maximum Likelihood technique was employed for image classification.

QGIS 3.28 version and Erdas Imagine software were used for data generation, analysis and map preparation. The study area was divided into seven land use categories, namely, cultivated land, Builtup, Scrub, Waterbody, Barren land, Forest and Plantation. To collect regions of interest from the Landsat data and validate the accuracy of the generated results, virtual Google Earth images and Survey of India (1:50,000) topographical maps were utilized. Climatic data of rainfall and temperature were collected from IMD for climate change analysis. Statistical tools such as the Mann-Kendall test were applied to analyze trends in rainfall and temperature variations.

The vegetation condition and land use land cover are the important factors determining the land degradation. The land degradation varies geographically and strongly dependent on various factors such as intensity of the rainfall, slope, topographic wetness index (TWI), land-use/land-cover pattern, soil type and vegetation type among other factors. The methodology adopted for the present study is shown in fig. 1.

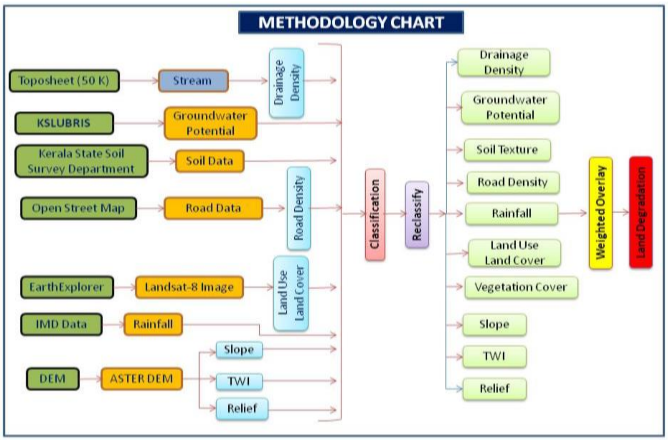


Fig. 1: Methodology Chart

Table 1
Land Use Land Cover 1991-2021

Land Use Land Cover	1991		2005		2021	
	Area in Km^2	Area in %	Area in Km^2	Area in %	Area in Km^2	Area in %
Barren Land	2.99	0.36	7.21	0.87	12.79	1.54
Built-Up	1.47	0.18	2.06	0.25	4.05	0.49
Forest	575.64	69.42	431.89	52.06	354.18	42.68
Cultivated Land	95.41	11.51	179.47	21.63	210.61	25.38
Plantations	0.27	0.03	15.95	1.92	49.94	6.02
Scrub	149.59	18.04	189.23	22.81	194.77	23.47
Waterbody	3.81	0.46	3.82	0.46	3.45	0.42
Total	**829**	**100**	**829**	**100**	**829**	**100**

Table 2
Effect of influencing factor, relative rates and score for each potential factor

Influencing Factors	Major Effect A	Minor Effect B
Vegetation Type	LULC, Soil, Groundwater Prospects, TWI and Rainfall	Drainage Density, Road Density, Relief and Slope
Soil	Vegetation, Rainfall, LULC, Relief, Slope	Road Density, Groundwater Prospects, TWI, Drainage Density
LULC	Soil, Vegetation Type, Groundwater Prospects, Rainfall, TWI	Road Density, Drainage Density, Slope and Relief
Drainage Density	Groundwater Prospects, Rainfall, Slope, TWI and Soil	LULC, Road Density, Relief, Soil
Rainfall	Vegetation, LULC, TWI, Drainage Density, Soil and Groundwater	Road Density, Slope, Relief
Groundwater	Vegetation, Rainfall, Soil, Drainage Density, TWI, LULC	Road Density, Slope and Relief
TWI	Slope, Relief, Rainfall and Drainage Density	Groundwater Prospects, Vegetation, Soil, Road Density and LULC
Slope	TWI, Soil, Groundwater Prospects, Drainage Density	Rainfall, LULC, Vegetation Type, Relief and Road Density
Relief	TWI, Slope, Drainage Density	Vegetation Type, LULC, Soil, Road Density, Groundwater and Rainfall
Road Density	Slope, Relief, LULC	Rainfall, TWI, Groundwater Prospects, Vegetation Type, Soil, Drainage Density

Table 3
Proposed Score for Each Influencing Factor

Influencing Factors	Major Effect A	Minor Effect B	Proposed Relative Rates (A+B)	Proposed Score for Each Influencing Factors
Vegetation Type	1+1+1+1+1	0.5+0.5+0.5+0.5	7	10
Soil	1+1+1+1+1	0.5+0.5+0.5+0.5	7	10
LULC	1+1+1+1+1	0.5+0.5+0.5+0.5	7	10
Drainage Density	1+1+1+1+1	0.5+0.5+0.5+0.5	7	10
Rainfall	1+1+1+1+1+1	0.5+0.5+0.5	7.5	11
Groundwater	1+1+1+1+1+1	0.5+0.5+0.5	7.5	11
TWI	1+1+1+1	0.5+0.5+0.5+0.5+0.5	6.5	10
Slope	1+1+1+1	0.5+0.5+0.5+0.5+0.5	6.5	10
Relief	1+1+1	0.5+0.5+0.5+0.5+0.5+0.5	6	9
Road Density	1+1+1	0.5+0.5+0.5+0.5+0.5+0.5	6	9
Sum			**68**	**100**

These layers are geo-referenced and vectorised from various spatial data sources such as Survey of India toposheets scaled 1:25,000, Geological Survey of India Maps, Satellite Images (LANDSAT 7 and 8), Soil Survey Organization Reports and Google earth web applications. These thematic layers were converted into a raster format of 30m resolution and subjected to weighted overlay analysis in QGIS environment. The weight for each individual parameter is assigned based on the Multi Influencing Factor (MIF) technique.

