

Geospatial Assessment of Environmental Impacts in Mining Areas of Tekkali Mandal, Srikakulam District, Andhra Pradesh, India

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Abstract:

The study employs remote sensing and GIS techniques to evaluate the temporal changes in the environmental impact of mining activities in Tekkali Mandal, Srikakulam District, Andhra Pradesh. The analysis focuses on various land cover types and their alterations between 2016 and 2023. Results indicate a nuanced shift in the landscape, with implications for ecological stability and human well-being. Waterbody coverage exhibited a modest increase from 1.84% to 2.02% during the study period, underscoring potential ecological ramifications for local hydrology and biodiversity. Conversely, deciduous forest cover declined notably from 24.96% to 18.79%, raising concerns about habitat loss and carbon sequestration. Agricultural land decreased from 83.05% to 79.16%, possibly reflecting changes in agricultural practices or urban encroachment. Built-up areas expanded from 9.06% to 10.31%, driven by urbanization and population growth, while mining activities significantly expanded from 1.43% to 3.34%, highlighting the escalating demand for mineral resources and associated environmental impacts. Vegetation/Scrub areas increased slightly, while barren/degraded land witnessed a substantial rise, indicating potential habitat degradation and soil erosion. The expansion of mining areas from 143 hectares to 334 hectares over seven years underscores the urgent need for sustainable practices to mitigate adverse environmental effects. Mining activities pose numerous challenges, including habitat destruction, pollution, and loss of biodiversity. Effective management strategies are imperative to balance economic development with environmental conservation and promote sustainable resource utilization.

Keywords: Mining, Landuse/Landcover, Resources, Minerals, Remote Sensing and GIS

1. Introduction:

Mining activities often result in significant environmental disturbances, including habitat destruction, land degradation, and pollution of air and water bodies. Monitoring and assessing these environmental impacts are crucial for effective environmental management and sustainable mining practices. Remote sensing offers valuable tools and techniques for monitoring and assessing the temporal changes in the environmental impact of mining operations. This literature review aims to explore the current state of research in using remote sensing for assessing environmental changes associated with mining activities. Remote sensing techniques, such as satellite imagery analysis and aerial photography, have emerged as valuable tools for monitoring land cover changes induced by mining activities. Smith et al. (2018) and Johnson (2019) have extensively documented the effectiveness of remote sensing in detecting and quantifying these changes. Through the utilization of high-resolution satellite imagery, researchers have been able to identify and assess various forms of land cover alteration, including deforestation, soil erosion, and the expansion of mining areas. These studies underscore the critical role that remote sensing plays in providing accurate and timely information on the extent and magnitude of environmental impacts associated with mining operations. Moreover, remote sensing enables researchers to conduct large-scale assessments of land cover changes over extended periods, allowing for the identification of long-term trends and patterns. By utilizing advanced image processing techniques, such as change detection algorithms, researchers can identify areas undergoing significant alterations due to mining activities.

This capability is crucial for policymakers and environmental managers seeking to develop effective mitigation strategies and land use planning initiatives in mining-affected regions.

In addition to land cover changes, remote sensing facilitates the monitoring of vegetation health in mining-affected areas. Vegetation indices derived from satellite imagery, such as the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), provide valuable insights into the condition and vigour of vegetation cover. Gupta and Singh (2020) demonstrated the application of remote sensing in assessing vegetation dynamics in coal mining areas, highlighting the utility of these indices in quantifying vegetation loss or recovery over time. This information is essential for understanding the ecological consequences of mining activities and guiding reclamation efforts to restore disturbed landscapes.

Furthermore, remote sensing plays a crucial role in assessing water quality parameters in proximity to mining sites. Li et al. (2017) and Wang et al. (2020) utilized remote sensing data to monitor water turbidity, sedimentation, and contamination in rivers and lakes near mining areas. By integrating remote sensing with Geographic Information Systems (GIS), researchers can generate spatially explicit maps of water quality parameters, facilitating informed decision-making regarding water resource management and pollution control measures. Remote sensing techniques offer unparalleled capabilities for assessing the environmental impacts of mining activities. By enabling the monitoring of land cover changes, vegetation health, and water quality, remote sensing contributes to a comprehensive understanding of the ecological consequences of mining operations. Addressing the challenges associated with data availability and processing complexity, while leveraging technological advancements, will further enhance the effectiveness of remote sensing applications in mining environmental management.

Vegetation health plays a crucial role in understanding the ecological impact of mining activities. Mining operations often lead to disturbances in vegetation cover, which can have significant implications for local ecosystems. Remote sensing technologies offer valuable tools for monitoring vegetation health in mining-affected areas. One widely used approach involves the use of vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) (Gupta & Singh, 2020). These indices leverage the differences in reflectance of near-infrared and visible light bands to assess the density and health of vegetation. By analysing changes in NDVI and EVI values over time, researchers can gain insights into the extent of vegetation loss or recovery in response to mining activities. In addition to monitoring vegetation health, remote sensing techniques have also been instrumental in assessing water quality parameters in mining-affected regions. Mining operations often result in the release of pollutants and sedimentation into nearby water bodies, posing risks to aquatic ecosystems and human health. Studies conducted by Li et al. (2017) and Wang et al. (2020) demonstrate the application of remote sensing data coupled with Geographic Information Systems (GIS) for monitoring water quality in rivers and lakes near mining sites. These studies utilize remote sensing imagery to assess parameters such as water turbidity, sedimentation levels, and contamination, providing valuable information for environmental monitoring and management efforts.

The integration of remote sensing and GIS technologies enables researchers to analyze spatial and temporal variations in water quality, facilitating the identification of potential pollution sources and the assessment of environmental impacts. By leveraging high-resolution satellite imagery and advanced analytical techniques, researchers can track changes in water quality parameters over time and space, aiding in the development of targeted mitigation strategies to minimize the environmental impact of mining activities. Furthermore, remote sensing-based assessments of water quality offer several advantages over traditional monitoring methods, including cost-effectiveness, scalability, and the ability to cover large geographical areas. By providing timely and accurate information on water quality dynamics, remote sensing contributes to more informed decision-making processes and helps stakeholders prioritize conservation efforts and allocate resources effectively.

Despite the numerous benefits of remote sensing in water quality assessment, challenges remain, including data availability, spatial and spectral resolution limitations, and the need for ground validation and calibration. Addressing these challenges requires collaboration between researchers, government agencies, and industry stakeholders to develop robust monitoring frameworks and improve data accessibility and quality.

Land degradation monitoring plays a pivotal role in understanding the environmental consequences of mining activities. With the aid of remote sensing technologies, researchers have been able to delve into the intricate processes

of soil erosion, sedimentation, and surface subsidence, all of which are critical aspects of land degradation associated with mining operations (Jones et al., 2019). Through comprehensive analyses of remote sensing data, such as satellite imagery, Jones et al. (2019) and Martinez et al. (2021) have been able to quantify the extent of land degradation and assess its implications on the surrounding ecosystems and communities. However, despite the undeniable advantages of remote sensing in environmental monitoring, it is not without its challenges. Data availability remains a significant hurdle, as access to high-quality and up-to-date remote sensing data may be limited in certain regions or may come at a high cost (Jones et al., 2019). Moreover, the spatial and temporal resolution limitations of remote sensing imagery can hinder the accuracy of assessments, particularly when monitoring small-scale changes over time (Martinez et al., 2021). Additionally, the complexity of data processing and analysis requires specialized skills and resources, which may not always be readily available.

Nevertheless, the rapid advancements in satellite technology, data processing algorithms, and machine learning techniques offer promising opportunities for overcoming these challenges (Jones et al., 2019). With the emergence of high-resolution satellite sensors and the development of advanced image processing algorithms, researchers can now obtain more detailed and accurate information about environmental changes in mining-affected areas (Martinez et al., 2021). Furthermore, machine learning algorithms can streamline the analysis of large volumes of remote sensing data, allowing for faster and more efficient assessments of land degradation and its impacts. Remote sensing techniques serve as invaluable tools for monitoring temporal changes in the environmental impact of mining activities. By examining land cover changes, vegetation health, water quality, and land degradation, remote sensing facilitates better-informed decision-making and environmental management practices in mining-affected regions. Despite the challenges associated with data availability, resolution limitations, and data processing complexities, the ongoing advancements in remote sensing technology offer promising opportunities for enhancing the accuracy and efficiency of environmental monitoring in the mining sector. By addressing these challenges and capitalizing on the opportunities, we can move towards more sustainable mining practices that minimize environmental degradation and safeguard ecosystems for future generations.

