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DIGITAL SOIL MAPPING FOR SOIL DEGRADATION ASSESSMENT AND SUSTAINABLE LAND MANAGEMENT IN KWARA STATE, NIGERIA

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ABSTRACT

Soil degradation poses a significant threat to agricultural productivity and environmental sustainability in Kwara State, Nigeria. Traditional soil surveys with coarse-resolution analogue maps inadequately capture the spatial variability necessary for effective assessment and management. This study develops a Digital Soil Mapping (DSM) framework integrating Geographic Information Systems (GIS) and remote sensing to produce high-resolution, spatially explicit soil property maps and identify degradation hotspots. Spatial and non-spatial data, including satellite imagery and field soil samples, were collected, processed, and analyzed using geospatial and statistical techniques. The results reveal substantial heterogeneity in soil texture, pH, and nutrient content, with pronounced degradation linked to erosion and nutrient depletion in intensively farmed areas. DSM demonstrated superior capability over traditional methods by accurately delineating vulnerable landscapes and informing targeted soil conservation strategies. The study highlights challenges, including data availability and technical capacity, recommending enhanced data integration, capacity building, and stakeholder engagement for sustainable land management.

KEYWORDS: *Digital Soil Mapping, Geographic Information Systems (GIS), Kwara State, Nigeria, Remote Sensing, Soil Degradation Assessment.*

1. INTRODUCTION

Soil degradation is a critical environmental challenge affecting agricultural productivity (Hossain *et al*., 2020), ecosystem sustainability, and food security globally (Rehman, Farooq, Lee, & Siddique, 2022; Telo da Gama, 2023), particularly in developing regions such as Kwara State, Nigeria. The complex interplay of natural factors, including climate variability and topography, combined with anthropogenic activities like intensive agriculture, deforestation, and improper land use practices, has accelerated soil deterioration in the state (Ekka, et al., 2023; Iwuchukwu *et al*., 2023). Traditional soil survey methods, while valuable, are often limited by their spatial coverage, cost, and time requirements, making it difficult to capture the spatial heterogeneity of soil properties necessary for informed land management decisions (Abdulraheem, et a., 2023; Adeniyi, Bature, & Mearker, 2024).

Digital Soil Mapping (DSM) has emerged as a transformative approach that integrates soil observations with environmental covariates derived from remote sensing, geographic information systems (GIS), and advanced statistical techniques (AbdelRahman & Afifi, 2024; Adeniyi, Bature, & Mearker, 2024; Mondal, et al., 2024). By leveraging high-resolution geospatial data and GIS technology, DSM enables the creation of detailed, accurate, and scalable soil property and degradation maps. This capability is crucial for areas like Kwara State, where soil degradation threatens agricultural productivity and sustainable land use (Hossain *et al*., 2020).

Despite significant technological advancements, challenges remain in applying DSM effectively, including limited availability of high-resolution soil datasets, resolution constraints of satellite imagery, and the need for rigorous ground-truth validation (Abdulraheem *et al*., 2023). Addressing these challenges requires a comprehensive soil information infrastructure, capacity building in geospatial technologies, and collaborative efforts among government agencies, research institutions, and local stakeholders (Panagos, Borrelli, & Robinson, 2020).

This study aims to assess soil degradation in Kwara State using DSM techniques by integrating multiple data sources, including Shuttle Radar Topography Mission (SRTM) elevation data, Sentinel-2 land cover imagery, Landsat 8-9 vegetation indices, and rainfall records in a harmonized coordinate system. Advanced GIS techniques are employed to capture the spatial variability and relationships between soil properties and environmental factors (Sediqi, Naseri, & Haidari, 2025). The resulting soil degradation maps provide valuable insights for land use planning, precision agriculture, erosion risk assessment, and targeted soil conservation strategies. Ultimately, this research contributes to the sustainable management of soil resources in Kwara State and offers a methodological framework applicable in similar environments across Africa.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Kwara State (Figure 1), Nigeria, located in the North-Central region between latitudes 7°30′N to 10°15′N and longitudes 2°30′E to 6°25′E, covering about 36,825 km². It borders the Republic of Benin, Niger, Kogi, Oyo, Osun, and Ekiti states (Aderamo, 2007). The capital, Ilorin, is a key commercial and administrative hub with an estimated population of 4 million, primarily engaged in farming and trade.