Slope, groundwater, soil, TWI, drainage density, road density, land use land cover and vegetation condition, geomorphology and lineament density, are the parameters considered for the present study. Each parameter is interdependent on other parameters viz. each parameter has a major effect (A) and minor effect (B) upon other parameters (table 2). For each major and minor inter-related factor, a weightage of 1 and 0.5 is assigned respectively (table 3). A relative rate is calculated for each factor by cumulating all the weights of major and minor interrelated factors (A+B). A factor with higher relative rate shows larger impact on the land degradation and vice versa. This relative rate is further used to calculate a score for each influencing factor using the following formula (equation 1):

$$= \left\{ \frac{A+B}{\sum A+B} \right\} X100 \quad (1)$$

where A is the major inter-relationship between two factors, B is the minor inter-relationship between two factors and A+B is the relative weight of each factor The inter-relationship between the parameters chosen for the present study, their relative weight and the scores derived for each parameter is detailed in table 4.

Study Area

The research area Attappady is situated in the Palakkad district of Kerala and lies in between the Nilgiri hill ranges in the North and Vellinkiri hill ranges in the South, both having a height of over 1200 meters. Attappady is an extensive mountain valley located between 10◦ 55’10” N and 11◦ 14’19” north latitudes and between 76◦ 27’11” E and 76 ◦48’8” east longitudes stretching from Mukkali in west to Anakkatty in east and Thazhemulli in north to Muthikulam in south covering an area of 829.53 sq.km (Fig. 2). Physically Attappady is a plateau with 750 – 1000 meters rising from the undulating mid lands beyond the east of Mannarkkad taluk.

This area is flanked by mountain ranges, the Nilgiris in the north and extension of the Western Ghats in the south and the east and merges with the plains of Coimbatore and its general slope is towards north-east. The western extremity at Mukkali is 550 metres and the northern Attappady is having an elevation of 2300 metres and forms a fragment of Nilgiri peak. The eastern side of Attappady has an extremity of 450 metres and shares the border with Tamil Nadu. The total land area of Attappady is spread over three panchayaths (local self-government, institutions) namely, Agali, Puthur and Sholayur, straddling the ecological divide between the region of orographic precipitation to the west and the rain shadow to the east[29].

Attappady is divided into two: Western and Eastern Attappady**.** The average rainfall of eastern and western Attappady is 839 mm and 2084 mm per annum and thus dry land and rain-fed region respectively[29]. The Attappady valley differs from the rest of the humid tropical area in Kerala State mainly because of the rainfall characteristics and its peculiar geographical location and physiography. Average rainfall in the Western region is 2500 mm/year whereas the Eastern region gets less than 600 mm/year. Rainfall patterns are intimately linked to the terrain's topographical complexity. The western hills are taller and steeper and the dryness in the eastern section has been linked to the mountains' rain shadow effect.

Presently, more areas are degraded due to the combination of climatic and anthropological factors that caused severe damage to the ecology of the area and livelihood support systems of the people and this turned Attappady into a totally degraded zone of the Western Ghats region. Moreover, mountains' rain shadow effect on the eastern part of Attappady makes Attappady as more vulnerable tract in the southern parts of Western Ghats, India. Under this circumstance the study of the rain shadow region of Attapady taluk is essential.

Results and Discussion

Land degradation, influenced by factors like land use/cover change, rainfall, vegetation condition, soil texture, slope, relief, road density, ground water and human-induced processes, poses a significant threat to environmental sustainability globally. These factors play significant roles in exacerbating land degradation processes. Changes in land use and land cover such as deforestation or urbanization, can lead to soil erosion and loss of vegetation, contributing to land degradation. Soil texture, particularly the clay content, affects water holding capacity and hydraulic conductivity, influencing soil salinity levels. Climate change impacts like increased heavy precipitation and heat stress, can worsen land degradation processes.

Groundwater potential, relief and slope also play crucial roles in determining the extent of land degradation with factors like terrain elevation and precipitation frequency affecting soil salinity levels and erosion rates. Statistics, remote sensing and GIS play a crucial role in integrating these factors and help in monitoring and assessing land degradation.

Land use Land cover: Land is the most basic of all natural resources and it provides the space for living and livelihood. Land carries ecosystems and is itself a part of these ecosystems[49].

Table 4
Classification of Weighted Factors influencing the Land Degradation

Land Degradation Parameters	Features	Land Degradation	Weightage
Rainfall	Very Low	Very High	11
	Low	High	10
	Medium	Medium	8
	High	Low	6
	Very High	Very Low	4
Land Use Land Cover	Agricultural Land	Medium	8
	Barren Land	Low	6
	Builtup	Very High	10
	Forest	Very Low	4
	Plantation	Medium	8
	Scrub	Low	6
	Waterbody	Low	2
Vegetation Type	Very Low	Very High	10
	Low	High	8
	Medium	Medium	6
	High	Low	4
	Very High	Very Low	2
Drainage Density	Very Low	Very High	10
	Low	High	8
	Medium	Medium	6
	High	Low	7
	Very High	Very Low	2
Soil	Clay	Low	4
	Gravelly Clay	Medium	6
	Gravelly Loam	High	10
Groundwater Prospects	Poor	Very High	11
	Moderate	High	9
	Good to Moderate	Medium	7
	Very Good to Good	Low	5
	Very Good	Very Low	3
Slope	0-5	Very High	9
	5-15	High	8
	15-25	Medium	7
	25-55	Low	5
	>55	Very Low	3
Road Density	Low	Low	2
	Moderate	Moderate	5
	High	High	7
	Very High	Very High	9
Topographic Wetness Index	Very Low	Very High	10
	Low	High	8
	Medium	Medium	6
	High	Low	4
	Very High	Very Low	2
Relief	0 – 100	Very Low	2
	100 – 500	Low	4
	500 – 1000	Moderate	6
	1000 - 1500	High	8
	Above 1500	Very High	9

