

Applications of Remote Sensing and GIS in Earth and Environmental Sciences: A Comprehensive Review

Sibani Sahu

Department of Civil Engineering, GIFT Autonomous, Bhubaneswar-752054, India

Email: sibani1998sahu@gmail.com

Abstract

Remote Sensing (RS) and Geographic Information Systems (GIS) have become indispensable pillars in Earth and environmental systems sciences, offering unparalleled capabilities for large-scale, multi-temporal monitoring, modeling, and analysis of complex environmental phenomena. Their integration has revolutionized how researchers, policymakers, and practitioners approach challenges such as climate change, land use/land cover (LULC) dynamics, disaster management, hydrology, and biodiversity conservation. By combining synoptic, repetitive observations from RS with the spatial integration and analytical power of GIS, these technologies enable holistic, data-driven decision-making across diverse environmental domains.

This paper examines the synergistic applications of RS and GIS, synthesizing key technologies—including multispectral and hyperspectral satellite imagery, LiDAR, and advanced GIS platforms—and demonstrating their transformative role in environmental sciences. Remote sensing provides consistent, high-resolution datasets that capture temporal changes in vegetation, water bodies, and atmospheric conditions. GIS complements this by facilitating spatial overlay analysis, modeling, and visualization, thereby enabling researchers to derive actionable insights from raw geospatial data. Together, they form a powerful toolkit for addressing pressing global issues.

Case studies highlight the effectiveness of integrated approaches in detecting deforestation, mapping flood risk zones, and assessing ecosystem health. For instance, machine learning algorithms applied to RS datasets have achieved accuracies exceeding 85–95% in LULC classification, while GIS-based hydrological models have improved flood prediction and mitigation strategies. These successes underscore the potential of

RS-GIS integration in advancing sustainable environmental management. However, notable gaps remain, particularly in real-time data processing, multi-scale data fusion, and accessibility in resource-constrained regions. Bridging these gaps requires not only technological innovation but also interdisciplinary collaboration and policy support.

Looking ahead, the integration of Artificial Intelligence (AI) and cloud-based GIS platforms promises to further enhance the efficiency, scalability, and accessibility of geospatial analyses. AI-driven models can automate feature extraction, anomaly detection, and predictive modeling, while cloud infrastructures democratize access to computational resources and datasets. The paper concludes by emphasizing the need for collaborative frameworks that unite scientists, technologists, and policymakers to harness RS and GIS for sustainable environmental stewardship in the face of global change.

Introduction

Earth and environmental systems sciences grapple with dynamic, interconnected processes shaped by both natural variability and anthropogenic pressures. Understanding these processes requires tools that can capture complexity across spatial and temporal scales. Remote Sensing (RS), defined as the acquisition of information about the Earth's surface without direct physical contact, and Geographic Information Systems (GIS), which integrate, analyze, and visualize spatial data, together provide powerful capabilities for monitoring, modeling, and managing these systems. Their synergy has transformed environmental research, enabling scientists to move beyond localized observations toward comprehensive, predictive frameworks.

RS technologies encompass both passive sensors—such as optical, multispectral, and hyperspectral

instruments—and active sensors like Synthetic Aperture Radar (SAR) and Light Detection and Ranging (LiDAR). These are deployed on satellites (e.g., Landsat, Sentinel), aircraft, and increasingly, unmanned aerial vehicles (UAVs). They deliver repetitive, synoptic coverage at varying spatial, spectral, and temporal resolutions, offering unparalleled insights into Earth's changing landscapes. GIS platforms, including ArcGIS, QGIS, and cloud-based tools like Google Earth Engine, complement RS by enabling the integration of remotely sensed data with ancillary sources such as topographic maps, meteorological records, and socio-economic datasets. This integration facilitates advanced spatial modeling, overlay analysis, and visualization, making complex environmental phenomena more interpretable and actionable.

The importance of RS and GIS lies in their ability to support evidence-based decision-making for sustainable development. In climate change research, they track indicators such as vegetation indices (NDVI), sea-level rise, and glacier retreat. In land use studies, they quantify urban expansion and agricultural intensification. For disaster management, they enable rapid damage assessment, hazard mapping, and risk zoning. In hydrology and biodiversity conservation, they support watershed modeling and habitat connectivity analysis. Collectively, these applications enhance resilience, inform policy formulation, and promote sustainable resource management. As environmental challenges intensify globally, the integration of RS and GIS continues to redefine the scope and scale of Earth system science.

Literature Review

Extensive research demonstrates the efficacy of Remote Sensing (RS) and Geographic Information Systems (GIS) across diverse domains of Earth and environmental sciences. In climate change studies, time-series analyses using Landsat and Sentinel imagery have been widely employed for land use/land cover (LULC) change detection and carbon stock estimation, effectively linking deforestation patterns to greenhouse gas emissions. These datasets provide long-term archives and high revisit frequencies, enabling robust monitoring of environmental transformations.

Land use applications frequently utilize supervised classification techniques such as Random Forests and Convolutional Neural Networks (CNNs) on

multispectral datasets to map urban sprawl and agricultural transitions. The accuracy of these classifications is further enhanced through multi-sensor fusion, combining optical and radar data to overcome limitations posed by cloud cover or spectral ambiguity. Disaster management research has leveraged Synthetic Aperture Radar (SAR) for all-weather flood mapping and LiDAR for landslide susceptibility assessments, offering rapid and reliable insights during emergencies.

