Application of Geophysical Prospecting Methods in Environmental Monitoring

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Abstract: *With the accelerated pace of global industrialization and urbanization, environmental pollution and ecological degradation have escalated into pressing challenges, imposing stringent demands on the precision, spatial coverage, and real-time performance of environmental monitoring protocols. Conventional monitoring techniques, such as borehole drilling and laboratory sample analysis, are inherently constrained by their point-scale discretization, prohibitive costs, and inability to achieve continuous, large-area surveillance. As a non-invasive, high-efficiency, and spatially extensive detection methodology, geophysical exploration has garnered widespread adoption in environmental monitoring and demonstrated immense application potential. This paper systematically elaborates on the fundamental principles and technical attributes of mainstream geophysical approaches, encompassing electrical methods, electromagnetic methods, seismic wave methods, gravity and magnetic surveys, nuclear geophysical techniques, and remote sensing technologies. It focuses on the practical implementation of these methods across critical environmental domains: soil and groundwater pollution investigations, solid waste landfill monitoring, geological hazard environmental assessment, and ecological surveillance for carbon neutrality initiatives. Through in-depth analyses of representative case studies, this research elucidates the unique advantages of geophysical technologies in characterizing pollution plumes, tracing leakage pathways, evaluating stratum stability, and monitoring carbon sequestration processes. Finally, the paper examines the prevailing challenges confronting geophysical techniques—including interpretational non-uniqueness, environmental noise interference, and inadequate quantitative accuracy—and forecasts future development trends, such as multi-method data fusion, intelligent data processing, construction of real-time online monitoring networks, and the integration of novel sensing technologies. The findings indicate that geophysical exploration has evolved into an indispensable component of modern environmental monitoring frameworks. Its seamless integration with geographic information systems (GIS) and artificial intelligence (AI) will furnish robust scientific and technological underpinnings for achieving precision early warning, efficient remediation, and long-term regulatory oversight of environmental issues.*

Keywords: *Geophysical prospecting; Environmental monitoring; Soil and groundwater pollution; Non-invasive detection; Multi-method integration; Intelligent monitoring*

1. Introduction

The natural environment constitutes the fundamental cornerstone of human survival and sustainable development. Yet, rampant anthropogenic activities—ranging from unregulated industrial wastewater discharge[1], excessive application of pesticides and fertilizers, illegal landfill of solid hazardous waste, to intensive mineral resource exploitation—have precipitated pervasive contamination of soil, groundwater, and atmospheric media, concomitantly triggering secondary geological hazards including land subsidence and slope failure. Effective and precise environmental monitoring serves as the prerequisite for scientifically deciphering environmental degradation mechanisms, assessing ecological risk thresholds, implementing targeted remediation projects, and formulating evidence-based environmental protection policies.

Conventional environmental monitoring strategies predominantly rely on discrete point-scale borehole drilling, field sampling, and subsequent laboratory-based chemical analysis. While such approaches yield highly accurate data at specific locations, they are plagued by inherent limitations that undermine their applicability in large-scale, dynamic monitoring scenarios. First, their spatial representativeness is severely constrained, rendering them incapable of continuously tracing the heterogeneous spatial distribution of pollutants across extensive planar areas. Second, these methods

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are inherently destructive: drilling operations risk breaching impermeable pollution containment layers and inadvertently inducing secondary contamination events. Third, they suffer from prolonged turnaround times and prohibitive costs, which preclude the implementation of large-scale, high-density dynamic monitoring campaigns. Fourth, there exists an inherent temporal lag in data acquisition and analysis, making it impossible to capture the real-time dynamic migration processes of sudden pollution incidents.