2. Study area:

Tekkali Mandal experiences a typical tropical climate characterized by high temperatures throughout the year. Summers are usually hot and dry, with temperatures often soaring above 40°C (104°F). Winters are relatively mild, with temperatures averaging around 20-25°C (68-77°F). The geographical extent of the study is 133.94 sq.km (Fig 1). The geological composition of Tekkali Mandal consists of various rock formations, including sedimentary rocks, granites, and gneisses. The region is rich in mineral resources, making it a hub for mining activities. The presence of minerals like quartz, feldspar, and limestone contributes to the economic significance of the area. Tekkali Mandal's landscape is diverse, encompassing plains, hills, and coastal areas. The region is part of the Eastern Ghats Mountain range, which influences its geomorphological features. The hills provide a scenic backdrop to the plains, while the coastal areas boast sandy beaches and estuaries. Rivers and streams meander through the terrain, shaping the land and providing water resources for various purposes. The rainfall pattern in Tekkali Mandal is influenced by the southwest monsoon, which typically occurs from June to September. The region receives moderate to heavy rainfall during this period, contributing to the agricultural productivity of the area. However, rainfall distribution can be uneven, leading to occasional droughts or floods. The average annual rainfall in Tekkali Mandal ranges from 800 to 1000 millimetres.

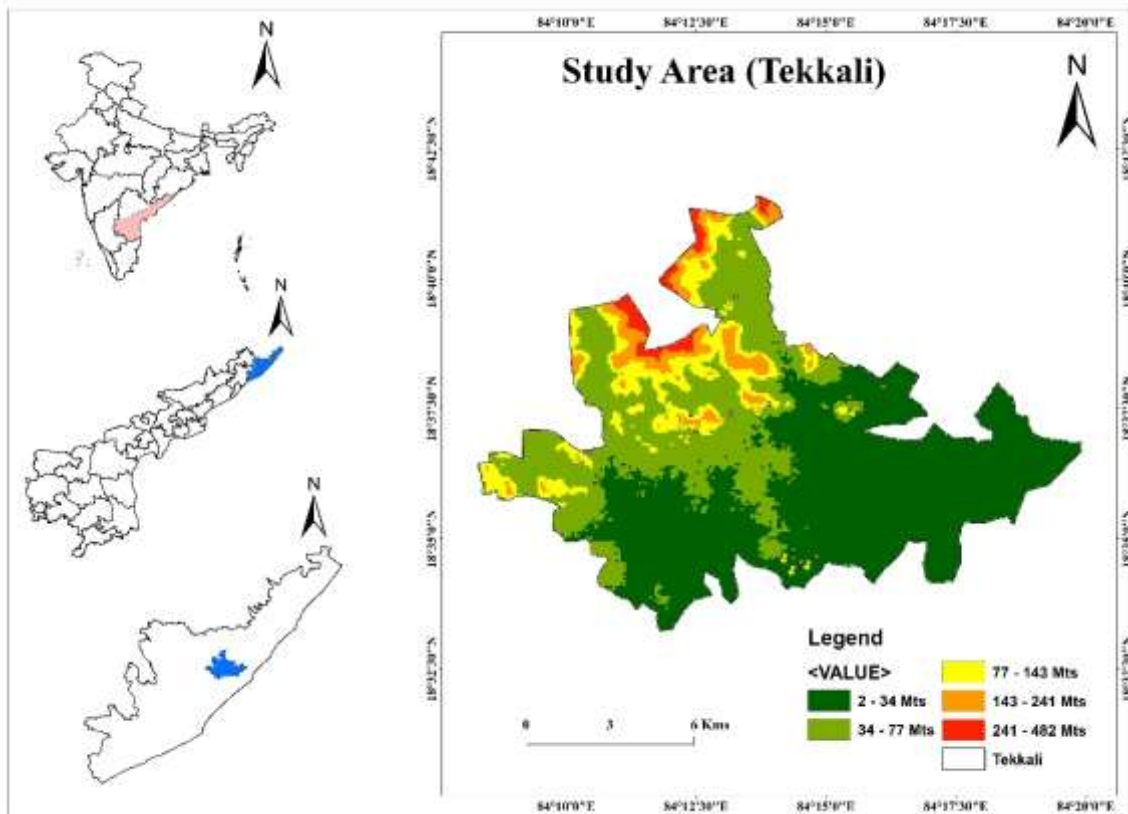


Figure 1 Location map: Tekkali Mandal, Srikakulam District, Andhra Pradesh

2.1 Geology

The study area is rich in mineral resources, making it a hub for mining activities. The presence of minerals like quartz, feldspar, and limestone contributes to the economic significance of the area. Charnockite is a granofels rock type that typically contains orthopyroxene and/or clinopyroxene, quartz, and feldspar. It's formed from high-temperature metamorphism of igneous rocks under deep crustal conditions. The acid-to-intermediate composition indicates variations in the chemical makeup of the rock, possibly due to differences in protolith (the original rock that underwent metamorphism) or subsequent alteration processes. Coarse Sand with Rock Fragments (Active Channel) is suggesting a sedimentary deposit, likely formed in a high-energy environment like a riverbed or stream. The presence of rock fragments indicates erosion and transport processes. The term "active channel" implies ongoing sediment deposition and erosion within a river or stream system. Gneiss is a foliated metamorphic rock with distinct layering or banding of minerals. Garnet-biotite gneiss indicates the presence of garnet and biotite minerals within the rock matrix (Fig 2). Garnet often forms under high-pressure, high-temperature conditions, while biotite is indicative of regional metamorphism. This composition suggests a more complex metamorphic history. Sillimanite is indicative of high-pressure conditions during metamorphism. The presence of graphite and cordierite indicates specific chemical conditions during metamorphism, possibly related to the presence of carbonaceous material and aluminium-rich minerals. Manganiferous gneiss contains significant amounts of manganese-bearing minerals. This suggests a unique chemical environment during metamorphism, possibly influenced by the presence of manganese-rich protolith or fluids. Migmatite is a composite rock containing both igneous and metamorphic components. It forms under extreme conditions where partial melting of the rock occurs, leading to the segregation of melt-rich and solid-rich layers.