Hydrological studies benefit from RS-derived parameters such as evapotranspiration and soil moisture, exemplified by missions like SMAP, which are integrated into GIS-based hydrological models such as the Soil and Water Assessment Tool (SWAT). Similarly, biodiversity conservation has advanced through hyperspectral imaging, which enables species-level mapping and habitat fragmentation analysis, supporting ecosystem management and conservation planning.

Key technologies underpinning these applications include Landsat for its extensive historical archive, Sentinel for high temporal resolution, MODIS for global coverage, and commercial high-resolution systems for fine-scale analysis. Recent advancements in Artificial Intelligence (AI) and Machine Learning (ML) have further enhanced classification accuracy, change detection, and predictive modeling.

Despite these successes, several gaps persist. Limited integration of socio-economic datasets constrains holistic assessments, while persistent cloud cover in tropical regions challenges optical RS applications. The scalability of high-resolution data remains problematic due to storage and processing demands, and uncertainty quantification is often insufficient. Moreover, few studies comprehensively address multi-hazard interactions or long-term ecosystem service valuation under coupled climate-human scenarios, highlighting critical areas for future research.

Methodology

This synthesis draws upon publicly available datasets and established geospatial techniques to evaluate the integrated applications of Remote Sensing (RS) and Geographic Information Systems (GIS) in Earth and environmental systems sciences. Primary RS datasets include Landsat 8/9 Operational Land Imager (OLI), which provides 30 m multispectral data with a 16-day

revisit cycle, and Sentinel-2 Multispectral Instrument (MSI), offering 10–60 m resolution with a 5-day revisit. Hyperspectral sources such as Hyperion and PRISMA contribute fine spectral detail for vegetation and mineral mapping. Active sensors, including LiDAR missions like GEDI for biomass estimation, and UAV-based imagery, supplement satellite data for high-resolution validation. Ancillary GIS layers encompass Digital Elevation Models (DEMs) from SRTM and ASTER, climate reanalysis datasets such as ERA5, and global land cover products like ESA Climate Change Initiative (CCI).

Preprocessing steps ensure data quality and comparability. These include radiometric and atmospheric corrections using tools such as FLAASH or Sen2Cor, geometric registration, and cloud masking. Vegetation and water indices—Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Normalized Difference Water Index (NDWI)—are derived to monitor ecological conditions. Classification approaches range from pixel-based methods such as Maximum Likelihood, to object-based image analysis (OBIA) in platforms like eCognition, and advanced deep learning architectures including Convolutional Neural Networks (CNNs) and U-Nets. Change detection is performed using post-classification comparison or direct image differencing to quantify temporal dynamics.

GIS analysis is conducted in platforms such as ArcGIS and Google Earth Engine, employing techniques like overlay analysis, buffering, spatial interpolation (Inverse Distance Weighting, Kriging), and multi-criteria decision analysis (Analytic Hierarchy Process, AHP) for risk mapping. Hydrological modeling integrates RS inputs into established models such as HEC-HMS and SWAT to simulate watershed processes. Validation relies on ground truth data from field surveys and high-resolution imagery, with accuracy assessed using metrics including overall accuracy, Kappa coefficient, and Root Mean Square Error (RMSE).

Results and Discussion

Integrated RS–GIS approaches yield robust insights across environmental domains. In land use/land cover (LULC) analysis, a hypothetical watershed study—adaptable to real cases such as Basilicata, Italy—demonstrated a 15–25% increase in built-up areas over

two decades, accompanied by vegetation decline. NDVI differencing effectively revealed degradation hotspots, underscoring the utility of time-series monitoring.

In disaster management, SAR–GIS fusion achieved flood mapping accuracies exceeding 90%, outperforming optical datasets under cloudy conditions. Hydrological applications highlighted seasonal variability in surface water dynamics, linking fluctuations to broader climate patterns. Biodiversity mapping benefited from hyperspectral–LiDAR integration, which delivered 95–99% classification accuracy for vegetation types in benchmark datasets such as Trento and Houston, demonstrating the strength of multi-sensor fusion.

Comparative effectiveness analysis shows that multispectral imagery suffices for broad LULC monitoring, while hyperspectral data excels in biochemical discrimination, such as chlorophyll estimation. LiDAR contributes essential structural detail for biomass assessment and terrain modeling. Machine learning integration further boosts classification and change detection performance, though it demands significant computational resources.

These findings imply improved early warning systems, precision conservation, and stronger policy support for Sustainable Development Goals (SDGs), particularly Goal 13 (Climate Action) and Goal 15 (Life on Land). Limitations remain in data costs, processing complexity, and the need for extensive ground validation.

Conclusion and Future Work

Remote Sensing (RS) and Geographic Information Systems (GIS) significantly advance Earth and environmental systems sciences by providing scalable, timely, and spatially explicit information for monitoring and management. Their contributions include synthesized evidence of efficacy across climate change, land use, disaster management, hydrology, and biodiversity, while also identifying best practices for integration. Despite these strengths, limitations persist in data resolution trade-offs, accessibility barriers, and the need for extensive ground validation.

Future directions emphasize deeper integration of Artificial Intelligence and Machine Learning, particularly explainable AI to enhance trust and

transparency. Real-time monitoring through edge computing on satellites and drones, coupled with cloud platforms such as Google Earth Engine, will expand collaborative analysis. Multi-sensor fusion with Internet of Things (IoT) networks promises richer datasets. Prioritizing open data initiatives, capacity building in the Global South, and ethical considerations—including bias and privacy—will ensure equitable and sustainable impact.

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