Kwara experiences a tropical wet and dry climate with annual rainfall from 1000 mm to 1,500 mm and temperatures ranging between 22°C and 37°C (Fabiyi & Ashaolu, 2015). . Vegetation includes Guinea Savannah in the central and southern areas and Sudan Savannah in the north (Adejini, Owolabi, & Abdulsalam, 2019). The landscape features gentle slopes, valleys, and floodplains, influencing soil dynamics. Soils are mainly ferruginous tropical types with sandy loam textures and moderate acidity (pH 5.1–6.4), showing signs of degradation from intensive agriculture and deforestation. Key crops include maize, yams, cassava, rice, sorghum, millet, and vegetables (Adejini *et al*, 2019).

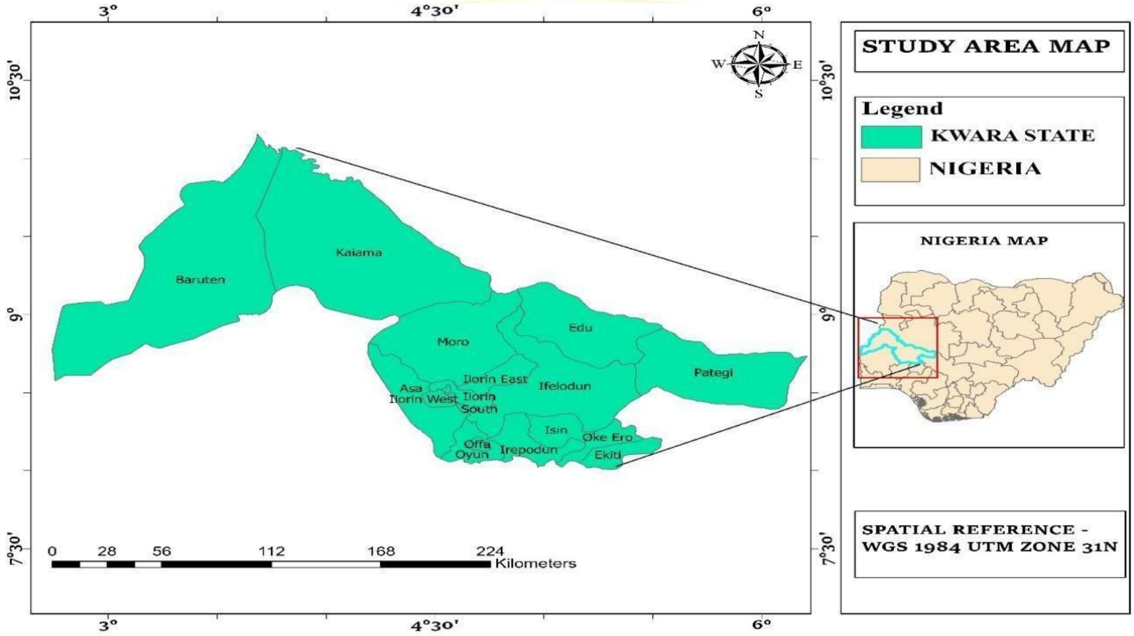


Figure 1: The Map of Kwara State, Nigeria.

2.2 Methods

2.2.1 Data Sources and Data Collection

Data collection incorporated both spatial and non-spatial data sources. Spatial data were acquired from satellite remote sensing platforms and existing geospatial datasets relevant to soil characteristics and environmental variables. Non-spatial data included field soil sample analyses and records from previous soil surveys and agricultural land assessments. Multiple geospatial datasets were utilized to capture the environmental factors influencing soil degradation (Table 1). Geospatial datasets used include SRTM elevation (30 m), Sentinel-2 land cover (10 m), Landsat vegetation indices, and rainfall records, standardized to WGS 1984 UTM Zone 31N for assessment of soil degradation using digital soil mapping techniques.

Table 1: Geospatial datasets used and their attributes

Data Type	Source	Description
Shuttle Radar Topographic Mission (SRTM) elevation data	USGS Earth Explorer	30 m resolution; used to derive elevation, slope, flow accumulation, topographic wetness index, and curvature
Land cover imagery	Esri Sentinel 2 Land Cover Explorer	10 m resolution; used for land use/land cover classification
Vegetation indices	Landsat 8-9 (USGS Earth Explorer)	Derived NDVI for vegetation health and cover
Rainfall data	Center for Hydrometeorology and Remote Sensing (CHRS)	Long-term average rainfall data impacting soil moisture and erosion
Soil factor data	FAO-UNESCO soil factor database (1971–81)	Baseline soil properties data
Administrative boundaries	Office of the Surveyor General, Kwara State	Shapefiles for state, local government area, and ward boundaries

Spatial Data Sources
Satellite imagery and remote sensing data employed in the study comprised multi-spectral datasets suitable for soil and land cover classification. Geographic Information System (GIS) layers representing terrain attributes, land use, climate, and vegetation were integrated. These spatial datasets provided multi-dimensional information essential for predicting soil variability and degradation patterns. All spatial datasets were projected to and harmonized in the WGS 1984 UTM Zone 31N coordinate system using the "Project Raster" geoprocessing tool to ensure positional consistency.