Against this backdrop, geophysical exploration methods have emerged as a transformative technological paradigm and experienced rapid advancement and widespread adoption in the environmental monitoring sector[2,3], owing to their distinctive merits of non-invasiveness, high operational efficiency, broad spatial coverage, and high-resolution subsurface imaging capabilities. Geophysical techniques operate by measuring the spatial variability of intrinsic physical properties of subsurface media—such as electrical conductivity, dielectric constant, elastic wave velocity, bulk density, and magnetic susceptibility—to indirectly infer the structural and compositional alterations of underground environmental media. This enables the identification of pollution sources, delineation of contamination plumes, and real-time monitoring of pollutant migration and diffusion dynamics. This paper systematically synthesizes the state-of-the-art applications of various geophysical methods in environmental monitoring, critically analyzes their inherent advantages and technical limitations, and delineates prospective future development directions for the field.

2. Main Geophysical Methods and Their Principles for Environmental Monitoring

2.1 Electrical and Electromagnetic Methods

Electrical and electromagnetic methods represent the most extensively applied techniques in environmental monitoring, grounded in the core principle that pollution-induced alterations typically trigger substantial variations in the electrical properties—including resistivity/conductivity and polarizability—of subsurface media.

The High-density Resistivity Method deploys surface array electrodes to map the apparent resistivity distribution of underground media. The infiltration of pollutants such as heavy metals, organic solvents, and salts generally induces a marked reduction in the resistivity of soil or groundwater in the case of inorganic contaminants, or a notable increase for non-aqueous phase liquids (NAPLs). This distinct electrical response enables the precise delineation of the three-dimensional morphology of pollution plumes.

The Induced Polarization Method quantifies the voltage attenuation characteristics (polarizability) of media following power cutoff. It exhibits exceptional sensitivity to pollution systems containing clay minerals or metal ions, and is thus widely employed to distinguish pollution types and assess the aging degree of contaminants.

Time-domain and Frequency-domain Electromagnetic Methods generate underground eddy currents by means of artificial or natural electromagnetic fields, thereby probing the subsurface geoelectric structure. Boasting the advantages of large detection depth and high operational efficiency, these methods are ideally suited for regional surveys of groundwater salt-fresh water interfaces, monitoring of seawater intrusion, and rapid screening of large-scale contaminated sites.

Ground-penetrating Radar (GPR) transmits high-frequency electromagnetic pulses and captures reflected waves from subsurface interfaces with differing dielectric constants[4]. It delivers ultra-high resolution for shallow anomalous bodies (typically within 30 meters), such as buried waste, pipeline leakage points, and soil stratification boundaries. As a result, it is commonly utilized in landfill boundary delineation and leakage detection of underground storage tanks.

2.2 Seismic Wave Methods

Seismic wave methods rely on artificial seismic sources to excite elastic waves, then analyze the velocity, attenuation, and reflection characteristics of these waves during their propagation through the subsurface.

The Refraction Wave Method and Reflection Wave Method are primarily dedicated to determining the thickness of overburden layers, mapping the undulation of bedrock surfaces, and locating fault structures. These data provide a fundamental geological framework for analyzing pollutant migration pathways and assessing the risks of geological disasters.

The Surface Wave Method (Multi-channel Analysis of Surface Waves, MASW) extracts the dispersion curve of Rayleigh surface waves to invert the near-surface shear wave velocity profile. Since shear wave velocity is directly correlated with the shear modulus of soil, it is highly sensitive to stratum compaction and porosity changes. This method serves as an effective tool for evaluating soil liquefaction potential, gauging landfill compaction degree, and detecting underground cavities.

2.3 Gravity and Magnetic Methods

Microgravity Survey detects minute fluctuations in the Earth's gravitational field, with high sensitivity to subsurface density contrasts. It is capable of identifying underground cavities, karst caves, and abandoned mine roadways, and plays a critical role in assessing land subsidence risks caused by the over-exploitation of groundwater or oil and gas resources.

High-precision Magnetic Method measures variations in the intensity of the Earth's magnetic field. Pollution by ferromagnetic substances, such as iron-containing waste residues and emissions from steel plants, generates distinct magnetic anomalies. This method is therefore frequently applied to locate pollution sources in historical industrial sites and search for unexploded ordnance.

