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Geo AI technology and its applications in environmental monitoring

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Abstract

The emergence of artificial intelligence has become a driving force behind the intelligent transformation of geospatial technologies and data. The integration of artificial intelligence with geospatial science has given rise to Geospatial Artificial Intelligence (Geo AI), enabling the automation of information extraction, analysis, and the accurate and timely prediction of spatial and temporal changes in natural resources and environmental components. This paper presents an overview of Geo AI technology and evaluates its potential applications in monitoring natural resources and environmental components, thereby contributing to the effective implementation of green growth models toward sustainable development goals.

Keywords: Geospatial artificial intelligence, Geo AI, environmental monitoring

1. Introduction

Geospatial technologies and equipment are becoming increasingly advanced, allowing the acquisition, exploitation, and processing of increasingly rich and diverse datasets with improving quality and lower costs. Thanks to prominent advantages such as rich information content, short data acquisition cycles, and large-area coverage, geospatial technologies and data have become effective tools for monitoring changes in natural resource and environmental components across space and time. Geospatial technologies form a multi-layer observation network (Figure 1).

In addition to ground-based instruments, satellite technology is considered a key component in Earth observation. In low Earth orbit (LEO), besides remote sensing satellites such as Landsat, Sentinel, and SPOT, there are also gravity satellites and laser satellites dedicated to studying tectonic plate movements as well as determining sea-level rise in oceans and seas. GNSS systems, including GPS (United States), GLONASS (Russia), Galileo (European Union), and COMPASS (China), continue to be upgraded and improved in terms of both the number of satellites and signal strength. In recent years, the advent of Unmanned Undersea Vehicles (UUVs) has enabled effective, accurate, and timely seabed mapping and environmental monitoring. Geospatial technologies can operate independently or be integrated into multi-source, multi-resolution, and multi-temporal systems for monitoring natural resource and environmental components on a global scale.

The continuous development of satellite systems and geospatial technologies has resulted in an explosion of data that far exceeds the capabilities of traditional analytical approaches or customized programming methods. These methods are unable to effectively process large, heterogeneous, and complex datasets. The emergence of Geo AI stems from the practical need to apply artificial intelligence to big-data processing in order to address urgent global challenges. The world currently faces complex issues requiring rapid response and accurate forecasting, including environmental pollution and degradation, climate change, urbanization, precision agriculture, smart infrastructure planning, and disaster management. In most of these domains, Geo AI serves as a tool for intelligent and real-time decision support.

To date, commercial Geo AI models around the world are often regarded as “black boxes.” For the Vietnamese geospatial science community, Geo AI remains a relatively new

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technology. This review study focuses on collecting and analyzing documents to evaluate technological architectures, technology combinations, data types, and application capabilities of Geo AI models. Scientific papers and reports from reputable domestic and international journals were reviewed, analyzed, compared, and synthesized to generalize the scientific foundations and methodologies of published studies, with particular emphasis on research outcomes and practical applications in agriculture and environmental management.