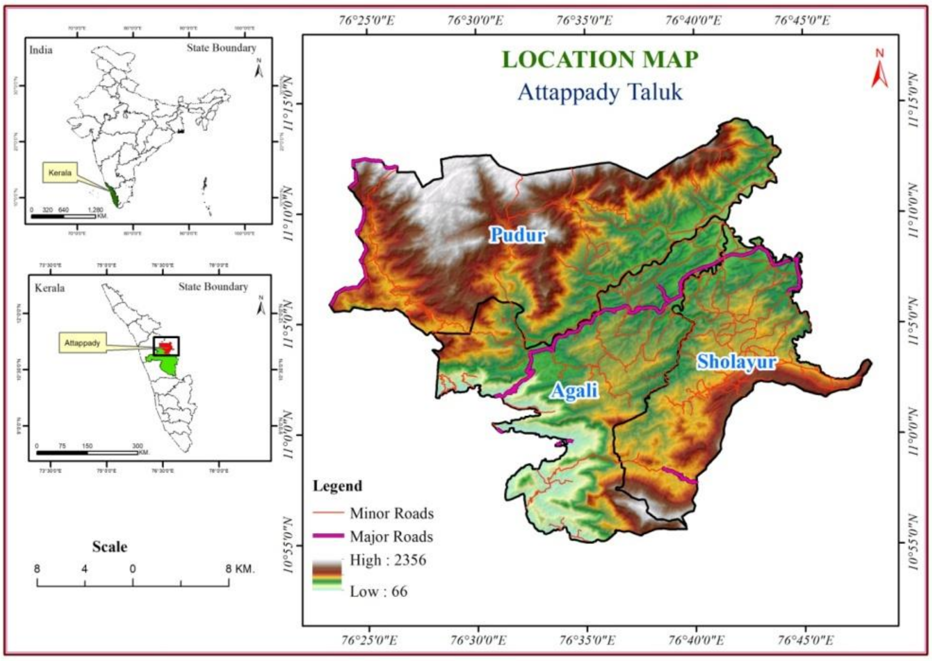


Fig. 2: Geographical Location of the Study Area

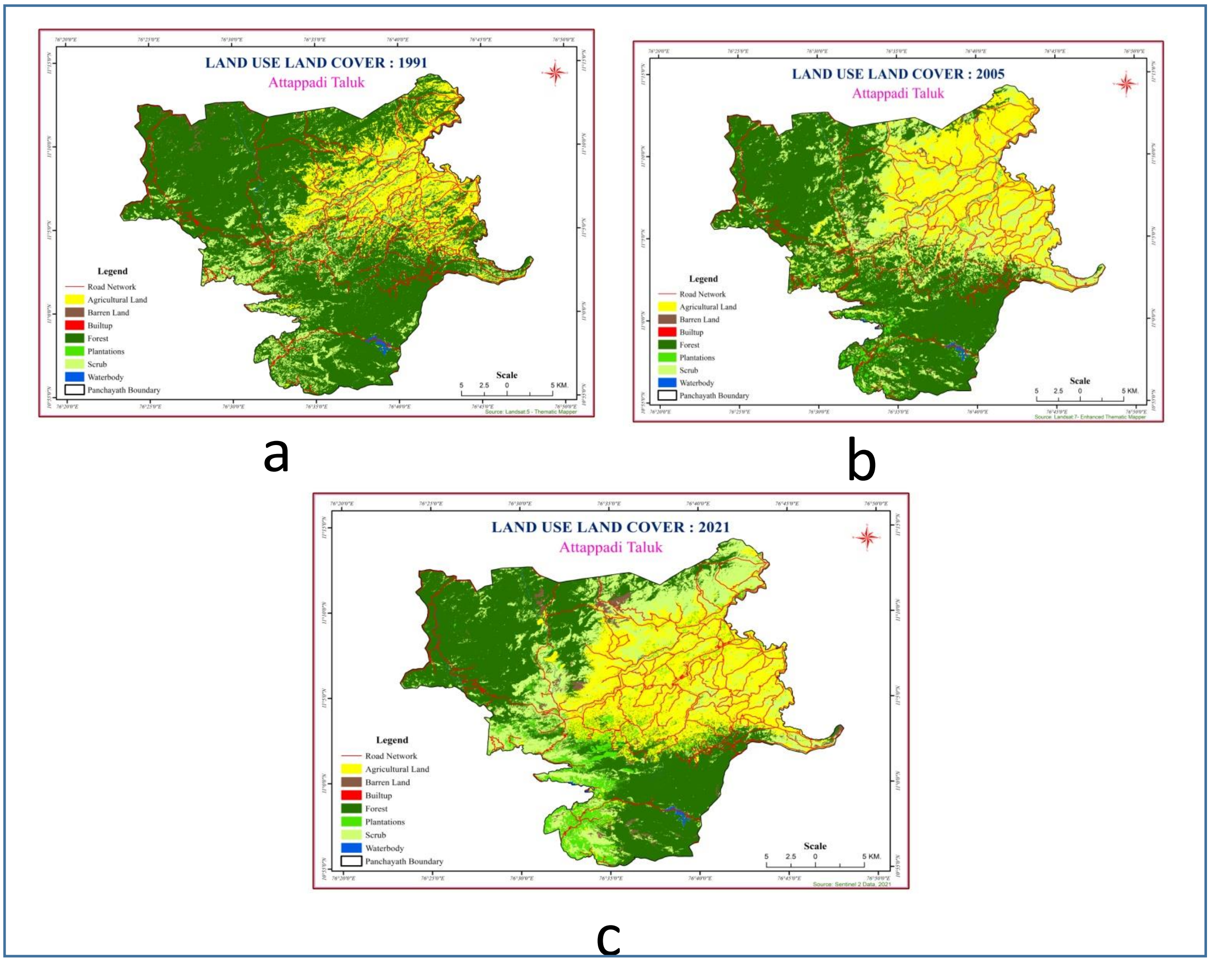


Fig. 3: Land Use Land Cover (a-1991 land use land cover, b-2005 land use land cover, c-2021 land use land cover)

Soil is a main component of land and is also a complex ecosystem containing animals and plants of different sizes and activities. Land use simply refers to the human uses of land. The term land use relates to the human activity or economic function associated with a specific piece of land[28]. It means how the land is being used by human beings or can be considered as the human employment of land[31]. Land cover relates to the type of feature present on the surface of the earth[28]. It means the biophysical materials found on the land[31]. In short, land use refers to the management regime humans impose on a site (e.g. plantations or agro forestry) and land cover is the descriptor of the status of the vegetation at a site (e.g. forest, crop)[12].