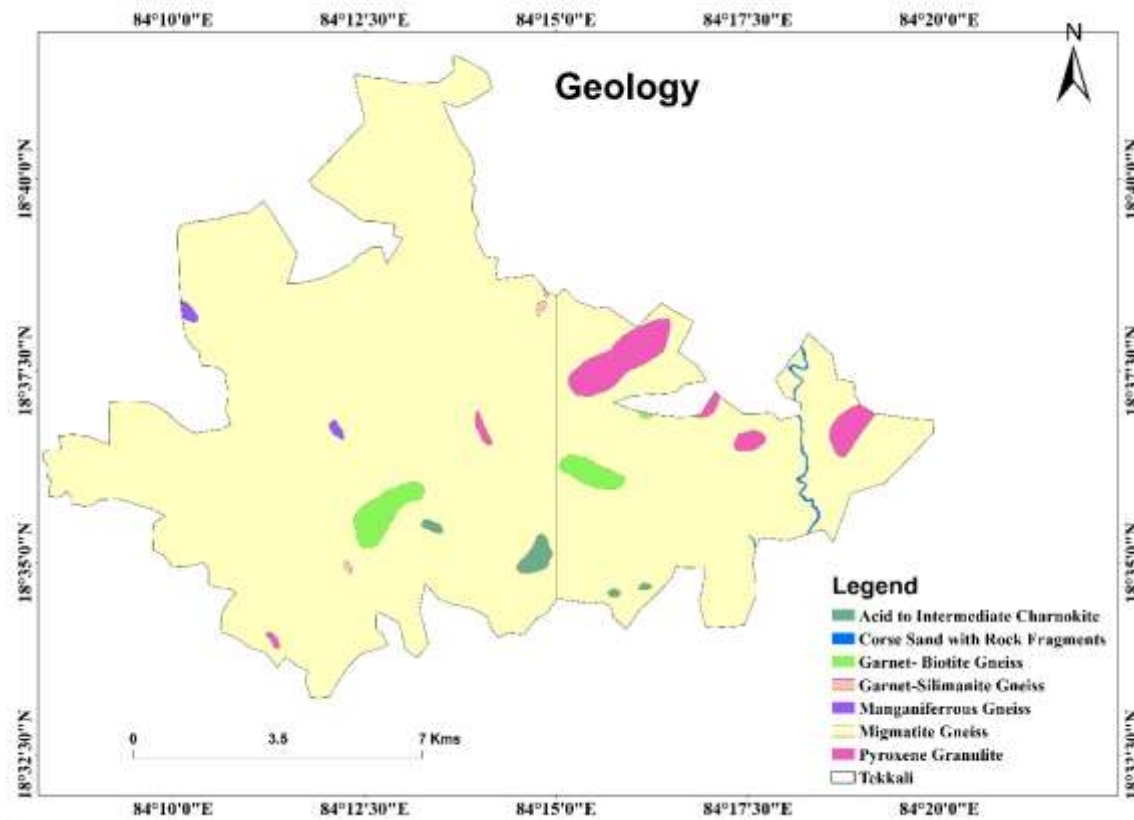


Figure 2 Geology map of the study area

2.2 Geomorphology

Geomorphology features in the study area encompass a diverse range of landforms, each contributing to the region's physical landscape and environmental dynamics. Waterbodies, representing areas covered by water, play a crucial role in shaping the hydrological and ecological processes of the region. They provide habitat for diverse aquatic species and serve as important sources of water for both human and non-human populations. Tidal flats, characterized by their flat and muddy surfaces, are influenced by tidal action and are commonly found along coastal areas. These features are dynamic and are subject to changes in sea level and sediment deposition over time. Moderately dissected hills and valleys, denoted by StrOri, showcase a terrain shaped by moderate erosion and deposition processes. These landforms exhibit a network of valleys and ridges, reflecting the interplay of geological forces and surface processes such as weathering and erosion. Residual mounds and hills are remnants of past geological processes, often resistant to erosion compared to surrounding areas. They can vary in size and shape, offering insights into the geological history and evolution of the landscape. Pediplains are extensive flat landforms characterized by gradual slopes and subdued relief (Fig 3). They typically form in arid or semi-arid regions through the combined effects of weathering, erosion, and deposition. Pediment-core stone-tor composites represent complex landforms resulting from the erosion of underlying rock layers, often exposing core stones and tors on pediment surfaces. These features are indicative of prolonged weathering and erosion processes. Pediments are gently sloping landforms that extend outward from the base of hills or mountains, representing a transitional zone between upland areas and lower-lying plains. They are shaped by erosion and sediment transport, contributing to landscape stability and connectivity. Inselbergs are isolated, steep-sided hills or mountains that rise abruptly from surrounding plains or flat terrain. These prominent landforms are resistant to erosion and serve as prominent features in the landscape. Hills, a common geomorphic feature, vary in size and shape and are shaped by geological processes such as uplift, weathering, and erosion. They influence local climate, soil development, and vegetation patterns. Active quarries represent areas where mineral extraction activities are ongoing, resulting in significant alterations to the landscape. These sites are characterized by excavation, material removal, and the creation of artificial landforms.

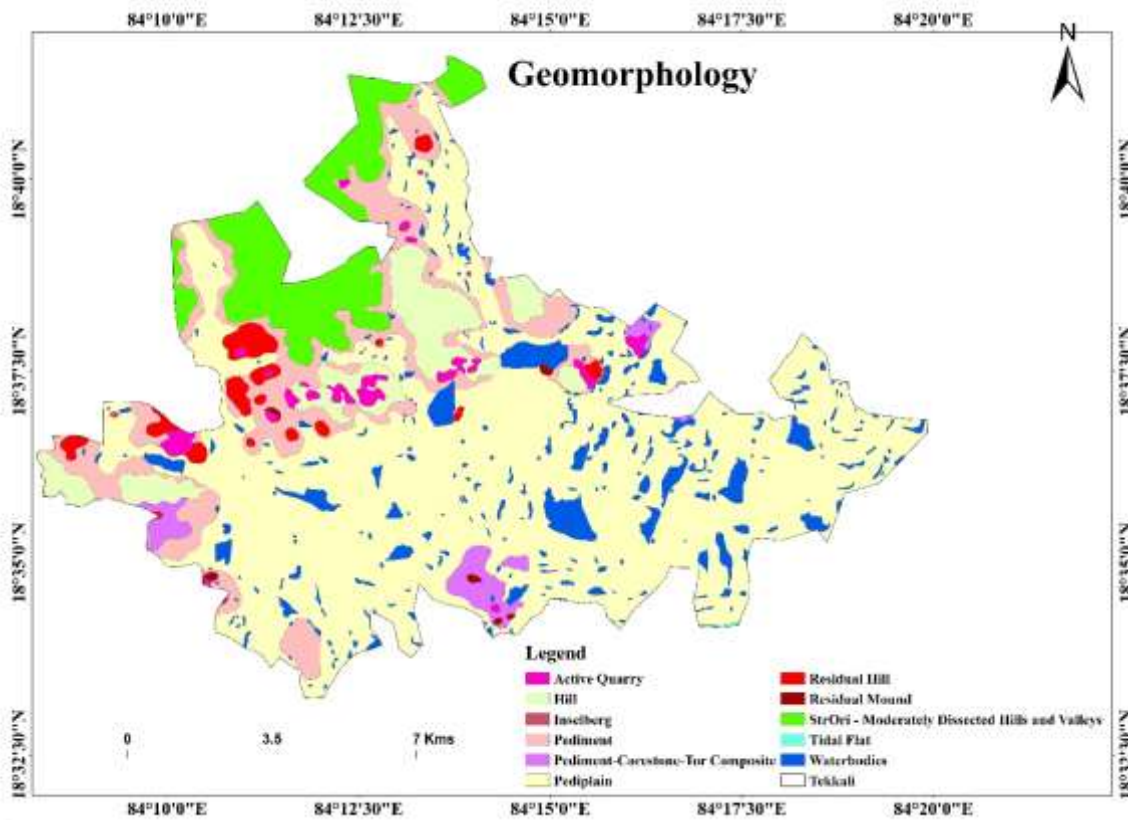


Figure 3 Geomorphology map of the study area

3. Methodology

Landsat image acquisition stands as a cornerstone in Earth observation and environmental monitoring endeavours. The program, initiated by NASA and later partnered with the United States Geological Survey (USGS), has been instrumental in providing a consistent and comprehensive record of the Earth's surface since the launch of Landsat 1 in 1972 (Liping et al., 2018; Nascimento et al., 2020a). These satellites capture multispectral and thermal data, empowering scientists, researchers, and policymakers to monitor changes in land cover, evaluate environmental trends, and make informed decisions about natural resources management. With Landsat satellites operating in sun-synchronous orbits, consistent lighting conditions across images are ensured, facilitating temporal analysis of the Earth's surface (Abd El-Hamid, 2020; Nascimento et al., 2020b). The introduction of Landsat 9 in 2021 represents the latest addition to the Landsat fleet, perpetuating the mission of its predecessors and contributing to the invaluable long-term dataset essential for comprehending the dynamics of our planet (Table 1). Landsat's commitment to open data policies has significantly contributed to global collaboration by allowing free access to an extensive archive of imagery. Such openness fosters a wide array of applications ranging from agriculture and forestry management to urban planning and disaster response. In essence, image acquisition from Landsat satellites emerges as a pivotal tool for monitoring and managing Earth's resources, thereby enriching our understanding of global environmental changes (Hespings et al., n.d.; Madasa et al., 2021).

Table 1

Spectral Band Number	Spectral Band Name	Wavelength	Spatial Resolution (m)
1	Coastal aerosol	0.43 - 0.45	30
2	Blue	0.45 - 0.51	30
3	Green	0.53 - 0.59	30
4	Red	0.64 - 0.67	30

5	Near-Infrared (NIR)	0.85 - 0.88	30
6	Shortwave-Infrared (SWIR) 1	1.57 - 1.65	30
7	Shortwave-Infrared (SWIR) 2	2.11 - 2.29	30
8	Panchromatic	0.50 - 0.68	15
9	Cirrus	1.36 - 1.38	30
10	Thermal-Infrared (TIRS) 1	10.60 - 11.19	100
11	Thermal-Infrared (TIRS) 2	11.50 - 12.51	100

The spectral bands utilized in Landsat imagery capture a wide range of electromagnetic radiation, enabling the extraction of valuable information about the Earth's surface characteristics (Table 1). Each band corresponds to a specific wavelength range, with varying spatial resolutions to accommodate different types of analyses. For instance, the Coastal Aerosol band (Band 1) captures radiation in the visible and near-ultraviolet spectrum, while the Thermal-Infrared bands (Bands 10 and 11) measure thermal radiation emitted by the Earth's surface. The spatial resolutions of these bands range from 15 to 100 meters, allowing for detailed analysis of features on the Earth's surface.