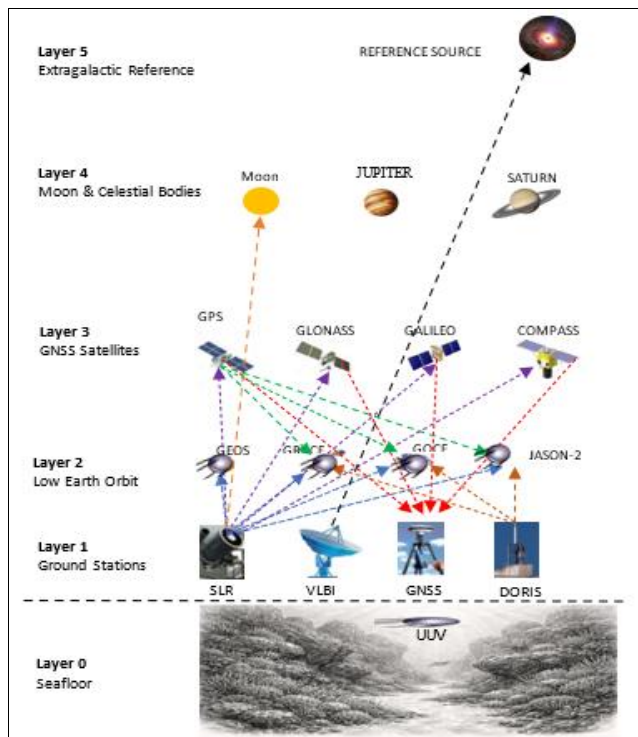


Fig 1: Multi-layer observation system of geospatial technology ^[1]

2. Geo AI Technology

Geo AI is the abbreviation of Geospatial Artificial Intelligence, a term first introduced at a conference organized by the Association for Computing Machinery (ACM) Special Interest Group on Spatial Information (SIGSPATIAL) in Redondo Beach, California, USA. Since then, Geo AI has undergone continuous development and advancement. The emergence of Geo AI is an inevitable trend driven by the explosion of data, the increasing computational power of cloud computing and graphics processing units (GPUs), and especially the rapid advancement of artificial intelligence.

Artificial intelligence had already been applied in Earth sciences in general and geography in particular. However, Geo AI truly emerged and evolved with the advent of machine learning and deep learning models capable of effectively processing large, diverse, and complex datasets. These models can automatically classify, analyze spatial information, extract features from raw data, perform generalization, and support transfer learning ^[2, 3, 14] (Figure 2). Geo AI is therefore positioned at the intersection of Earth sciences, geospatial science, and artificial intelligence, with machine learning and deep learning serving as its key enabling technologies.

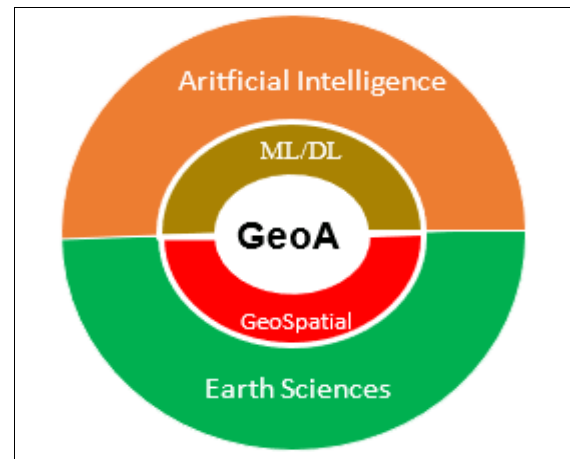


Fig 2: Machine Learning and Deep Learning as Core Technologies of GeoAI

In the satellite sector alone, the past five years have witnessed unprecedented growth in both the volume of satellite-acquired data and the maturity of artificial intelligence techniques, particularly machine learning and deep learning algorithms capable of exploiting these datasets (Figure 3). As of May 2025, more than 12,000 active satellites orbit the Earth three times more than in 2020. Approximately one-third of these satellites are dedicated to Earth observation missions and continuously transmit petabytes of imagery every day ^[14].

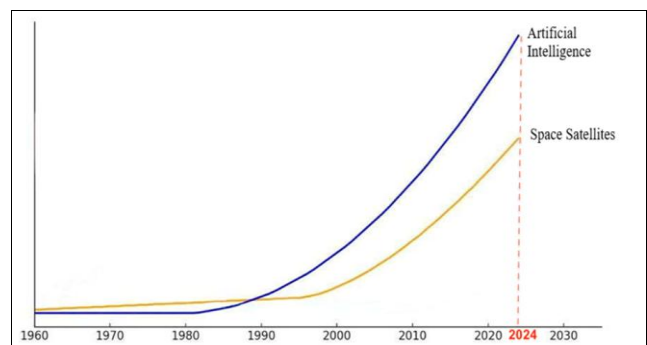


Fig 3: Parallel Development of Space Satellites and Artificial Intelligence during the Period 1960-2024 ^[14]

