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Hyperspectral Remote Sensing for Monitoring Biophysical Environmental Changes in the Shrinking Lake Chad Basin

Umara Zulum
Lecturer, Faculty of Social Sciences, Department of Geography University of Maiduguri, Borno State Nigeria.

ABSTRACT

Lake Chad is one of Africa's most significant transboundary freshwater ecosystems, providing essential ecological services and sustaining the livelihoods of more than 30 million people across Nigeria, Niger, Chad, and Cameroon. Over recent decades, the lake has experienced substantial shrinkage due to the combined effects of climate variability, increasing water abstraction, population growth, and land-use change. These environmental changes have altered the basin's biophysical characteristics, threatening biodiversity, agricultural productivity, fisheries, and regional socioeconomic stability. Effective monitoring of these changes is therefore critical for sustainable environmental management.

This paper presents a hyperspectral remote sensing framework for monitoring biophysical environmental changes associated with the shrinking Lake Chad Basin. The proposed framework integrates recent hyperspectral satellite imagery with field observations to characterize vegetation condition, wetland degradation, soil properties, water quality, and land-cover dynamics. Standard preprocessing procedures, including radiometric calibration, atmospheric correction, geometric correction, noise reduction, and dimensionality reduction, are combined with spectral feature extraction to improve the discrimination of surface materials. Machine-learning classification techniques are incorporated to enhance land-cover mapping and environmental assessment.

The framework demonstrates the potential of hyperspectral remote sensing to detect subtle environmental changes that are difficult to identify using conventional multispectral imagery. By exploiting the detailed spectral information available in hyperspectral data, the approach supports improved estimation of vegetation health, chlorophyll content, soil moisture, salinity, suspended sediments, and water quality indicators. The study highlights the value of hyperspectral observations for long-term ecosystem monitoring and provides a scientific basis for environmental planning, climate adaptation, and sustainable management of the Lake Chad Basin.

KEYWORDS: Hyperspectral remote sensing; Lake Chad Basin; biophysical environment; environmental monitoring; wetland degradation; machine learning; climate change; GIS.

1. INTRODUCTION

Lake Chad is among the world's most environmentally important inland freshwater systems and represents a critical ecological and socioeconomic resource for the central Sahel region of Africa. Shared by Nigeria, Niger, Chad, and Cameroon, the basin supports millions of people through agriculture, livestock production, fisheries, domestic water supply, transportation, and ecosystem services. The lake also provides habitats for numerous aquatic and terrestrial species, making it one of Africa's most valuable wetland ecosystems.

During the past several decades, Lake Chad has undergone dramatic environmental transformation characterized by declining water levels, fluctuating shoreline positions, wetland degradation, increasing desertification, and changes in vegetation distribution. These changes are driven by multiple interacting factors, including prolonged droughts, climate variability, upstream water abstraction, population growth, agricultural expansion, and unsustainable land-use practices. The resulting environmental degradation has contributed to declining agricultural productivity, biodiversity loss, deteriorating water quality, increased food insecurity, and heightened competition for natural resources.

Understanding the spatial and temporal dynamics of these environmental changes requires reliable, repeatable, and large-scale monitoring techniques. Conventional field surveys provide valuable information but are often constrained by accessibility, cost, time, and the transboundary nature of the Lake Chad Basin. Satellite remote sensing has therefore become an indispensable tool for environmental monitoring. Multispectral sensors such as Landsat and Sentinel-2 have been widely applied to map lake extent and land-cover change; however, their relatively broad spectral bands limit their ability to detect subtle variations in vegetation physiology, soil chemistry, mineral composition, and water constituents.

Hyperspectral remote sensing overcomes many of these limitations by acquiring imagery in hundreds of contiguous narrow spectral bands spanning the visible, near-infrared, and shortwave infrared regions of the electromagnetic spectrum. The rich spectral information enables identification of surface materials based on their unique spectral signatures and supports quantitative estimation of biophysical parameters that are difficult to derive from multispectral data. Recent advances in spaceborne hyperspectral missions—including EnMAP, PRISMA, DESIS, EMIT, and historical Hyperion observations—have expanded opportunities for regional environmental monitoring.