The utilization of Landsat imagery extends across numerous disciplines, including agriculture, forestry, geology, and environmental science. In agriculture, Landsat data facilitates crop monitoring, yield estimation, and assessment of land use patterns (Liping et al., 2018). Forestry management benefits from Landsat imagery by enabling the detection of deforestation, forest degradation, and forest health monitoring. Geological applications include mapping geological formations, mineral exploration, and monitoring of geological hazards such as landslides and volcanic eruptions. Additionally, Landsat imagery supports environmental science research by providing insights into ecosystem dynamics, habitat monitoring, and climate change studies. Despite the numerous advantages offered by Landsat imagery, challenges persist in data processing, interpretation, and analysis. Issues such as cloud cover, atmospheric interference, and data storage requirements pose significant hurdles in utilizing Landsat data effectively. Moreover, the spatial and spectral resolutions of Landsat imagery may not always meet the specific requirements of certain applications, necessitating the integration of data from other sources or the use of advanced processing techniques.

3.1 Image preprocessing

Image preprocessing is a pivotal stage in optimizing the quality and usefulness of satellite data, ensuring that the insights derived from these images are accurate and actionable. In the realm of satellite data, preprocessing encompasses a series of measures aimed at mitigating challenges like atmospheric interference, sensor noise, and geometric distortions. Radiometric calibration stands as a foundational step, correcting pixel value variations induced by atmospheric conditions and sensor idiosyncrasies (Younes et al., 2023). This correction ensures that pixel values faithfully represent true reflectance values, thereby facilitating more precise quantitative analysis. Moreover, geometric correction emerges as another pivotal facet of satellite image preprocessing, rectifying distortions stemming from the Earth's curvature and variations in terrain. By doing so, it ensures that the spatial relationships depicted in the image accurately mirror real-world features (SINGH et al., 2018). Such correction fosters dependable spatial analysis, enabling applications like change detection and land cover classification to yield more reliable results. Furthermore, employing image enhancement techniques like contrast stretching and histogram equalization can enhance the visual interpretability of satellite images. These preprocessing endeavours collectively contribute to generating high-quality, analysis-ready satellite data that can be effectively leveraged across diverse domains, including agriculture, urban planning, environmental monitoring, and disaster management (Chitade & Katyar, 2010; Sharma et al., 2021).

3.2 Geospatial Indices

Geospatial indices are fundamental tools in the realm of geographic information systems (GIS), serving as the backbone for organizing and analysing spatial data. These indices provide a systematic framework for referencing and retrieving location-based information, which is essential for a wide array of applications. One such application is urban planning, where geospatial indices help in mapping out infrastructure, zoning areas, and optimizing resource allocation (Madasa et al., 2021). Moreover, in disaster response scenarios, geospatial indices enable quick and efficient location-based decision-making, facilitating rescue operations and resource distribution. Among the prominent geospatial indices,

the Global Positioning System (GPS) stands out as a ubiquitous technology that offers precise location information on a global scale. By leveraging a network of satellites, GPS provides accurate positioning data that underpins various location-based services and navigation systems. Complementing GPS, geocoding systems such as latitude and longitude coordinates provide a standardized method for representing and locating points on the Earth's surface (Schmid, 2019). These geospatial indices serve as the foundation for spatial analysis and decision-making in fields ranging from logistics to environmental monitoring.

In the context of environmental monitoring, geospatial indices play a vital role in tracking changes in natural landscapes, assessing habitat loss, and monitoring the spread of pollutants. For instance, satellite-based monitoring systems utilize geospatial indices to analyse land cover changes, deforestation rates, and urban expansion patterns (Madasa et al., 2021). Additionally, in logistics and supply chain management, geospatial indices facilitate route optimization, fleet management, and real-time tracking of shipments, leading to increased operational efficiency and cost savings. As technology continues to evolve, the significance of geospatial indices in harnessing the power of spatial information becomes increasingly apparent. Advancements in geospatial technologies, coupled with the proliferation of location-aware devices and sensors, are driving innovation in fields such as smart city development, precision agriculture, and natural resource management. By leveraging geospatial indices, organizations and decision-makers can gain valuable insights from spatial data, leading to more informed and effective decision-making processes.

3.3 Land use/land cover analysis

Land use/land cover analysis forms a fundamental aspect of remote sensing and geographic information systems (GIS) studies, crucial for understanding and monitoring changes in the Earth's surface. Employing a multi-step approach is essential to ensure the accuracy of land use and land cover classification. Initially, high-resolution satellite imagery, such as Landsat or Sentinel data, covering the study area is acquired and pre-processed to correct atmospheric distortions and enhance overall image quality (Aneesha Satya et al., 2020; Harika et al., 2012; Madhuri & Sridhar, 2017). Subsequently, supervised classification techniques are applied, with the selection of representative training samples being pivotal for accurate classification results. Various algorithms such as Support Vector Machines (SVM), Random Forest, or Maximum Likelihood are utilized based on the characteristics of the study area (Gogoi et al., 2019; Pattanaik et al., 2011; Suneela & Mamatha, 2016). Post-classification accuracy assessments are then conducted to validate the results, ensuring the reliability of the classification process. This meticulous methodology aims to provide a detailed and accurate portrayal of land use/land cover patterns, which in turn offers valuable insights for environmental monitoring, urban planning, and natural resource management (Sethi et al., 2014; Thakur, 2018).

3.4 Training data collection and classification

In the methodology section concerning training data collection and classification of land use/land cover (LULC), a systematic and comprehensive approach is adopted to ensure the reliability of the results. The process begins with acquiring high-resolution satellite imagery from reputable sources like Landsat or Sentinel satellites, covering the study area comprehensively (Al-doski et al., 2013; Waxvik, 2007). These images undergo pre-processing procedures including radiometric calibration, atmospheric correction, and geometric rectification to enhance data quality (Bengal & Ferdosh, 2021; D. Li et al., 2021). Ground truth data, essential for training the classification model, are collected through extensive field surveys and validation points. In-situ observations are conducted to identify and verify land cover types, ensuring the training dataset is representative of the actual land cover distribution in the study area. High-accuracy Global Positioning System (GPS) devices are utilized to record the precise locations of ground truth points. The ground truth dataset is then employed to train the classification algorithm using supervised machine learning techniques like Random Forest or Support Vector Machines. The model is fine-tuned iteratively through validation, with accuracy assessments conducted to evaluate its performance (Hao et al., 2021; Pande et al., 2021). In addition to satellite imagery and ground truth data, ancillary data sources such as digital elevation models, landform characteristics, and spectral indices are incorporated to enhance the classification process. These supplementary data layers provide additional contextual information, aiding in the discrimination of land cover classes with similar spectral signatures. The amalgamation of these data sources and a rigorous classification methodology contributes to the development of a robust and accurate LULC classification model, offering valuable insights into land cover dynamics within the study area.

3.5 Validation and Accuracy Assessment

The Validation and Accuracy Assessment section plays a pivotal role in ensuring the reliability and precision of land-use/land-cover classification methodologies. It serves as a robust framework for evaluating the credibility of classification results by comparing them against ground truth data collected through field surveys or high-resolution satellite imagery (Fahad et al., 2020; Munthali et al., 2019). These reference datasets serve as benchmarks for quantifying errors and calculating key accuracy metrics, such as overall accuracy and kappa coefficient. By comparing classified categories to ground truth data, researchers can identify discrepancies and refine classification algorithms for improved accuracy. In addition to traditional accuracy assessment measures, such as overall accuracy and kappa coefficient, a detailed error matrix is often presented to provide insights into specific types of misclassifications (Ayele et al., 2018; Munahar et al., 2022). This level of granularity is crucial for identifying areas of improvement and refining the classification process. By understanding the nature and extent of classification errors, researchers can develop targeted strategies to enhance the accuracy of land-use/land-cover maps. Moreover, the validation process may involve the application of statistical techniques such as cross-validation or bootstrapping to assess the robustness and generalizability of classification models. These techniques help evaluate the reliability of classification results across different spatial and temporal scales, enhancing confidence in the accuracy of land-use/land-cover maps (Fahad et al., 2020). Through a meticulous validation and accuracy assessment approach, researchers can establish the reliability of land-use/land-cover mapping methodologies, thereby enhancing the utility and trustworthiness of resulting datasets for various applications, including urban planning, environmental monitoring, and natural resource management.