Non-Spatial Data Sources
In addition to remote sensing data, soil samples were collected across the study area following systematic sampling protocols to measure physical and chemical soil properties. Historical soil survey data from the Federal Department of Agricultural Land Resources (FDALR) were also utilized to complement and validate contemporary findings.

2.2.2 Data Processing
Collected spatial and non-spatial data underwent preprocessing steps, including geometric correction, radiometric calibration, and coordinate referencing to ensure uniformity. Soil sample laboratory results were digitized and linked spatially within the GIS environment. Data cleaning and normalization techniques were applied to enhance analysis reliability.

2.3 GIS Analysis and Soil Degradation Assessment
GIS-based multi-criteria decision analysis (MCDA) and spatial modeling techniques were employed to assess soil degradation. Digital soil mapping methods involve integrating remote sensing data with soil sample information to model the spatial distribution of degraded soils. Morphogenetic soil characterization and multi-source data fusion were applied to improve prediction accuracy. Validation involved comparing modeled outputs with field observations and existing soil maps to ascertain reliability.

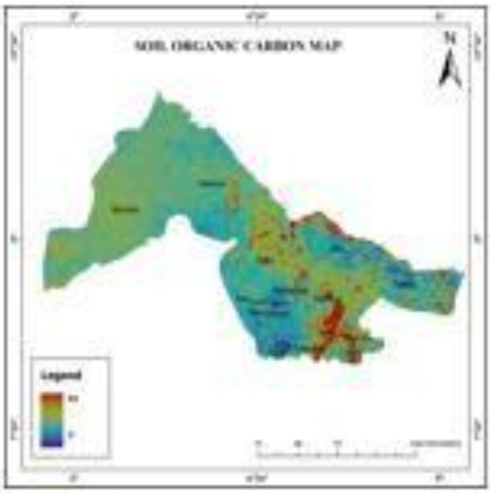
3. RESULTS AND DISCUSSION

3.1 Spatial Distribution of Soil Properties in Kwara State

The Digital Soil Mapping (DSM) framework, which integrates field observations with GIS and remote sensing data, revealed significant spatial heterogeneity in soil properties across Kwara State. Generated spatial maps indicate that soils predominantly feature sandy loam to sandy clay loam textures, particularly in the central and southern regions, consistent with the underlying basement complex geology. Soil pH values range from moderately acidic (5.1 to 6.4), with more acidic areas observed in intensively cultivated zones, indicating acidification due to fertilizer use and mono-cropping practices.

Nutrient analyses revealed widespread depletion of organic matter, total nitrogen, and available phosphorus, especially in regions of prolonged and intensive farming without adequate nutrient replenishment. Additionally, soils exhibit poor structural aggregation and suboptimal drainage, increasing susceptibility to erosion and soil compaction. These soil factor patterns are illustrated in Figure 2a-2s

(a)



(b)

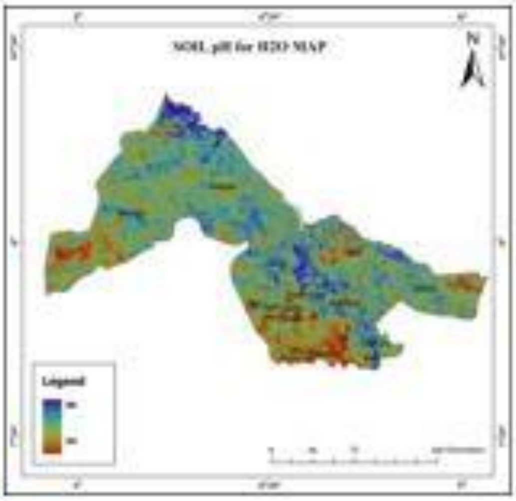
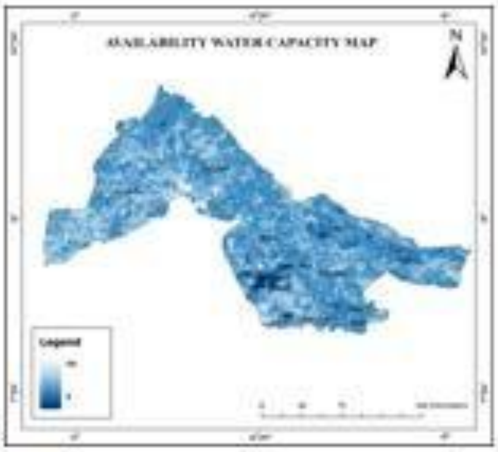