The land use and land cover statistics for the Attappady rain shadow region for the years 1991, 2005 and 2021 provide valuable insights into changes in the distribution of land cover over time (Fig. 3). In 1991, the region was primarily covered by forests (69.42%), indicating a significant forested area. The presence of scrub (18.04%) and cultivated land (11.51%) also suggests some human activity in the region, likely for agriculture. The percentages of barren land, built-up areas and plantations were relatively low. By 2005, there was a noticeable decrease in forest cover (52.06%) and an increase in cultivated land (21.63%). This shift suggests that land was converted for agricultural use, which often involves deforestation. The increase in scrub (22.81%) may also indicate land degradation.

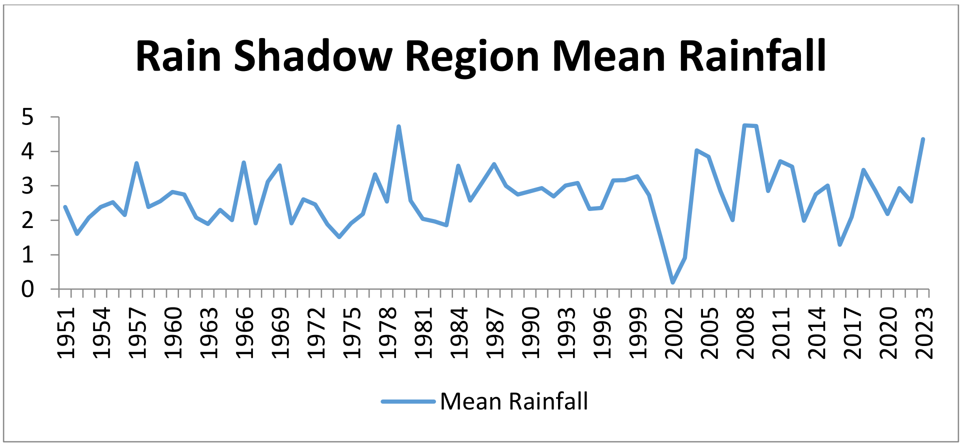
Additionally, there was a slight increase in built-up areas and plantations. In 2021, forest cover continued to decline (42.68%) while the percentage of cultivated land increased (25.38%). The expansion of cultivated land may signify ongoing agricultural development. There was also a notable increase in plantations (6.02%), suggesting the establishment of organized tree crops, which might be used for timber or other agricultural products. Scrubland remained significant (23.47%) and there was an increase in built-up areas (0.49%), which could indicate urban or infrastructure development (table.1).

Over the three decades, there has been a consistent decline in forest cover, which is a cause for concern due to its potential environmental impact including deforestation, loss of biodiversity and increased vulnerability to climate change. The increase in cultivated land and plantations indicates a shift toward agricultural and agro forestry activities in the region, possibly driven by changing land-use patterns and agricultural practices. The increase in built-up areas suggests that urbanization and infrastructure development have slowly begun to influence the region's land use.

Scrubland remains a prominent feature in all three years, signifying areas with a mix of vegetation and human disturbance. The presence of barren land has also increased, indicating land degradation or a lack of vegetation. The trends in land use and land cover statistics reflect the complex interplay of human activities, environmental factors and potential policy changes in the Attappady rain shadow region. It is important for local authorities and environmental organizations to monitor and manage land use changes to ensure the sustainable use of natural resources and the preservation of ecological balance in the region.

Rain shadow Region Temperature and Rainfall: The mean rainfall is also showing high fluctuation variation. In 2002, rainfall recorded very low in the last seven decades. The findings reveal decreasing rainfall trends and rising temperatures, emphasizing the urgent need for effective adaptation measures to mitigate the direct and indirect impacts on the farming community in the region. The correlation value of -0.55 indicates that the vegetation is decreasing paved the way for increasing surface temperature and also over the last three years, the green vegetation cover decreasing drastically whereas the land surface temperature has been increasing significantly. The average annual rainfall data for the Attappady rain shadow region from 1950 to 2023 has several trends and patterns.

The IMD rainfall data shows significant variability in annual rainfall amounts over the years (Graph 1). Some years experience higher rainfall, while others have much lower levels. The overall average annual rainfall for the region appears to be around 2 to 3 mm, with some years falling above or below this range. There are instances of extreme rainfall events such as the maximum value of 4.75mm and minimum value of 0.19mm, indicating years of exceptionally high and low rainfall respectively.



Graph 1: Mean Rainfall in Rain Shadow Region

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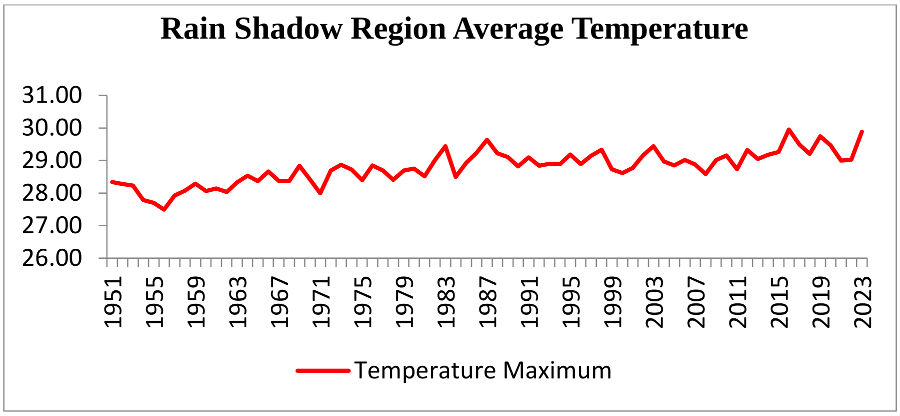

Graph 2: Mean Temperature in Rain Shadow Region

The amount of rainfall variation directly affects various aspects of the environment including vegetation, water availability and soil moisture. It also influences agricultural productivity, with both excess and insufficient rainfall posing challenges for farming communities. Long-term changes in rainfall patterns can have profound implications for the region's ecosystem, biodiversity and socio-economic conditions.