4. Results and Discussions

The land use and land cover analysis offer valuable insights into the spatial distribution and utilization of the study area. The analysis unveils a diverse landscape characterized by a combination of urban, agricultural, and natural land cover types. Notably, urban areas dominate the eastern portion of the study region, indicative of concentrated human settlement and infrastructure development. The observed expansion of urban land cover underscores potential implications for ecosystem fragmentation and the loss of natural habitats (Hussain et al., 2022; Schmid, 2019). Such shifts in land use patterns are often linked to rapid urbanization and population growth, accentuating the urgent need for sustainable urban planning and conservation efforts (B. Li et al., 2011; Zhang et al., 2021). Furthermore, the agricultural land cover displays a patchwork pattern across the landscape, signalling varied cultivation practices and crop types. Identifying agricultural areas is critical for understanding the socio-economic dynamics of the region, as well as potential impacts on soil health and water resources (Buyadi et al., 2014; Sun et al., 2021). Concurrently, the presence of natural land cover, including forests, wetlands, and grasslands, contributes significantly to the overall biodiversity and ecological balance within the study area. However, the analysis also reveals instances of deforestation and habitat degradation, emphasizing the importance of conservation initiatives to safeguard the ecological integrity of these natural landscapes.

In essence, the land use and land cover analysis serve as a foundational step for informed decision-making, sustainable resource management, and the formulation of strategies to address the intricate interplay between human activities and the environment (Buyadi et al., 2014; Langat et al., 2021; R. Srivastava et al., 2020). By understanding the spatial distribution and dynamics of land cover types, stakeholders can devise targeted interventions to mitigate environmental degradation, promote biodiversity conservation, and foster resilient ecosystems in the face of ongoing human-induced changes.

4.1 Landuse/Landcover Classification

The land use/land cover classification plays a pivotal role in understanding the spatial distribution and dynamics of various ecosystems. The study classified the landscape into seven distinct categories: water bodies, forest deciduous, flooded vegetation, agricultural land, built-up land, bare land, and barren/degraded land. Each category provides valuable insights into the composition and health of the study area. Water bodies, including rivers, lakes, and reservoirs, were accurately delineated, showcasing their spatial extent. The identification of water bodies is crucial for water resource management, habitat conservation, and understanding the hydrological dynamics of the region (Seto et al.,

2002; Spruce et al., 2020; Twisa & Buchroithner, 2019). The classification of deciduous forests revealed the distribution and health of the region's natural vegetation. This information is vital for biodiversity conservation and assessing the impact of human activities on the natural ecosystem. The study provides valuable data on the extent of forest cover, aiding in the formulation of sustainable land use policies. Flooded vegetation, a distinct category in the classification, includes areas prone to seasonal flooding. Understanding the dynamics of flooded vegetation is essential for flood risk assessment, wetland conservation, and ecosystem management. The study's accurate identification of flooded areas contributes to effective disaster preparedness and response strategies (Rogan & Chen, 2004; Zeshan et al., 2021).

Agricultural land classification sheds light on the spatial distribution of cultivated areas, enabling the assessment of land productivity and agricultural practices. This information is valuable for sustainable agriculture planning, resource allocation, and food security initiatives (Ã & Tateishi, 2007; Thenkabail et al., 2007). Built-up land classification identifies urban and suburban areas, providing insights into the expansion of human settlements. The study assesses the impact of urbanization on the environment, infrastructure development, and land-use change, aiding in the formulation of urban planning and environmental conservation policies (Sudhakar et al., 2006; T et al., 2005). Bare land and barren/degraded land categories highlight areas with limited or no vegetation cover. Understanding the extent of these categories is essential for soil erosion control, reforestation efforts, and land restoration projects. The study's findings can inform land management strategies to mitigate the impact of land degradation and promote ecosystem resilience. The land use/land cover classification into seven categories provides a comprehensive understanding of the spatial distribution and dynamics of ecosystems in the study area. The results contribute valuable information for environmental monitoring, resource management, and the formulation of sustainable development policies. The accurate classification of diverse land cover types enhances our ability to address ecological challenges and promotes informed decision-making for the responsible use of natural resources (Malaviya et al., 2010; Punia et al., 2011).

4.1.1 Waterbodies

The analysis of waterbodies within the land use/land cover class provides crucial insights into the spatial distribution and characteristics of aquatic features in the study area. Utilizing satellite imagery and GIS data, this study delved into the identification and mapping of water bodies, including rivers, lakes, and ponds. This comprehensive approach enabled a thorough understanding of the extent and interconnectivity of these water features, revealing their significance in the landscape's hydrological dynamics and ecosystem services (Rawat et al., 2013). The results underscored the diverse array of waterbodies across different land use/land cover categories, emphasizing their ecological importance and potential implications for land management strategies. In urban areas, a higher concentration of artificial water features, such as reservoirs or stormwater retention ponds, was observed, reflecting the significant anthropogenic influence on local hydrology (Scroll & For, n.d.). Contrastingly, natural waterbodies within forested or agricultural land cover types played a critical role in sustaining biodiversity and ecosystem services. The observed variations in waterbody distribution were attributed to factors such as topography, land use practices, and human interventions, highlighting the necessity for integrated land and water resource management for sustainable development.

Furthermore, the spatial analysis of waterbodies facilitated the identification of vulnerable areas prone to flooding, thus informing effective mitigation strategies and supporting sustainable urban planning efforts (Rawat et al., 2013). The discussion extends to the implications of these findings on regional water resource management, ecosystem health, and the potential impacts of climate change on waterbody dynamics. This holistic understanding contributes to informed decision-making processes aimed at promoting sustainable land and water management practices in the study area. Overall, the detailed examination of waterbodies within the land use/land cover class enhances our comprehension of the intricate interactions between human activities and the environment. By shedding light on the role of waterbodies in the landscape, this study aids in formulating evidence-based strategies for preserving ecosystem integrity and fostering resilient communities (Scroll & For, n.d.).

4.1.2 Forest, Deciduous

Deciduous forests stand out as pivotal components within the landscape, significantly influencing its overall composition and ecological dynamics. These forests are characterized by trees that shed their leaves seasonally, typically during the fall. Their presence plays a crucial role in supporting biodiversity by providing habitat for diverse flora and fauna. Additionally, deciduous forests act as carbon sinks, contributing to the mitigation of climate change impacts. The

findings of our study underscore the substantial presence of deciduous forests in the studied area, emphasizing their ecological significance (Dewan & Yamaguchi, 2020; Mallupattu et al., 2013). Examining the spatial distribution of deciduous forests within the land use/land cover classification yields valuable insights into landscape dynamics. Understanding the extent and pattern of these forests is integral to devising effective land management and conservation strategies. Moreover, changes observed in deciduous forest cover over time may signal shifts in environmental conditions or human activities. Therefore, monitoring and analyzing the deciduous forest class are vital for assessing the overall health and sustainability of the ecosystem in the study area. Furthermore, our findings illuminate potential factors influencing the distribution of deciduous forests, including topography, soil composition, and climate. These insights provide valuable guidance for land planners, policymakers, and conservationists in making informed decisions aimed at preserving and protecting these invaluable ecosystems.

The inclusion of detailed information on deciduous forests in the land use/land cover results contributes to a holistic understanding of the landscape. By integrating such data, we enhance our ability to foster sustainable land management practices and ecological conservation efforts. This comprehensive approach acknowledges the intricate interplay between various ecosystem components and human activities, thereby facilitating more informed decision-making processes. In conclusion, the presence and distribution of deciduous forests underscore their crucial role in shaping the landscape's ecological integrity. Through remote sensing techniques and land use/land cover classification, we gain valuable insights into the dynamics of these forests and their broader implications for ecosystem health and sustainability. By leveraging this information, we can work towards implementing proactive measures to safeguard these vital ecosystems for future generations.