Figure 2a: Soil Organic Carbon Map Figure 2b: Soil pH for H_2O Map

(c)



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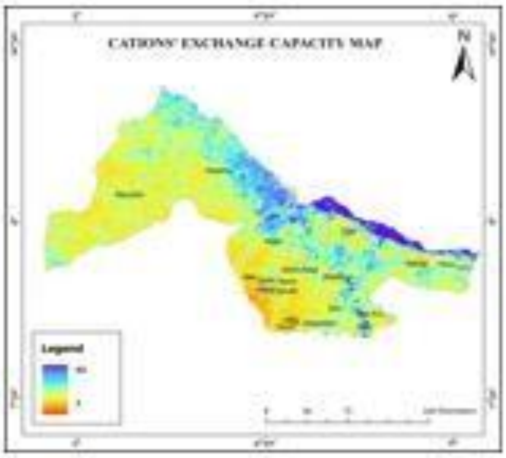
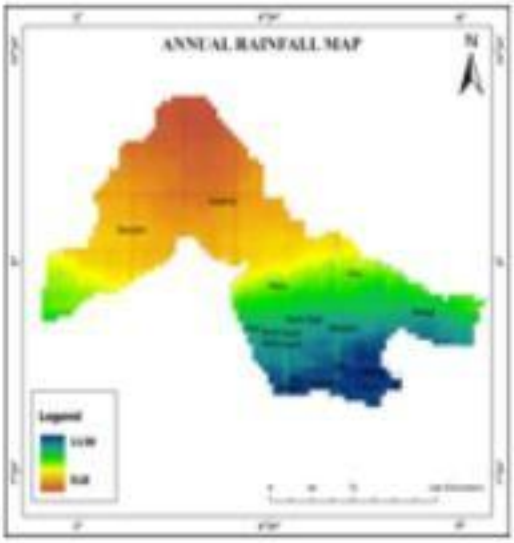


Figure 2c: Availability Water Capacity Map Figure 2d: Carbon Exchange Capacity Map

(e)



(f)

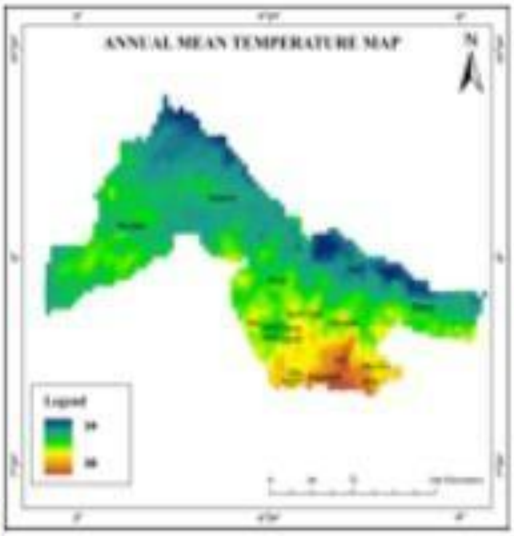
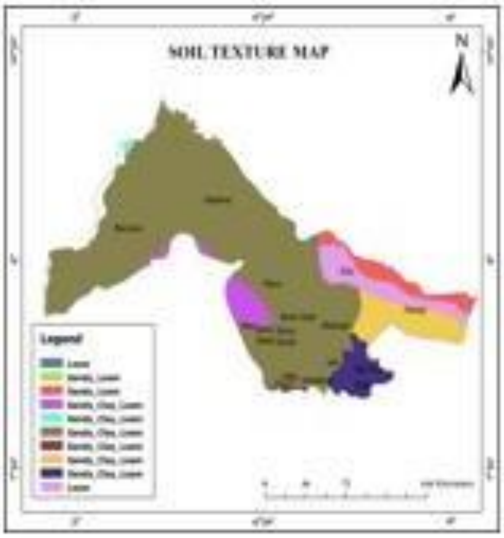