3. Technologies Used in Geo AI

Machine Learning

Machine Learning (ML) is one of the fundamental components of Geo AI. Machine learning models are commonly applied to regression, classification, and clustering problems. Two major learning paradigms can be distinguished: supervised learning, where training data are labeled, and unsupervised learning, where labels are unavailable ^[3]. Typical machine learning models used in regression and classification tasks include Random Forest (RF), Decision Tree (DT), K-Nearest Neighbors (KNN), and Support Vector Machine (SVM).

Deep Learning

Deep Learning (DL) is a subfield of machine learning that employs multilayer artificial neural networks to learn complex data representations. Inspired by the structure of the human brain, neural networks consist of interconnected

“neurons” whose weights are adjusted and updated during the training process. Common deep learning models include Multi-Layer Perceptrons (MLP), Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), and Long Short-Term Memory (LSTM) networks. Deep learning is capable of automatically identifying and classifying complex objects directly from raw data, making it particularly useful for unstructured datasets such as satellite imagery, audio recordings, and textual data.

Satellite Remote Sensing

Satellites orbiting the Earth collect enormous quantities of imagery data. As of May 2025, more than 12,000 active satellites were operating in orbit, three times the number recorded in 2020, transmitting petabytes of imagery data every day ^[14]. In recent years, satellite constellation technology has developed rapidly. With major advantages including multi-source sensor integration, high temporal resolution, and continuous coverage, satellite constellations such as DMC (Disaster Monitoring Constellation), RapidEye, Planet, and the THEIA network enable highly accurate, reliable, and near-real-time monitoring of changes in natural resources and environmental components on the Earth's surface.

Geographic Information Systems (GIS)

Traditional GIS analyses have long focused on describing and comparing spatial data. They enable the identification of relationships among spatial objects, land-use patterns, and the distribution of environmental and natural-resource factors. However, these analyses are largely static in nature. In Geo AI, machine learning and deep learning algorithms analyze multidimensional and multitemporal GIS data, uncover trends, and detect nonlinear relationships. Geo AI-enhanced GIS not only improves the accuracy of spatial analysis but also accelerates the processing of large datasets to near-real-time levels. Through integrated analytical tools, GIS supports a transition from reactive problem-solving approaches to predictive methodologies, which are crucial for preventing and mitigating environmental impacts effectively.

Big Data

Big Data plays a central role in the “intelligentization” of geospatial data, not only by increasing data volume but also by enhancing analytical depth and processing speed. When combined with technologies such as GIS and remote sensing, Big Data provides a large-scale, multi-source infrastructure encompassing spatial and non-spatial data, as well as structured, semi-structured, and unstructured datasets.

Cloud Computing: Cloud computing provides the essential infrastructure for Geo AI development by enabling free or low-cost access to petabyte-scale data repositories and powerful analytical tools. Cloud computing not only addresses challenges related to massive data volumes and computational requirements but also fundamentally transforms the ways in which geospatial information is shared, accessed, and collaboratively analyzed.

Internet of Things (IoT)

Within the Geo AI ecosystem, the Internet of Things (IoT) functions as the “sensory system” that continuously collects

real-world data in real time. If Big Data represents the “data warehouse” and artificial intelligence serves as the “brain,” then IoT acts as the source of continuously updated and spatially explicit information from the physical world. The development of sensor technologies and cloud computing has enabled IoT to become an important data source, significantly enhancing Geo AI capabilities in natural resource management, environmental monitoring, and disaster prevention.

Blockchain

Blockchain is a foundational technology that ensures transparency, security, reliability, and decentralized data sharing within the Geo AI ecosystem. In Geo AI applications, data are collected from numerous sources such as UAVs, satellites, IoT devices, and GIS platforms. Blockchain serves as an auditing mechanism that verifies data provenance and prevents unauthorized modification or falsification. Owing to its distributed, immutable, and transparent characteristics, blockchain provides an effective solution for managing and exploiting geospatial data for environmental and natural-resource monitoring purposes.