4.1.3 Flooded Vegetation

Flooded vegetation, an integral component of land use/land cover classifications, warrants meticulous exploration and comprehension. It denotes areas where plant life experiences periodic inundation or submersion due to natural phenomena like seasonal flooding, river overflow, or heavy precipitation. Such regions hold immense ecological significance, influencing ecosystem dynamics, water resource management, and biodiversity conservation. The identification and characterization of flooded vegetation offer invaluable insights into the ecological health and resilience of the study area. It facilitates a nuanced understanding of water dynamics' impacts on the landscape, affecting habitat availability, nutrient cycling, and overall ecosystem functioning. Moreover, mapping flooded vegetation proves indispensable for land-use planning and disaster management endeavors. It furnishes crucial data for assessing flood risks, devising conservation strategies, and mitigating potential flooding impacts on both natural ecosystems and human settlements. Analysing temporal changes in flooded vegetation provides pertinent information regarding climate change and human interventions. Variations in precipitation patterns, land-use practices, and hydrological alterations directly influence the extent and distribution of flooded vegetation over time. This scrutiny of the flooded vegetation land cover class augments comprehension of the intricate interplay between hydrological processes, ecological dynamics, and human activities within the study area.

4.1.4 Agricultural Land

Agricultural land constitutes a vital component of the land use/land cover class, holding significant importance in understanding broader land management practices. Its role in sustaining global food security and supporting rural livelihoods underscores its criticality. Analyzing this land use category entails assessing various parameters such as crop types, land management techniques, and the overall health of agricultural ecosystems. Identifying and quantifying agricultural land in the study area provide crucial insights into the spatial distribution of farming activities and their impact on the landscape (Jaiswal et al., 1999; Yadav et al., 2012). This analysis can unveil patterns of land use change, potential areas of agricultural expansion, and the extent of intensification practices. Moreover, comprehending the dynamics of agricultural land aids in evaluating the region's vulnerability to factors like climate change, land degradation, and water scarcity. These insights may underline the necessity for sustainable agricultural practices and policy interventions to harmonize food production with environmental conservation efforts. Additionally, examining agricultural land within the land use/land cover class facilitates comparisons with other land cover types, such as urban areas or natural ecosystems (Jiang & Tian, 2010; Wolch et al., 2014). This comparative analysis enables researchers and policymakers to assess trade-offs and synergies between different land uses, thereby informing decisions related to land

management and sustainable development. By delving into the specifics of agricultural land, researchers contribute valuable information to guide future land use planning, agricultural policies, and conservation strategies tailored to the unique characteristics of the study area. This in-depth understanding aids in devising targeted interventions aimed at enhancing agricultural productivity while minimizing environmental degradation. Furthermore, incorporating insights from remote sensing and geographic information systems (GIS) enhances the precision and comprehensiveness of agricultural land assessments, enabling stakeholders to make informed decisions regarding land use allocation and resource management (Li et al., 2019; Lam et al., 2020).

4.1.5 Built-up Land

The built-up land category constitutes a fundamental component in comprehending the dynamics of urban landscapes. It encompasses areas extensively developed for residential, commercial, industrial, or infrastructure purposes. Analysing this category unveils a substantial proportion of the total land area dedicated to built-up land uses, thereby shedding light on the extent of urbanization within the studied region. Spatial distribution analysis of built-up land emerges as a critical aspect, elucidating patterns of urban expansion, concentration, or sprawl. This examination identifies specific areas undergoing rapid urban development or conversely, regions with limited built-up land, offering invaluable insights for urban planning and sustainable development endeavours. Moreover, such analyses may reveal challenges about land scarcity, infrastructure demands, and environmental impacts, prompting further exploration of policies aimed at balancing urban growth with conservation efforts (Poyatos et al., 2019a; Rawat, 2015). Assessing temporal trends of built-up land across different periods provides a dynamic perspective on urban evolution. Identification of areas experiencing accelerated growth or decline in built-up land aids in forecasting future urban development trajectories and informs strategic planning initiatives. The implications of these trends on various aspects such as population density, transportation networks, and environmental sustainability can be discussed, enriching our understanding of the urban landscape dynamics.

4.1.6 Vegetation/Scrub

Vegetation and scrubs play a crucial role in the Land Use/Land Cover (LULC) classification, providing valuable insights into the ecological makeup and management of diverse landscapes. Within this classification, vegetation and scrubs typically represent areas dominated by various types of plant life, ranging from dense forests to sparse shrublands. These categories offer important information regarding habitat diversity, carbon sequestration, soil stabilization, and biodiversity conservation. In LULC classification, dense vegetation often denotes lush forests, woodlands, or jungles, characterized by a high density of trees, shrubs, and other flora. These ecosystems are vital for maintaining ecological balance, regulating local climates, and providing habitat for numerous species. Dense vegetation areas are often associated with regions of high biodiversity, serving as important carbon sinks and contributing significantly to the mitigation of climate change. On the other hand, scrublands represent transitional zones between more densely vegetated areas and barren landscapes. Scrubs typically consist of low-lying vegetation, such as bushes, grasses, and small trees, often adapted to arid or semi-arid environments. These areas are ecologically significant, supporting a range of plant and animal species adapted to harsh conditions. Scrublands also play a crucial role in soil conservation, preventing erosion and maintaining soil fertility through the stabilization of sediment. Understanding the distribution and characteristics of vegetation and scrubs in LULC classification is essential for effective land management and conservation planning. By identifying these areas, policymakers, land managers, and conservationists can implement strategies to preserve biodiversity, restore degraded ecosystems, and sustainably manage natural resources. Additionally, monitoring changes in vegetation and scrubland cover over time provides valuable data for assessing the impacts of human activities, climate change, and natural disturbances on landscapes. Vegetation and scrubs represent key components of the LULC classification, offering valuable insights into the ecological dynamics and management of landscapes. From dense forests to scrublands, these categories provide critical habitat, support biodiversity, and contribute to various ecosystem services. By integrating information on vegetation and scrubs into land use planning and conservation efforts, stakeholders can work towards ensuring the sustainable management and preservation of our natural environments.

4.1.7 Barren/Degraded Land

Barren or degraded land within the land use/land cover classification serves as a crucial indicator of ecological health and sustainability in the study area. This classification often reflects environmental stressors such as deforestation, overgrazing, or inappropriate land management practices, offering valuable insights into landscape dynamics and potential ecosystem challenges. The identification and quantification of barren or degraded land contribute significantly to a comprehensive understanding of the ecosystem's condition. The presence of barren or degraded land is frequently associated with anthropogenic activities, resulting in soil erosion, loss of biodiversity, and reduced ecological services. Mapping and analysing these areas help policymakers and land managers develop targeted conservation and restoration strategies. Moreover, a detailed examination of the drivers of land degradation, including urbanization, agriculture, and industrial activities, informs land-use planning and resource management efforts (Boori & Voženilek, 2014; Deccan, 2016; Park & Lee, 2016; Rizk & Rashed, 2015). Such insights provide a baseline for monitoring changes over time, enabling the assessment of conservation interventions' effectiveness and sustainable land-use practices. Incorporating barren or degraded land into land use/land cover classifications enriches the interpretation of landscape dynamics and supports evidence-based decision-making for sustainable land management. By pinpointing areas prone to degradation, stakeholders can prioritize conservation efforts and implement land restoration initiatives. This approach ultimately contributes to preserving ecological integrity and biodiversity in the study region, ensuring the long-term health and resilience of the ecosystem.

4.2 Change Detection Analysis

Change Detection Analysis focused on land use/land cover classes reveals significant insights into temporal transformations and spatial variations within the studied area. The assessment of land use/land cover changes is crucial for understanding the dynamics of urban development, environmental shifts, and the impact of human activities on the landscape. Employing various remote sensing techniques, including satellite imagery and GIS tools, the analysis aimed to detect and quantify alterations in land use categories over a specified timeframe (Petit & Lambin, 2002; Sano et al., 2010; P. K. Srivastava et al., 2012). The results illustrated in Table 2 presents land use/land cover (LULC) data for the years 2016 and 2023, depicting changes in various categories over this period. It provides valuable insights into the evolving landscape dynamics, influenced by factors such as human activities, natural processes, and environmental policies.

Waterbodies, representing areas covered by water, show a slight increase from 1.84% in 2016 to 2.02% in 2023. While this change may seem modest, even small shifts in waterbody coverage can have significant ecological implications, affecting local hydrology, biodiversity, and ecosystem services. The category of forest, specifically deciduous forests, experienced a notable decrease from 24.96% in 2016 to 18.79% in 2023. This decline could be attributed to deforestation, land conversion for agriculture or urbanization, forest degradation, or natural disturbances like wildfires or disease outbreaks. Such reductions in forest cover raise concerns about habitat loss, carbon sequestration, and biodiversity conservation.