To interpret the average annual temperature data for the Attappady rain shadow region from 1950 to 2023, we can observe the following; over the last seven decades: the average temperature has been increasing from 27.5^0 to 30^0C. The notable changes were observed only after 1985 (Graph 2). There seems to be a trend of increasing temperatures over the years. This is indicated by the generally higher average temperatures in recent years compared to earlier years. Similar to rainfall data, there is variability in annual temperatures. Some years experience higher temperatures while others have lower temperatures. The majority of the recorded temperatures are above 27°C, indicating a consistently warm climate in the region.

There are instances of particularly high temperatures, with the maximum value reaching nearly 30°C. These extreme temperatures could have implications for the region's ecology, agriculture and human health. Rising temperatures can have various impacts on the environment including changes in ecosystems, water availability and the frequency of extreme weather events. Additionally, higher temperatures can pose health risks, particularly during heat waves. Long-term increases in temperature can lead to shifts in climate patterns, affecting rainfall, vegetation and biodiversity. These changes can have complex socio-economic implications, requiring adaptive strategies for communities in the region.

Mann-Kendall tests for the rain shadow regions of Attappady, focusing on rainfall and temperature: In rain shadow region, the P-value of 0.10 for rainfall suggests that there is 10% chance of observing the given data if there were no trend in rainfall over time. Generally, a P-value less than 0.05 is considered statistically significant, indicating a strong likelihood that the observed trend is not due to random fluctuations. However, a P-value of 0.10 is borderline and may not reach conventional levels of significance. The Z-value of 1.63 indicates the magnitude and direction of the trend. A positive Z-value suggests an upward trend while a negative Z-value suggests a downward trend. In this case, the positive Z-value indicates a slight upward trend in rainfall, but it is not particularly strong.

The P-value of 0.05 for temperature in the rain shadow region suggests a 5% chance of observing the given data if there were no trends in temperature over time. This P-value is significant at the 0.05 level, indicating strong evidence of a trend in temperature. The extremely high Z-value of 29.78 indicates a very strong and significant trend in temperature. Such a high Z-value suggests a substantial increase or decrease in temperature over time, depending on the sign of the Z-value.

Vegetation Condition: Vegetation thickness is closely related to land degradation. Studies have shown that soil degradation intensity can lead to a decrease in the absolute density of vegetation, particularly in the second stratum. The relationship between vegetation cover indices and land degradation has also been examined, revealing an inverse relationship between the size of land degraded and tree density, leaf cover index, area covered by litters, surface cover index and tree crown fullness[44]. Furthermore, the investigation of soil thickness and hardness under different conditions has indicated that vegetation type significantly influences soil thickness and plant growth while soil hardness has a significant influence on plant growth as well[53].

The degradation of perennial steppe vegetation due to overgrazing has been found to alter soil physico-chemical characteristics and fertility, highlighting the reciprocal relationship between soil and vegetation[4]. Long-term vegetation degradation has been assessed using remote sensing techniques, showing that anthropogenic stressors are primarily responsible for vegetation degradation, leading to declining land productivity and ecosystem services[41]. Normalized difference vegetation index is one of the most prominent vegetation indices used in image processing to investigate the green cover of photosynthetic plants. The following is the mathematical formula (Equation 2) for calculating NDVI:

$$NDVI = (NIR - RED) / (NIR + RED) \quad (2)$$

The NDVI values are unit less and vary in a scale with an upper limit of +1 and a lower limit of -1, with higher value on the NDVI scale. Negative NDVI values are used to represent non-vegetated environments such as ice, lake bodies and rocks (i.e. values less than 0). Low vegetation is defined as having NDVI values between 0 and 0.2; medium vegetation is defined as having NDVI values between 0.2 and 0.4 and mature vegetation is defined as having NDVI values greater than 0.4[24]. In general, a region's NDVI reaches its maximum at the height of the growth season, which in Kerala is from June to December.

The NDVI-derived values are frequently employed as a geographical and temporal measure of vegetation health. Whether natural or farmed, the growth pattern of vegetation is constantly impacted by climatic elements such as precipitation, temperature and so on making it critical to investigate the impact of precipitation on vegetation pattern. Natural Breaks were used to further categorise the data once these factors were calculated. The elevated terrain and abundant rainfall contribute to a dense forest cover in the western section of the study area showing high positive value in the NDVI. In contrast, the eastern part, receiving limited rainfall, fosters vegetation growth characterized by scrub and thorny forests showing less positive value (Fig. 4a).

Drainage Density: Drainage density is a significant parameter for assessing land degradation[26]. It has been used to assess soil erosion and degradation in various regions including the lesser Himalayan region of Himachal Pradesh, India[26]. Studies have shown that successful implementation of subsurface drainage (SSD) projects can improve soil quality and restore productivity in waterlogged saline areas[47]. The implementation of SSD projects has also been found to increase carbon sequestration potential and crop productivity[6]. In the Russian Plain, cultivation of lands has led to a decrease in drainage valley density and increased sediment redistribution, resulting in small river aggradation[15]. Land degradation in the eastern Chotanagpur Plateau in India has been attributed to factors such as poor soil development, high drainage density and anthropogenic activities.