Figure 2e: Annual Rainfall Map

Figure 2f: Annual Mean Temperature Map

(g)



(h)

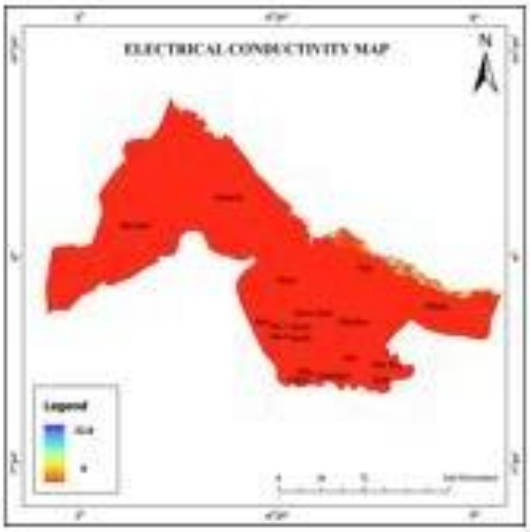
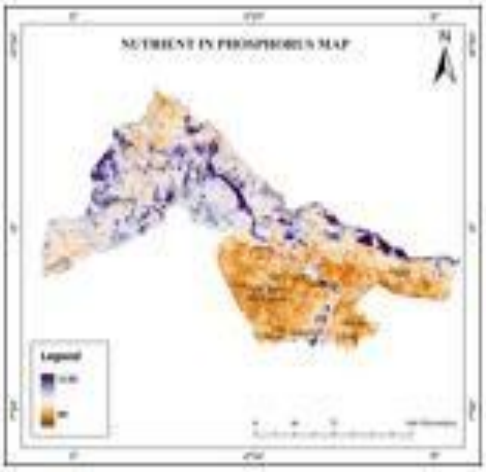


Figure 2g: Soil Texture Map

Figure 2h: Electrical Conductivity Map

(i)



(j)

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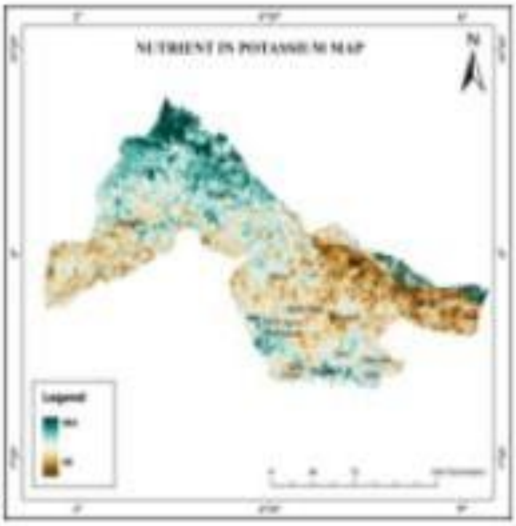
igure 2i: Nutrients Phosphorous Map Figure 2j: Nutrients Nitrogen Map

(k)



(l)

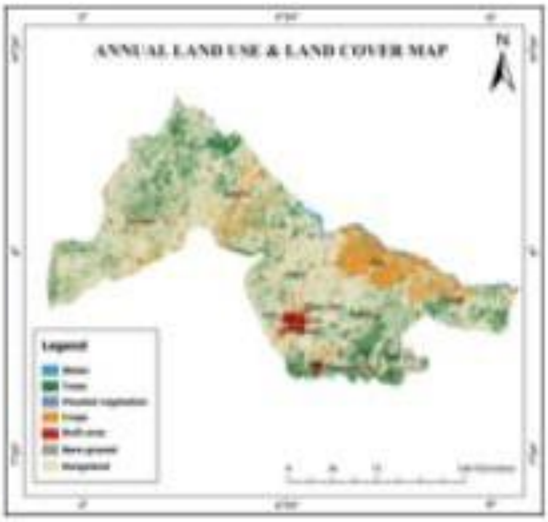
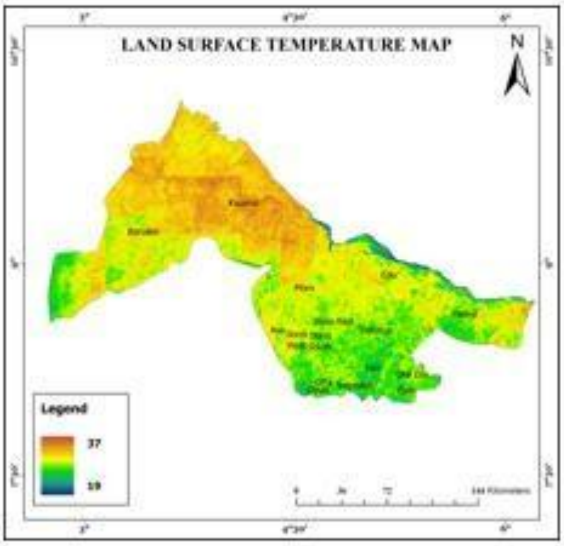