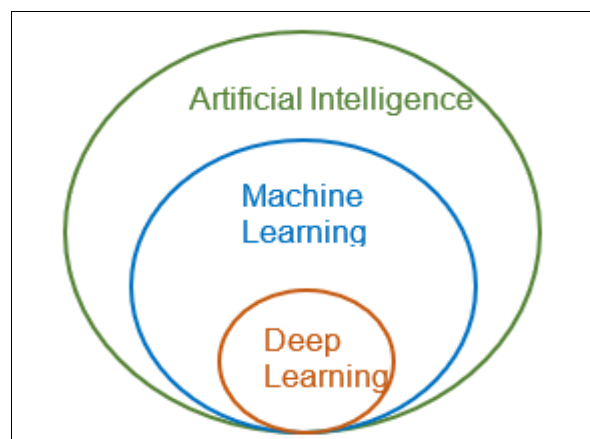


Fig 4: Machine learning and deep learning are key components of artificial intelligence

4. Applications of Geo AI in Environmental Monitoring

The integration of large-scale geospatial datasets from multiple sources with machine learning and deep learning algorithms enables Geo AI to become an effective tool for real-time environmental monitoring and accurate prediction of environmental changes, including pollution, degradation, and environmental hazards.

4.1. Geo AI for Land Cover Change Monitoring

Geo AI is an effective tool for land-cover and land-use mapping, as well as for detecting land-cover and land-use changes over time. These thematic maps play a crucial role in environmental monitoring, spatial planning, and natural resource management. The application of artificial intelligence has significantly improved the speed, accuracy, and scalability of classification processes ^[16].

The application of deep learning algorithms, particularly Convolutional Neural Networks (CNNs), integrated with cloud-computing platforms such as Google Earth Engine (GEE), enables the automation of object extraction from remote sensing imagery. This approach provides a parallel-processing solution for large satellite datasets, thereby substantially reducing analysis time. The advancement of

Geo AI is reflected not only in computational efficiency but also in improvements in classification accuracy, the ability to distinguish a larger number of land-cover classes within a

single observation period, and enhanced capacity for analyzing spatial and temporal dynamics [6, 7, 12].

Table 1: Effectiveness of Geo AI in Land-Cover Change Monitoring [11]

Indicator	Traditional Methods	Geo AI
Processing time for 500 km ²	6-8 weeks	72 hours
Land-cover classification accuracy	76-80%	92-95%
Number of land-cover classes identified	5-7	9
Change detection frequency	Periodic	Real-time

4.2. Geo AI for Environmental Pollution Monitoring

Geo AI is increasingly being applied to environmental pollution monitoring and emission-source identification, supporting activities related to air, soil, and water quality management as well as industrial emission control. Traditional monitoring systems, which rely on fixed monitoring stations or sampling points for air, noise, and surface water, provide highly reliable data. However, monitoring networks are often sparse or unevenly distributed, and measurements are generally conducted periodically. In most cases, alerts are generated only when pollutant concentrations exceed regulatory thresholds. Geo AI enables the interpolation of values at unsampled locations, prediction of future pollution levels, and identification of pollution sources through the analysis of spatiotemporal emission patterns [10, 13]. Using data collected from IoT-based smart sensors, Geo AI algorithms can accurately monitor industrial emissions. Sensors record environmental parameters at five-minute

intervals and transmit the data to AI models, where measurements are classified as either normal or anomalous. After integration with GIS components, the propagation trajectories of pollutants can be mapped in real time. Geo AI can integrate transformer-based deep neural networks for sequential data processing with Long Short-Term Memory (LSTM) networks for temporal analysis, combined with hyperparameter optimization using Particle Swarm Optimization (PSO), to estimate difficult-to-measure environmental variables such as PM2.5 concentrations [15]. In the field of natural-environment pollution management, Geo AI also supports the detection of newly emerging pollution sources. The application of Convolutional Neural Networks (CNNs) or Random Forest (RF) models to radar imagery (Sentinel-1) and optical imagery (Sentinel-2) enables the identification of marine oil spills and illegal waste-disposal sites with high spatial and temporal accuracy [9].