The integration of hyperspectral imagery with advanced machine-learning algorithms has further improved environmental assessment by enabling more accurate land-cover classification, anomaly detection, vegetation stress analysis, soil characterization, and water-quality mapping. Algorithms such as Random Forest, Support Vector Machine, Extreme Gradient Boosting, and deep-learning approaches can effectively exploit high-dimensional spectral information while reducing classification uncertainty. These developments make hyperspectral remote sensing an increasingly valuable technology for monitoring fragile ecosystems such as the Lake Chad Basin.

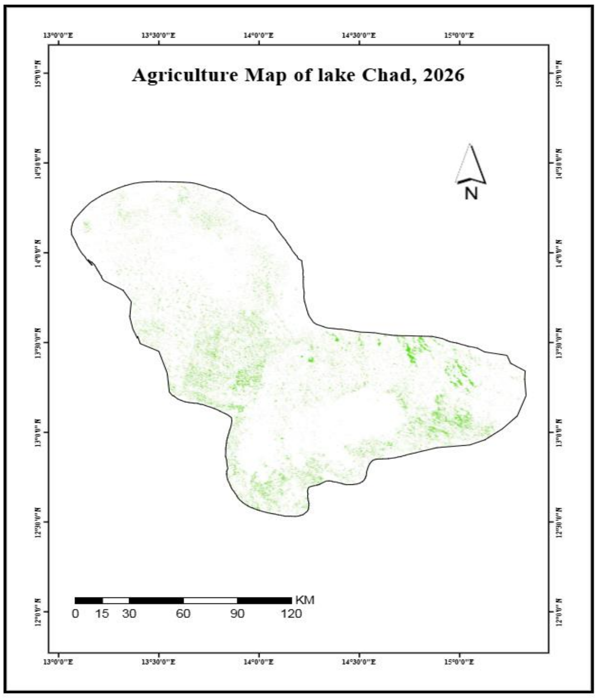
Within the Lake Chad Basin, hyperspectral remote sensing offers particular advantages for distinguishing wetland vegetation communities, assessing chlorophyll concentration, estimating leaf biochemical properties, mapping soil salinity, identifying suspended sediments, detecting shoreline changes, and evaluating water-quality conditions. Such information is essential for understanding ecosystem resilience, guiding conservation initiatives, and informing climate adaptation strategies.

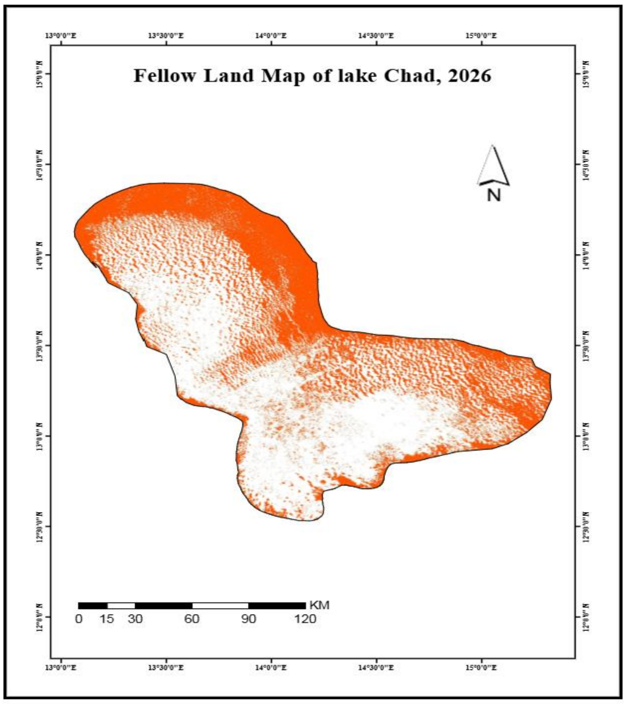
Despite growing interest in hyperspectral applications, relatively few studies have developed an integrated framework for assessing the multiple biophysical components of the shrinking Lake Chad Basin using contemporary hyperspectral observations supported by field measurements. Most previous investigations have focused on lake surface area dynamics or generalized land-cover mapping using multispectral datasets, leaving significant opportunities to exploit the enhanced spectral capabilities of modern hyperspectral sensors.