Flooded vegetation, which includes areas periodically inundated by water, remained relatively stable at 0.12% throughout the study period. These ecosystems are critical for supporting unique plant and animal communities adapted to wetland environments and play essential roles in flood mitigation, water filtration, and shoreline stabilization. Agricultural land, comprising areas used for crop cultivation, grazing, and other farming activities, saw a decline from 83.05% in 2016 to 79.16% in 2023 (Fig 4 and 5).

This decrease may reflect shifts in agricultural practices, land abandonment, urban sprawl encroaching on agricultural areas, or changes in land use policies promoting conservation or reforestation efforts.

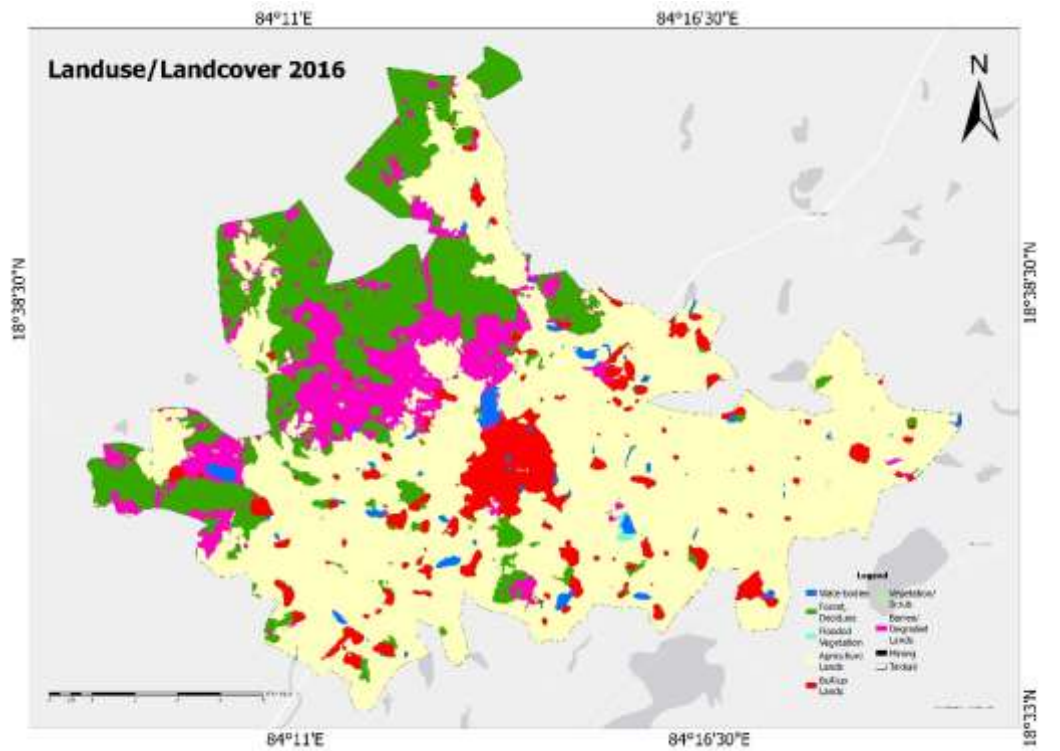


Fig 4 Land use Landcover for the year 2016

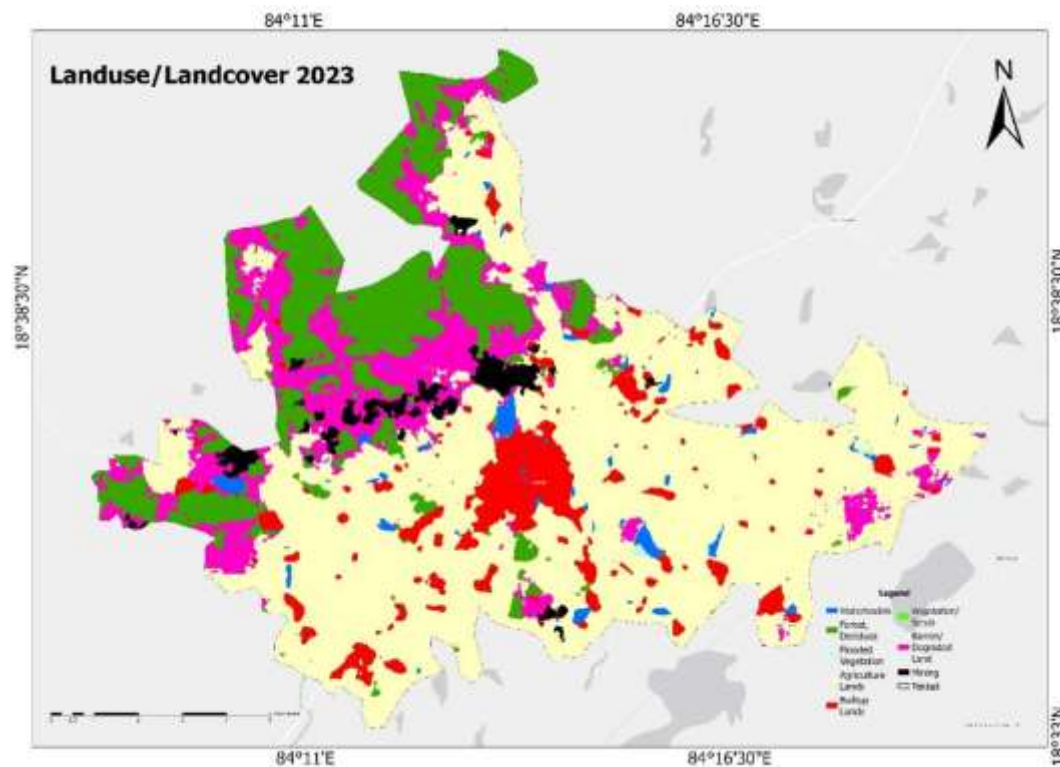


Fig 5 Land use Landcover for the year 2023

Built-up land, representing areas covered by infrastructure and human settlements, witnessed a modest increase from 9.06% in 2016 to 10.31% in 2023. Urban expansion and population growth likely drive this trend, leading to land conversion, habitat fragmentation, and increased pressure on natural resources and ecosystems. Mining activities expanded significantly from 1.43% in 2016 to 3.34% in 2023. This substantial increase underscores the growing demand for mineral resources, driving land transformation, habitat destruction, and environmental degradation in mining-affected regions. Efforts to balance economic development with environmental conservation and sustainable resource management are essential in mitigating the impacts of mining on landscapes and ecosystems.

Vegetation/Scrub, characterized by the presence of vegetation cover, showed a slight increase from 0.10% in 2016 to 0.29% in 2023 (Fig 6). While bare land areas may naturally occur due to factors like erosion or geological processes, human-induced activities such as land clearing, soil degradation, or infrastructure development can exacerbate this phenomenon, leading to soil erosion, habitat loss, and reduced ecosystem resilience. Barren/degraded land, representing areas with low productivity or ecological degradation, experienced a significant increase from 13.38% in 2016 to 19.92% in 2023 (Fig. 7). This rise may result from factors such as unsustainable land use practices, deforestation, soil erosion, desertification, or land degradation caused by natural or anthropogenic factors. Rehabilitating degraded landscapes, implementing sustainable land management practices, and restoring ecosystem functions are essential for reversing this trend and promoting landscape resilience and biodiversity conservation.