Table 2: Representative Applications of Geo AI in Environmental Pollution Monitoring [11]

Monitoring Target	Input Data	AI Algorithm	Spatial/Temporal Resolution
Industrial emissions	IoT, PM10, PM2.5, NOx	CNN	30 km ² / 5 minutes
Oil-spill pollution	Sentinel-1, Sentinel-2	CNN	10-30 m / day
Illegal waste dumps	Satellite imagery, terrain data	RF	10-30 m / month
Pollution dispersion	Meteorological data, LU/LC, sensors	LSTM, XGBoost	Regional scale / month

4.3. Geo AI in Habitat Modeling and Biodiversity

Conservation: Biodiversity is not only a “natural treasure” but also a fundamental pillar of green economic development and national ecological security. Within biodiversity conservation and habitat management strategies, Geo AI serves as a modern spatial-analysis tool powered by artificial intelligence. Geo AI is utilized to predict species distributions, identify threats, and forecast habitat-distribution changes under the influence of human activities and climate change. Geo AI enables habitat-distribution modeling through spatial models that estimate species occurrence probabilities based on environmental conditions such as climate, topography, land cover, and vegetation structure [8]. Geo AI can extrapolate information from fragmented field observations and remote sensing datasets distributed across space and time, thereby providing a more comprehensive understanding of species distributions and habitat conditions. Geo AI is also applied in predictive conservation. AI models can integrate remote tracking data, such as GNSS sensor observations, with environmental information to forecast changes, risks, and negative impacts in advance, allowing proactive conservation interventions. Geo AI further supports the prediction of habitat-distribution shifts caused by climate change and extreme

weather events. Neural networks are employed to model potential future refuges for different populations and identify areas likely to be affected by extreme climatic conditions. These analyses help prioritize regions requiring enhanced protection. In marine-environment studies, Geo AI is used to classify the conservation status of coral reefs based on imagery collected by underwater unmanned vehicles (UUVs) [5]. Convolutional Neural Network (CNN) models can identify stages of coral-reef degradation with an accuracy of 93%, demonstrating Geo AI’s capacity to detect patterns beyond human perception [4]. In summary, Geo AI can optimize habitat management and biodiversity conservation activities, providing more effective support for conservation efforts in the context of rapidly changing environmental conditions.

5. Discussion

Climate change, urbanization, and industrialization are causing increasingly severe and rapid degradation of environmental components. With its ability to process and analyze large volumes of multi-source, multi-resolution, and multi-temporal geospatial data including spatial and non-spatial, structured, semi-structured, and unstructured datasets Geo AI is increasingly recognized as a

breakthrough approach in monitoring natural resources and environmental systems. The reviewed Geo AI studies demonstrate the enormous potential and promising prospects of this emerging technology for accurate, transparent, and reliable spatiotemporal monitoring of natural resources and the environment.

Geo AI presents both opportunities and challenges. Geospatial data are often heterogeneous, originating from multiple sources, which complicates standardization and spatial-temporal integration. Furthermore, the enormous volume of data requires powerful computational infrastructure, large storage capacity, and high-quality labeled datasets. Geo AI models also require extensive training datasets, posing significant challenges, particularly in the Vietnamese context.

The future development of Geo AI in environmental research requires integrated tools and interdisciplinary training programs combining geospatial science with artificial intelligence, data science, and information technology. Such a multidisciplinary skill set represents a major challenge and opportunity for geospatial education institutions in Vietnam. This approach will enable fuller exploitation of Geo AI's potential in environmental research, contributing to the effective implementation of the nation's green-growth models and progress toward sustainable development goals

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