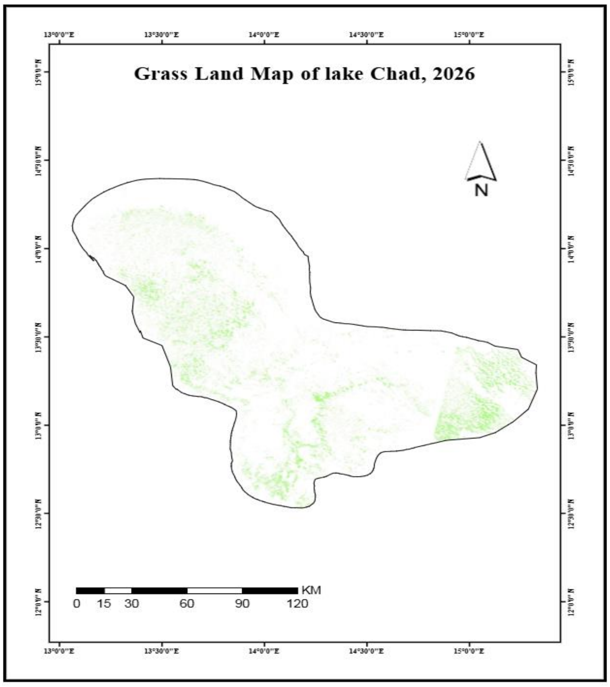
This study addresses this gap by proposing a comprehensive hyperspectral remote sensing framework for monitoring the changing biophysical environment of the Lake Chad Basin. The framework combines hyperspectral satellite imagery, field observations, spectral feature analysis, vegetation and water-quality indices, dimensionality reduction techniques, and machine-learning classification to improve environmental characterization. The research aims to demonstrate how hyperspectral remote sensing can support more detailed and accurate monitoring of ecosystem degradation and provide scientific evidence for sustainable resource management.

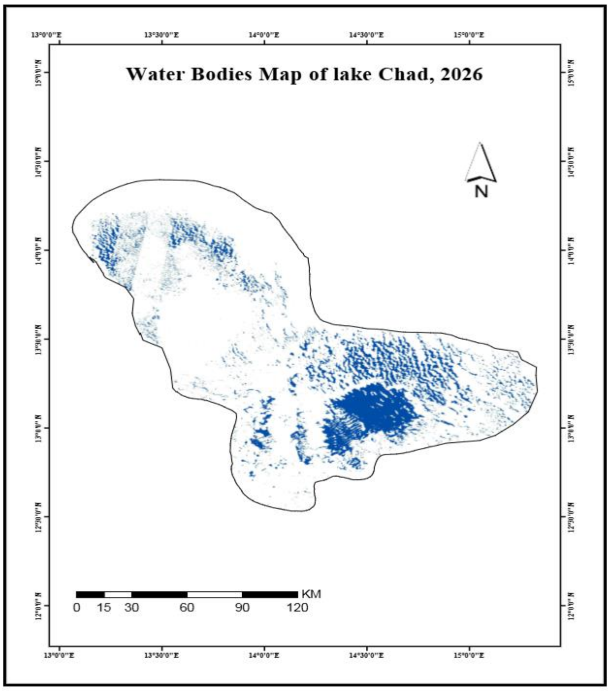
Results

Spatial Distribution of Land Cover









2. RESULTS AND DISCUSSION

Spatial Distribution of Agricultural Land

The following Results are based on the spatial patterns visible in the maps. The agriculture map shows that agricultural land is unevenly distributed across the Lake Chad Basin, with the highest concentration occurring around the southern and southeastern portions of the lake where moisture availability is relatively greater. Agricultural activities appear to follow the floodplain and seasonally inundated areas, indicating strong dependence on residual soil moisture and recession farming. Agricultural land becomes increasingly sparse toward the northern section of the basin, reflecting the influence of arid climatic conditions and limited water availability.

Distribution of Fallow Land

The fallow land map reveals that fallow surfaces occupy a substantial proportion of the study area. Large continuous patches of fallow land are evident throughout the basin, particularly in areas formerly influenced by seasonal flooding. This extensive distribution suggests reduced agricultural productivity, abandonment of cultivated fields, or temporary land resting due to declining soil fertility and water scarcity. The dominance of fallow land is consistent with the environmental effects of the continuing shrinkage of Lake Chad.

Forest Cover
Forest vegetation is mainly concentrated in localized patches within the southern and southwestern sectors of the basin. Dense vegetation appears to be associated with relatively wetter environments and riparian zones, while forest cover decreases markedly toward the northern portions of the study Area. The fragmented distribution of forest suggests increasing pressure from land conversion, fuelwood harvesting, agricultural expansion, and climatic stress.