2.4 Nuclear Geophysical Methods

Natural Gamma-ray Spectrometry quantifies the gamma-ray intensity emitted by natural radioactive elements (potassium-40, uranium series, and thorium series) in the stratum. Certain industrial activities, including phosphate processing and oil and gas exploitation, produce waste materials rich in radionuclides, and this method can effectively monitor the spatial distribution range of such radioactive contaminants.

Neutron Moisture Measurement determines the in-situ volumetric water content of soil based on the interaction mechanism between neutrons and hydrogen nuclei. It constitutes an important technique for monitoring soil moisture dynamics and tracing the migration of water-borne pollutants.

2.5 Remote Sensing and Airborne Geophysics

Satellite remote sensing and airborne geophysical techniques—encompassing airborne magnetic and airborne electromagnetic methods—can acquire environmental information at regional to global scales. These approaches are widely used for large-scale land use change monitoring, thermal pollution identification, vegetation stress assessment, and macro-scale geological structure interpretation.

3. Application of Geophysical Methods in Typical Environmental Monitoring Fields

3.1 Soil and Groundwater Pollution Survey and Monitoring

This represents the most technically mature domain for the application of geophysical methods, with a typical case illustrated as follows: After the relocation of a historical chemical plant, suspected organic matter leakage necessitated targeted investigation. First, the airborne electromagnetic method was deployed for rapid regional scanning, which delineated a large-scale low-resistivity anomaly zone indicative of potential contamination. Subsequently, high-density resistivity method and ground-penetrating radar were adopted for high-precision ground-based detailed detection. The combined data outlined that the primary pollution plume exhibited a strip-shaped diffusion pattern along the direction of groundwater flow; meanwhile, a strong reflection anomaly was identified beneath the former plant site, interpreted as a potential leakage source or buried waste mass. Finally, a small number of verification boreholes were strategically arranged at key anomaly locations, and laboratory sampling and testing confirmed the presence of chlorinated hydrocarbon pollutants. Throughout this process, geophysical methods enabled a cost-efficient, tiered approach to precise positioning—progressing from regional-scale screening to point-scale validation[5]—which significantly reduced the workload of blind drilling and optimized the overall investigation efficiency.

3.2 Solid Waste Landfill and Historical Contaminated Site Assessment

Environmental safety monitoring of both formal and informal solid waste landfills constitutes a core

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application task for geophysical technologies. The high-density electrical method can effectively monitor the downward and lateral diffusion of landfill leachate, which typically manifests as a distinct low-resistivity halo in geophysical profiles. The surface wave method is capable of evaluating the compaction degree and structural stability of waste piles, thereby providing early warnings of potential landslide risks. Ground-penetrating radar excels at detecting landfill boundaries, determining waste burial depths, and identifying hidden large-scale cavities within landfill sites. For closed and post-closure landfill sites, regular geophysical monitoring serves as a key technical means to assess the integrity of anti-seepage systems and ensure long-term environmental safety.

For historical contaminated sites such as decommissioned industrial zones, geophysical methods can rapidly pinpoint pollution sources and delineate the spatial scope of contamination plumes, laying a solid scientific foundation for the formulation of targeted and efficient site remediation schemes.

3.3 Geological Hazard and Environmental Geological Problem Monitoring

Land Subsidence and Collapse: The time-domain electromagnetic method can monitor groundwater level decline and aquifer structural changes induced by groundwater over-exploitation[6], which are key drivers of land subsidence. Microgravity survey and Interferometric Synthetic Aperture Radar (InSAR) technologies enable high-precision monitoring of large-scale ground vertical deformation, providing continuous and dynamic data for subsidence risk assessment.

Landslide Monitoring: Seismic refraction and surface wave methods can accurately determine the depth and morphological characteristics of potential sliding surfaces, clarifying the structural basis of landslide formation. The high-density electrical method can reflect the spatial distribution of water content within landslide bodies—a critical indicator, as elevated water content is often a direct precursor to landslide initiation.