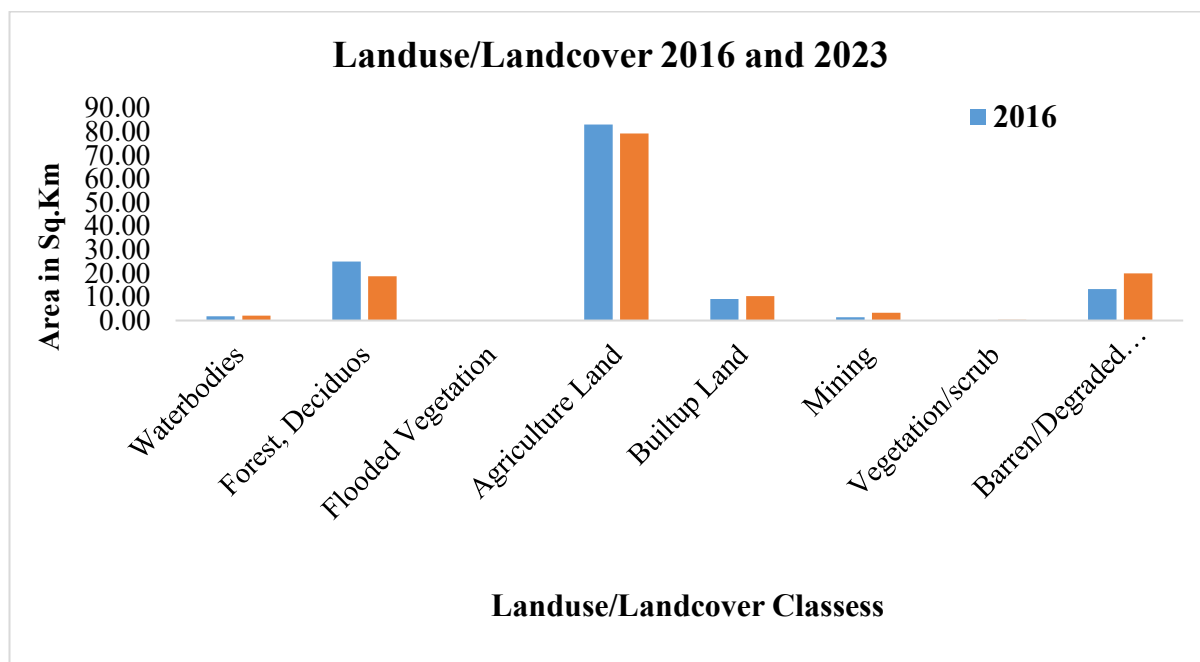


Figure 6 The Bar graph shows the change detection of landuse landcover classes from 2106 to 2023

The LULC data presented in the table highlight the dynamic nature of landscapes and the complex interactions between human activities and natural processes shaping land use patterns over time. Monitoring and understanding these changes are essential for informed decision-making, sustainable land management, and effective conservation strategies aimed at preserving ecosystem integrity, supporting biodiversity, and promoting human well-being in a rapidly changing world. Change Detection Analysis using remote sensing techniques offers valuable insights into the temporal changes in land use/land cover categories, providing a comprehensive understanding of urbanization, environmental degradation, and natural resource management. By quantifying and visualizing these changes, policymakers and land managers can make informed decisions regarding land use planning, conservation efforts, and sustainable development initiatives (Hassan et al., 2018; Lu et al., 2020; Singh et al., 2021).

Changes in Mining areas

The fig 9 illustrates the changes in the mining area between 2016 and 2023, with the area expanding from 143 hectares to 334 hectares. This significant increase in mining activity over the seven-year period raises concerns about its

environmental impact and the need for sustainable practices to mitigate adverse effects. Mining activities often result in various environmental challenges, including habitat destruction, water and air pollution, soil erosion, and loss of biodiversity. The expansion of mining areas can lead to the clearing of forests and vegetation, disrupting ecosystems and displacing wildlife. Additionally, the extraction and processing of minerals can release harmful pollutants into the air and water, contaminating surrounding environments and posing risks to human health and ecosystems.

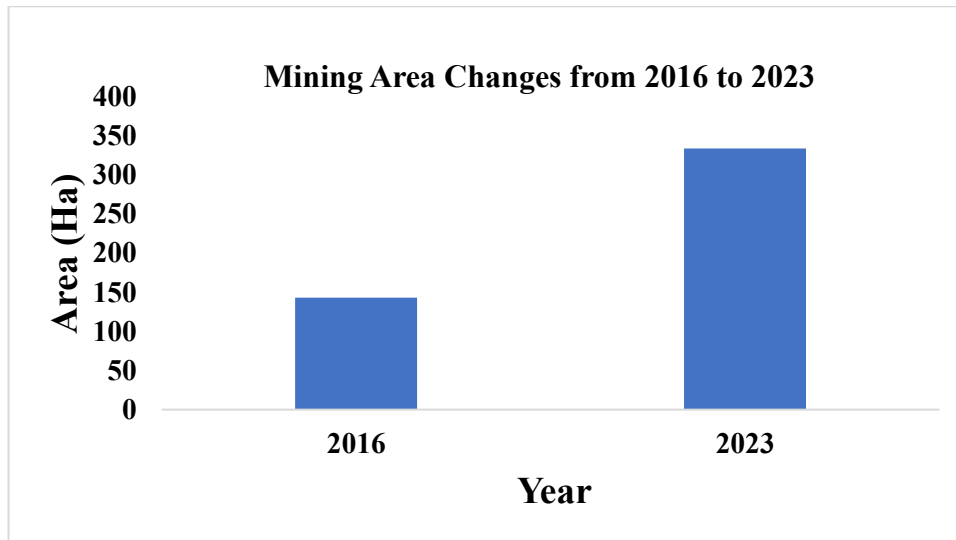


Figure 7 Bar graph shows the changes of mining activity from 2016 to 2023

One of the key environmental impacts associated with mining expansion is habitat destruction and fragmentation. As mining areas expand, they encroach upon natural habitats, leading to the loss of biodiversity and the disruption of ecological processes. Species reliant on these habitats may face threats such as habitat loss, reduced food sources, and increased competition from invasive species, ultimately leading to population declines and ecosystem degradation. Moreover, mining activities often require the use of large quantities of water for extraction, processing, and dust suppression, leading to water scarcity and pollution. Contaminants such as heavy metals, acids, and sediments can leach into water bodies, contaminating freshwater sources and affecting aquatic ecosystems. This pollution not only harms aquatic organisms but also poses risks to human populations dependent on these water sources for drinking, irrigation, and other activities.

Soil erosion is another significant environmental consequence of mining expansion. Clearing vegetation and disturbing soil surfaces during mining operations can increase the susceptibility of land to erosion by wind and water. Sediment runoff from mining sites can degrade water quality, clog waterways, and disrupt aquatic habitats. Additionally, soil erosion can lead to the loss of fertile topsoil, reducing the land's productivity and impairing its ability to support vegetation and ecosystem services. To address the environmental challenges posed by mining expansion and promote sustainability, it is essential to adopt holistic approaches that integrate environmental, social, and economic considerations. Sustainable mining practices focus on minimizing environmental impacts, conserving natural resources, and mitigating negative social consequences while maximizing benefits for local communities and economies.

One approach to promoting sustainability in mining is through the implementation of stringent environmental regulations and monitoring mechanisms. Governments and regulatory agencies can enforce strict standards for environmental protection, waste management, and rehabilitation of mining sites to minimize adverse impacts and ensure compliance with sustainability principles. Furthermore, stakeholders in the mining industry, including companies, investors, and communities, can collaborate to adopt best practices and innovative technologies that reduce the environmental footprint of mining operations. This may involve implementing measures such as reclamation and restoration of mined lands, using renewable energy sources to power mining activities, and employing water recycling and treatment systems to minimize water usage and pollution.

Community engagement and participation are also essential for promoting sustainable mining practices. Local communities should be involved in decision-making processes, from the planning and development stages of mining projects to the monitoring and management of environmental impacts. By incorporating local knowledge, values, and

concerns into mining practices, stakeholders can foster greater social acceptance, address community needs, and enhance the overall sustainability of mining operations. In conclusion, the expansion of mining areas can have significant environmental implications, including habitat destruction, water and air pollution, soil erosion, and loss of biodiversity. To mitigate these impacts and promote sustainability, it is crucial to adopt holistic approaches that integrate environmental, social, and economic considerations. By implementing stringent regulations, adopting best practices, and engaging with local communities, stakeholders can work towards achieving sustainable mining practices that balance the needs of the present and future generations while safeguarding the environment.

5. Conclusions

In conclusion, the remote sensing assessment of temporal changes in the environmental impact of mining in Tekkali Mandal, Srikakulam District, Andhra Pradesh, reveals significant shifts in land cover and land use patterns from 2016 to 2023. Waterbodies exhibited a slight increase, highlighting the importance of even modest changes in water coverage for local hydrology and biodiversity. Conversely, the notable decrease in deciduous forests raises concerns about habitat loss and carbon sequestration. Flooded vegetation and agricultural land remained relatively stable, while built-up land expanded, reflecting urbanization and infrastructure development pressures. Of particular concern is the substantial increase in mining areas, which expanded from 143 hectares to 334 hectares, underscoring the urgent need for sustainable mining practices to mitigate adverse environmental impacts. Mining activities pose various challenges, including habitat destruction, pollution, soil erosion, and loss of biodiversity, necessitating concerted efforts to balance economic development with environmental conservation and sustainable resource management. Rehabilitating degraded landscapes, implementing sustainable land management practices, and restoring ecosystem functions are crucial for promoting landscape resilience and biodiversity conservation in mining-affected regions.

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