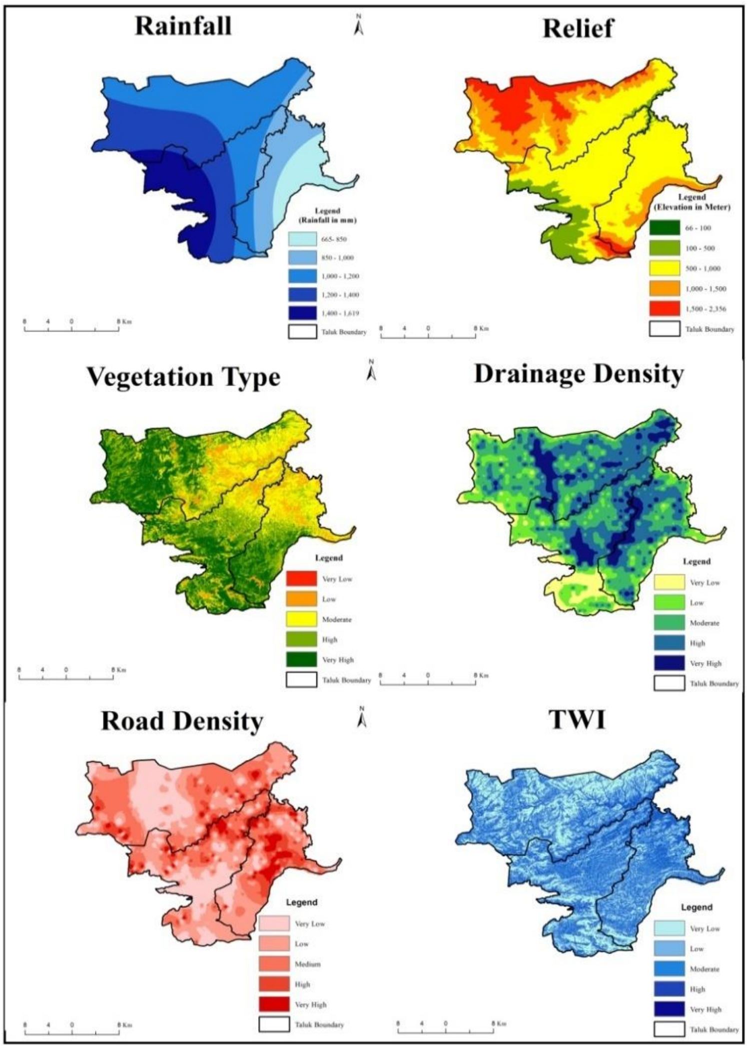

Fig. 4a: Land Degradation Factors

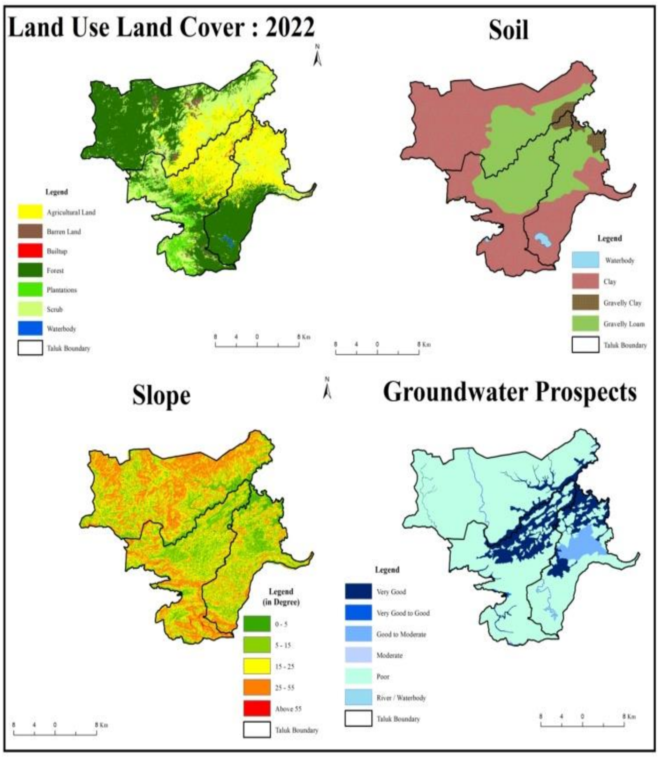

Fig. 4b: Land Degradation Factors

The concept of drainage density is also important in understanding the transition from unstable channel-forming processes to stable diffusive processes in landscapes. Drainage was generated from topographical maps (1: 50,000) and density has been calculated by applying 1km^2 GRID in QGIS. Despite the presence of numerous non-perennial east-flowing rivers, such as Bhavani and Siruvani, along with their tributaries in the study area, the undulating topography and steep slopes cause all drainage to flow out from the western part. Consequently, these watercourses accumulate in the central and eastern regions of the study area (Fig.4a).

Soil Texture: Soil texture plays a significant role in land degradation[11]. The study conducted in western Iran found that there were significant correlations between soil texture and soil erodibility. Clay content was positively correlated with soil erodibility while sand content was negatively correlated[17]. Woodland soils, which had higher clay content, had lower soil loss and land degradation compared to other land uses[32]. Additionally, shady slope aspects were found to have higher organic matter content and lower soil erodibility, likely due to less solar radiation and higher soil water content[34]. These findings suggest that soil texture, particularly clay content, can influence the susceptibility of soils to degradation and erosion, highlighting the importance of considering soil texture in land management practices to mitigate land degradation.

In Attappady, soil texture was derived from district wise benchmark of soils from Kerala State Soil Survey Department. Approximately 60% of the study area is characterized by clay-textured soil, with gravelly and clay-textured soil covering only a small portion in the eastern area. This indicates a significant correlation between robust vegetation growth and comparatively less vegetation in the eastern part (Fig.4b).

Groundwater Potential: Groundwater potential and land degradation are closely related. In Central Asia, which is an arid region with shallow groundwater tables, the role of groundwater in the impacts of climate change and regional anthropogenic activities on environmental risks, especially regional desertification, is inadequately understood due to limited research on groundwater-dependent ecosystems (GDEs)[9,39,40]. However, remote sensing-based methods have been used to map and identify GDEs in this region and the results have shown that GDEs are concentrated around large lakes and in central Kazakhstan[45,46].

Additionally, the level of groundwater can be used to monitor desertification and land degradation and models such as artificial neural networks (ANN) have been used to predict groundwater levels and land degradation indices. These studies emphasize the need for better understanding of the relationships among groundwater availability, ecosystem health and groundwater management policies to protect GDEs and prevent regional land degradation. Groundwater potential data for Attappady was vectorized from www.kslublris.com[51] (Fig. 4b).