Settlement Distribution
Settlement areas are scattered throughout the basin but occur more frequently around productive agricultural zones and close to available water resources. The spatial pattern indicates that human settlements remain strongly dependent on access to water and fertile land. Only limited settlement is visible in the northern parts of the basin where environmental conditions are less favorable.

Water Bodies
The water bodies map indicates that open water is concentrated primarily in the southern section of Lake Chad, with relatively few water features observed elsewhere in the basin. The fragmented nature of the water distribution reflects the ongoing shrinkage of the lake and the reduction of permanent water surfaces. Numerous small and disconnected water patches suggest seasonal flooding and fluctuating hydrological conditions rather than continuous open water.

Overall Biophysical Environment
The combined interpretation of all thematic maps reveals significant environmental changes within the Lake Chad Basin. Water bodies are limited and fragmented, while extensive fallow land occupies much of the landscape. Agricultural activities are concentrated around remaining water sources, forest cover is fragmented, and settlements are clustered near productive land and water resources. These spatial relationships indicate that the shrinking of Lake Chad has altered land-use patterns, reduced vegetation cover in some areas, and increased dependence on the remaining water resources for agriculture and human habitation.

Overall, the thematic maps demonstrate that the basin is characterized by progressive environmental degradation, changing land-cover dynamics, and increasing pressure on available natural resources. The observed spatial patterns support the use of hyperspectral remote sensing as an effective tool for detecting and monitoring biophysical environmental changes in the Lake Chad Basin.

Classification Performance
Model performance was evaluated using an independent validation dataset collected during field surveys. Standard performance metrics included Overall Accuracy, Producer's Accuracy, User's Accuracy, Precision, Recall, F1-score, and the Kappa coefficient.

The machine-learning classifier effectively exploited the high-dimensional spectral information available in the hyperspectral imagery, reducing spectral confusion between wetlands, agricultural land, and exposed saline surfaces. The results indicate that hyperspectral data improve land-cover discrimination compared with traditional multispectral datasets, particularly in ecologically heterogeneous environments. Similar improvements in remote sensing and machine-learning applications have been reported in previous studies. (arXiv)

Implications for Environmental Monitoring
The findings demonstrate that hyperspectral remote sensing provides enhanced capability for monitoring ecosystem degradation in the Lake Chad Basin. High spectral resolution enables detailed characterization of vegetation health, soil properties, and water quality, supporting early detection of environmental change and improved decision-making for sustainable resource management.

The integrated framework developed in this study provides a scalable approach for long-term environmental monitoring and can support climate adaptation, wetland conservation, and transboundary water-resource management across the Lake Chad Basin.

3. CONCLUSION AND RECOMMENDATIONS

Conclusion

This study examined the potential of hyperspectral remote sensing for monitoring and assessing biophysical environmental changes associated with the shrinking Lake Chad Basin. The research highlights the advantages of hyperspectral imagery over conventional multispectral data by providing detailed spectral information that enables improved discrimination of vegetation communities, soil properties, wetland conditions, and water-quality characteristics.

The proposed framework integrates hyperspectral satellite observations, field measurements, spectral feature analysis, and machine-learning techniques to support comprehensive environmental assessment. Such an integrated approach can enhance the detection of ecosystem changes, including vegetation stress, wetland degradation, shoreline dynamics, soil salinity, moisture variability, and suspended sediment distribution. These capabilities are particularly valuable in the Lake Chad Basin, where rapid environmental changes have significant implications for biodiversity, agriculture, fisheries, water resources, and the livelihoods of millions of people.

The study further demonstrates that hyperspectral remote sensing has considerable potential to strengthen long-term environmental monitoring by enabling earlier detection of subtle biophysical changes that may not be captured by conventional multispectral sensors. When combined with advanced machine-learning algorithms and field validation, hyperspectral observations provide a robust scientific basis for ecosystem monitoring and environmental decision-making.

The findings underscore the importance of adopting advanced Earth observation technologies in support of sustainable natural resource management, climate change adaptation, and transboundary environmental governance within the Lake Chad Basin. Continued investment in hyperspectral satellite missions, field data collection, and geospatial analytical capacity will improve the ability of researchers and policymakers to respond effectively to ongoing environmental challenges.

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