Figure 2k: Nutrients Potassium Map Figure 2l: Annual land use and land cover Map

(m)



(n)

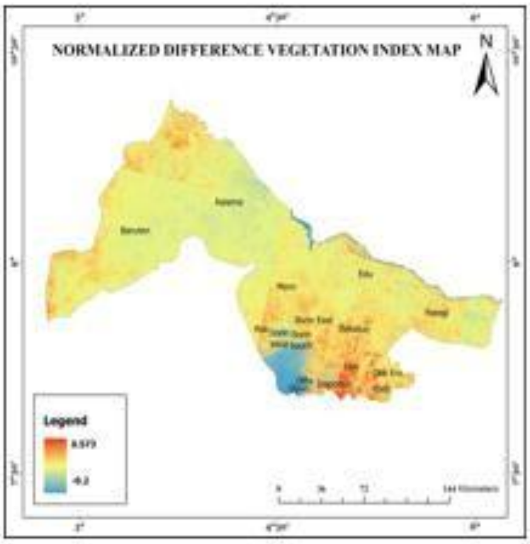


Figure 2m: Temperature Map Figure 2n: Normalized Difference Vegetation Index

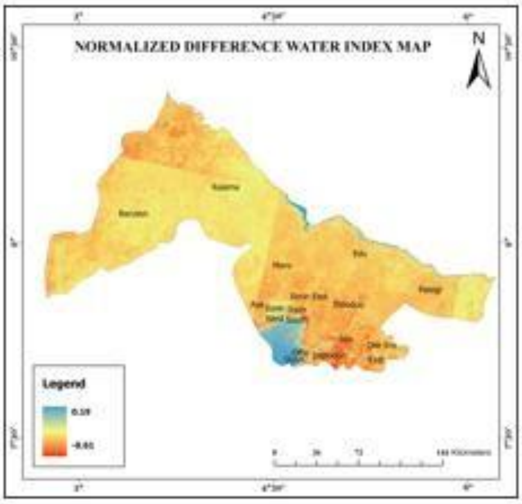
(o)


Figure 2o: Normalized Difference Water Index Map

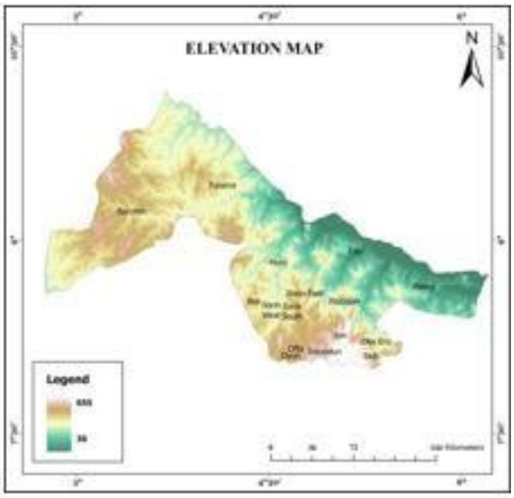
(p)


Figure 2p: Elevation Map

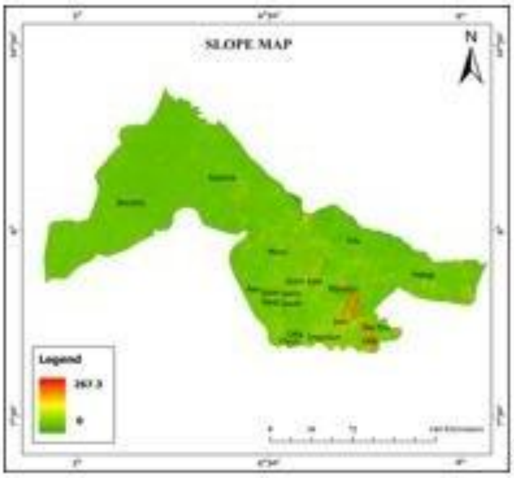
(q)


Figure 2q: Slope Map

(r)