Topographic Wetness Index: Topographic wetness index (TWI) indicates the effect of topography on runoff generation and the amount of flow accumulation at any location in a river catchment[14,18,35]. The formula to calculate the TWI can be expressed in equation 3:

$$TWI = Ln\left(\frac{Fa_{Scaled}}{\text{TanSlope}}\right) \quad (3)$$

where Fa_Scaled= (Fa+1) x 30; Fa= Flowaccumulation, TanSlope = Con(Slope1>0, Tan(Slope1),0.001) and Slope1 = Slope x 1.570796 /90. Fa Scaled represents flow accumulation. Higher TWI regions have a higher vulnerability of flood. Inversely, the lower TWI regions have lower vulnerability.

Calculation of the TWI has been carried out directly through processing of ASTERDEM (30 meter resolution) in QGIS. The Digital Elevation Model (DEM) analysis reveals that the topography inclines towards the east, resulting in flow accumulation and flow direction predominantly in the eastern part. Consequently, the topographic wetness is notably high along the major river courses and flow accumulation areas, particularly in the eastern section (Fig.4a).

Slope: Slope is a significant factor contributing to land degradation. High slopes, especially those between 16-25%, have been found to have the highest impact on soil degradation, leading to increased soil bulk density and decreased porosity[17]. Improper land use on steep slopes, combined with high rainfall, has been identified as one of the major causes of land degradation[37]. Additionally, the geological structure of an area, soil properties such as dispersibility and specific climate conditions can also contribute to slope failure and land degradation[7].

Understanding the relationship between slope and land degradation is crucial for formulating effective soil and water conservation measures to mitigate the negative impacts of land degradation and to promote sustainable development[13, 52]. Slope in degree was processed and derived from ASTER DEM (30 meter Resolution). The undulating topography of the area contributes to a varied slope, ranging from very gentle to extremely steep (Fig.4b).

Relief: Elevation has an important role in the distribution of climatic elements, especially in rainfall and humidity and wind speed. In the study area, the elevation divides the region into two sections: western side of the windward, which receives a lot of rain and eastern side of the leeward which receives less rain. Fig. 4 shows that central and eastern part have relatively low relief features and north and west parts have high relief.

Undulating topography affects the rainfall distribution of the study area. Topography of this region is carved out by tectonic, denudational and fluvial (Bhavani River and its tributaries) agents. The maximum height has been observed in the NW part (Anginda peak 2383 meter) and the lower elevation was recorded in the Bhavani's valley and the southern part of the study area (Fig.4a).

Road Density: Road density has been found to contribute to land degradation in several studies. In Central Ethiopian highlands, road construction has led to physical land degradation through gully erosion[43]. In Kuwait, off-road vehicle tracks and grazing points, which are associated with road density, have been identified as a leading cause of land degradation and soil compaction[3]. In western Iran, roads have been shown to negatively impact habitat fragmentation and loss, with road traffic noise playing a significant role[20]. Similarly, in Mongolia, unpaved roads have been found to cause soil erosion and degradation, particularly in agricultural areas. Additionally, a study analyzing five South Asian countries found that road infrastructure and road transport, energy consumption contributed to transport-generated emissions, indicating harm to environmental quality[5]. These findings highlight the negative effects of road density on land degradation and environmental quality. Prominent settlements like Kottathara, Pudur, Anaikatti, Attappadi, Sholayur, Agali, Mukkali, Kalkandi and Thavalam exhibit a high road density (Fig. 4a). In contrast, the study area, particularly in the western part with dense vegetation, experiences significantly lower road density.

Land Degradation: Land degradation is the process by which the quality and productivity of land deteriorate over time due to various natural and human-induced factors. This degradation can result from a variety of processes including soil erosion, deforestation, overgrazing, inappropriate land use, urbanization, pollution and climate change. The consequences of land degradation include reduced agricultural productivity, decreased biodiversity, soil erosion, desertification and the loss of ecosystem services. It is a significant environmental and socio-economic issue that can have far-reaching impacts on ecosystems and human well-being. In Attappady, very low land degradation is 15.58%. This category represents a relatively small portion of land in the Attappady region with very low levels of land degradation. It indicates areas where the land quality and productivity are in excellent condition, making them valuable for agriculture, biodiversity conservation and other land uses.

Low land degradation (27.12%): This category includes a larger portion of land that still maintains relatively good land quality and productivity. These areas are not experiencing severe degradation and can support various land uses with proper management practices.

Moderate land degradation (27.92%): A significant portion of the land in Attappady falls into this category, suggesting that these areas have moderate levels of land degradation. It implies that there is a need for attention and management to prevent further deterioration and to restore land quality where necessary.

High land degradation (18.05%): This category represents areas with a notable level of land degradation. These areas are likely to face challenges such as reduced agricultural productivity, soil erosion and the need for significant restoration and conservation efforts.

Very high land degradation (11.34%): This category signifies a relatively smaller but still significant portion of land that experiences very high levels of land degradation (Fig.5). This is a matter of great concern, as it indicates severe land quality deterioration, which may lead to desertification and significant loss of productivity.

From the study, it appears that a substantial portion of the Attappady rain shadow region faces some level of land degradation, with the majority being in the moderate and low degradation categories (Table 5). This suggests that the region needs focused efforts on land management and conservation to prevent further degradation and to rehabilitate the land where needed. The presence of areas with high and very high land degradation underscores the importance of addressing these issues to protect the ecosystem, biodiversity and the livelihoods of the local population.