Figure 2r: Slope Direction Map

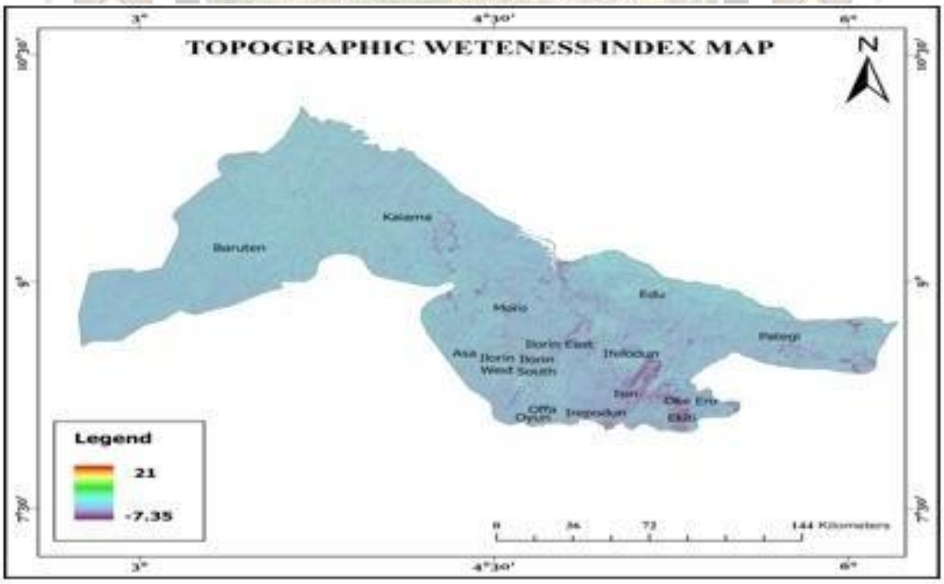
(s)


Figure 2s: Topographic Wetness Index Map

3.2 Identification of Soil Degradation Hotspots

DSM outputs, validated by soil sampling and laboratory analyses, identified hotspots of soil degradation marked by elevated erosion risk and nutrient depletion. Erosion-prone areas are concentrated mainly in upland and sloping zones in the northern and eastern parts of the state, where intensive agriculture and diminished vegetation cover prevail. Nutrient depletion hotspots primarily occur in central and southern Kwara, coinciding with higher population densities and farming intensities.
Land cover change analysis using satellite imagery revealed significant deforestation and conversion of savannah to cropland, accelerating soil degradation dynamics. These spatial patterns emphasize the strong link between anthropogenic activities and soil health deterioration (Ahn, Koriyev, & Juraev, 2024). The soil degradation risk map is presented in Figure 3.

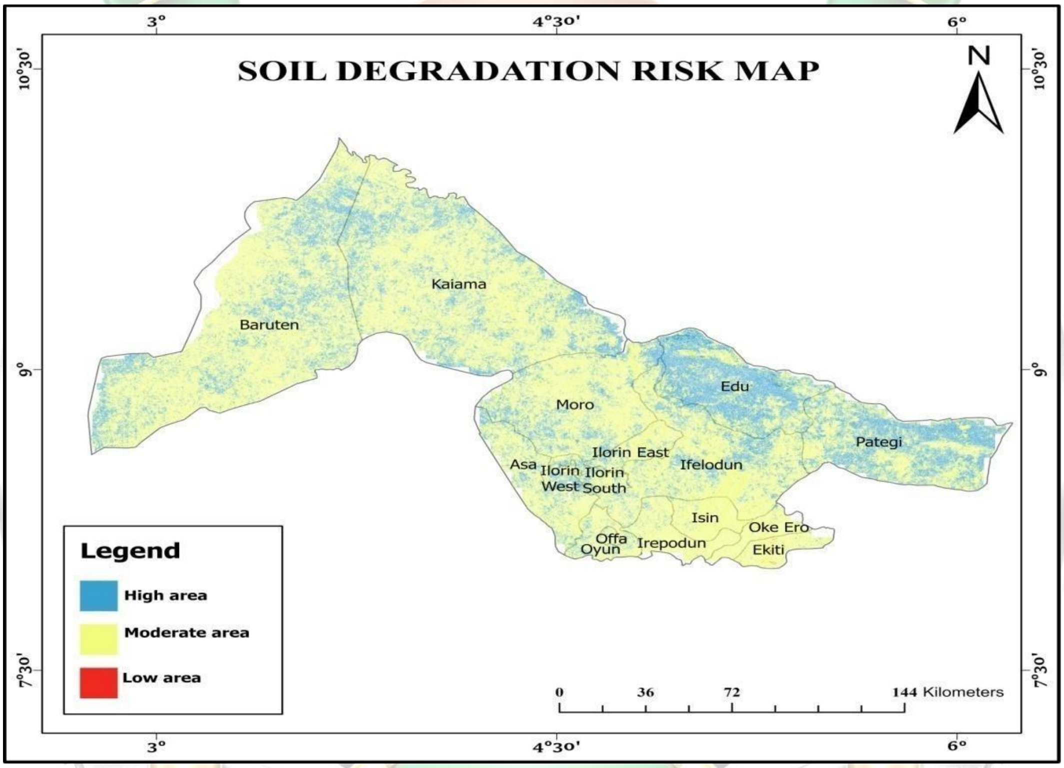


Figure 3: Soil Degradation Map of Kwara State

The integration of DSM with GIS and remote sensing provided a comprehensive understanding of soil degradation patterns and their driving factors in Kwara State. The results affirm DSM's capability to capture fine-scale spatial variability in soil properties, surpassing traditional soil maps that are limited by coarse resolution and outdated data.
The presence of acidic soil patches concurs with prior findings attributing acidification to continuous fertilizer application and monoculture, leading to declines in soil chemical fertility (Hao et al., 2022; Belete & Yadete, 2023). Observed nutrient depletion underscores the critical need for tailored fertilization strategies and sustainable soil management to restore productivity (Musa et al., 2024).
The identified erosion hotspots are consistent with areas of steep slopes and minimal vegetation cover, highlighting priority zones where soil conservation techniques such as contour farming and agroforestry should be promoted. Evaluation of vegetation indices like

NDVI proves to be a strong predictor of soil degradation risk, demonstrating the efficacy of remote sensing-derived covariates for dynamic environmental monitoring (Gruhn, Goletti, & Yudelman, 2000).
Despite these promising findings, challenges remain, including limited availability of high-resolution soil data, technical capacity constraints, and insufficient farmer awareness, which may hamper DSM's full operational potential. Strengthening institutional frameworks and integrating DSM results into policy and land management plans are crucial to promoting sustainable agricultural and environmental practices. This study highlights DSM's transformative potential in delivering spatially explicit, accurate, and actionable soil information to support evidence-based decision-making for soil conservation, precision agriculture, and land use planning in Kwara State and similar areas.

4. CONCLUSION

This study successfully developed a Digital Soil Mapping (DSM) framework integrating Geographic Information Systems (GIS) and remote sensing technologies to assess soil degradation in Kwara State, Nigeria. The results demonstrated the significant spatial variability of soil properties across the state and identified degradation hotspots linked to erosion, nutrient depletion, and land use changes. The DSM approach surpassed traditional soil survey methods by providing high-resolution, spatially explicit soil information essential for targeted soil management.
The findings underscore the value of combining multi-source environmental data with field observations to generate reliable, actionable soil maps that can inform sustainable land use planning and soil conservation strategies. However, challenges such as data availability, technical capacity, and stakeholder engagement must be addressed to maximize the benefits of DSM applications in the state.
Overall, this research contributes to a robust, data-driven soil degradation assessment framework suitable for supporting precision agriculture, environmental management, and policy development in Kwara State and similar environments. Future work should focus on enhancing data integration, expanding field validation, and promoting DSM adoption among farmers and land managers to bolster sustainable agricultural productivity and environmental resilience.

5. RECOMMENDATIONS

To enhance soil degradation assessment in Kwara State, it is essential to improve data collection by integrating high-resolution spatial and field soil data to strengthen digital soil mapping accuracy. Capacity building programs should be implemented to train local experts in GIS, remote sensing, and modeling techniques to ensure effective use of DSM technologies. Efforts to raise awareness and engage farmers, policymakers, and extension agents on the benefits and application of DSM outputs are crucial for wider adoption. Institutional support through dedicated funding, policy frameworks, and coordination among agencies will help sustain DSM initiatives. Targeted soil conservation practices such as contour farming and agroforestry should be promoted in degradation hotspots identified through DSM to improve soil health and productivity. Future research should focus on incorporating emerging technologies like UAVs and machine learning to refine soil mapping and update maps regularly. Addressing these recommendations can significantly contribute to sustainable land management, improved agricultural productivity, and environmental conservation in Kwara State and similar regions.

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