Conclusion and Suggestion

Attappady situated on the eastern part of Western Ghats has a predominant influence and effect on the atmosphere and on spatial patterns of precipitation. The western part of windward side receives more rainfall with flourish ecosystem and eastern leeward side receives less rainfall leading to more albedo effect and sparse vegetation. Lad degradation is an outcome of many interlinked direct and underlying causes including natural, socioeconomic and related agricultural practices. In Attappady, many types of land degradation are occurring such as forest deforestation, scrub land degradation, cultivated land degradation and soil degradation. In this study, we conducted an empirical study in Attappady and analysed the spatial variation of land degradation, the temporal land use land cover changes and the variation in rainfall

Table 5
Land Degradation

S.N.	Land Degradation	Area in Km^2	Area in %
1	Very Low	127.13	15.58
2	Low	221.34	27.12
3	Moderate	227.85	27.92
4	High	147.32	18.05
5	Very High	92.58	11.34
	Total	**816.22**	**100**

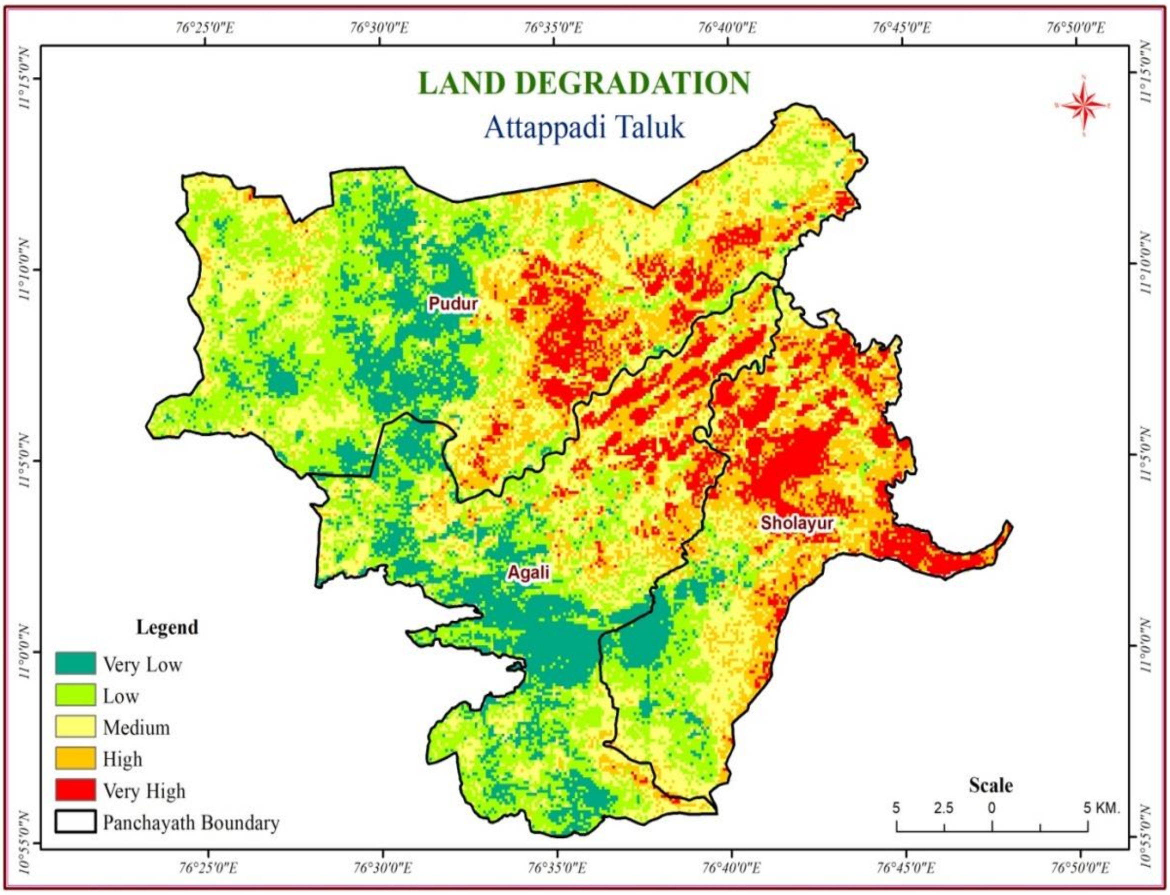

Fig. 5: Land Degradation

Land degradation levels were evidently performed using the geospatial analysis with the use of vegetation condition, relief features, drainage, groundwater, road density and soil as proxies in the study domain. We applied MIF technique in geospatial platform to integrate and analyse the relationship.

From the land degradation map, one can understand that more than half of the area is coming under moderate to high land degradation. This indicates that the land is now under pressure especially in the eastern part of Sholayur and Pudur. Unsurprisingly, the eastern part receives very less rainfall, has high temperature and warm wind coming from the neighboring Coimbatore which would affect natural vegetation, land conversion and land degradation. Anthropogenic activities such as land use changes and encroachment on tribal lands exacerbate environmental stressors, leading to land degradation and biodiversity loss.

According to the land use, land cover analysis for the last thirty years, forest land scrub has been decreased whereas plantation, built-up and agricultural land have shown increasing trend. The increase in built-up areas suggests that urbanization and infrastructure development would lead to land degradation. The expansion of basic infrastructure of transportation network further takes up land resources and further results in land over exploitation, soil sealing and degradation. The results of higher temperature and scanty rains would negatively affect the agriculture and plantation crops. Rising temperatures can have various impacts on the environment including changes in ecosystems, water availability and the frequency of extreme weather events.

To reduce the impact of infrastructure construction on land quality, the local Governments should take the assessment of land degradation into consideration during the construction of infrastructure. A sustainable way for managing land degradation in Attappady is through the implementation of eco-restoration projects that involve soil and water conservation interventions, agro-forestry, nutritional diversification, income generation activities and training. These projects have been shown to have positive impacts on both the environment and the livelihoods of the people living in the area.

Additionally, promoting sustainable land practices such as agro-forestry, integrated farming and practices that promote vegetation cover, can help address land degradation in the region. These practices provide soil cover to protect against erosion, to increase agricultural productivity and to diversify farmers' sources of income. By implementing these strategies, the productivity of salinized lands in Attappady can be enhanced, leading to more sustainable land use and improved livelihoods for the local community.

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