Seawater Intrusion: Given the significant contrast in electrical properties between saltwater and freshwater, resistivity imaging technology serves as a powerful tool for monitoring the spatial position and dynamic migration of seawater intrusion fronts, supporting the formulation of groundwater resource protection strategies.

3.4 Ecological and Carbon Neutrality-Related Monitoring

Against the backdrop of the "dual carbon" goal, the application scenarios of geophysical technologies in the ecological field are expanding continuously.

Soil Carbon Pool Assessment: There exists a clear correlation between soil organic carbon content and its electrical conductivity and dielectric constant. Research on using ground-penetrating radar and electromagnetic induction data to invert the spatial distribution of soil organic carbon content over large areas has emerged as a cutting-edge research direction, providing a non-destructive technical approach for regional carbon pool accounting.

Geological Carbon Sequestration Monitoring: Injecting carbon dioxide into deep saline aquifers or abandoned oil and gas reservoirs is a key carbon emission reduction technology. Four-dimensional (4D) seismic exploration—conducted by repeating three-dimensional seismic measurements at different time intervals—can clearly characterize the spatial distribution and dynamic migration of injected CO_2 within underground reservoirs, serving as a core technology to verify the long-term effectiveness and safety of geological carbon sequestration projects.

Wetland and Hydrological Process Monitoring: The resistivity method can delineate the fluctuation of groundwater levels and changes in groundwater salinity within wetland ecosystems, providing critical subsurface hydrological information to support wetland ecological restoration and protection efforts.

4. Challenges and Future Development Trends

4.1 Current Challenges

Despite the distinctive advantages of geophysical methods in environmental monitoring[7], their practical application is still confronted with multiple technical bottlenecks and scenario constraints that restrict the further improvement of monitoring accuracy and efficiency.

First, the intrinsic multi-solutionality of geophysical anomalies remains a core and long-standing challenge. Geophysical exploration relies on the detection of physical parameter differences to infer subsurface environmental conditions, yet the same type of anomaly may be induced by completely different geological or pollution factors. For example, a low-resistivity anomaly identified in a survey area could be attributed to naturally occurring high-water-content clay strata, freshwater-saturated sand layers, or the accumulation of inorganic salt-contaminated groundwater. This ambiguity leads to great uncertainties in the qualitative and quantitative interpretation of geophysical data, and even increases the risk of misjudgment if only a single method is adopted without sufficient verification data.

Second, severe interference from environmental noise significantly undermines the quality of geophysical survey data, especially in complex urban or industrial areas. Artificial electromagnetic radiation from power lines, subway systems, and communication base stations can distort the signals collected by electromagnetic or electrical methods; dense underground pipelines, building foundations, and other cultural relics will cause "false anomalies" in seismic wave or ground-penetrating radar detection; and vibrations generated by vehicle traffic and construction activities can interfere with the acquisition of high-precision seismic or microgravity data. These noise sources not only increase the difficulty of data processing and anomaly separation, but also reduce the reliability of subsequent interpretation results.

Third, the insufficient quantitative accuracy of geophysical data limits its direct application in pollution assessment. Most geophysical inversion results only provide macroscopic physical parameter distributions (e.g., resistivity, wave velocity, dielectric constant), while environmental monitoring requires specific indicators such as pollutant concentration, contamination scope, and migration flux. To convert physical parameters into pollution-related quantitative indexes, it is necessary to establish a reliable rock-soil physical model that correlates the electrical, seismic, and magnetic properties of media with pollutant types and concentrations. However, the construction of such models is often constrained by the heterogeneity of subsurface media and the lack of sufficient borehole sampling data for calibration, resulting in a large gap between inversion results and actual pollution conditions.

Fourth, the inherent contradiction between detection depth and shallow resolution fails to meet the demand for detailed shallow environmental monitoring. Many geophysical methods are designed to balance deep detection capability and shallow resolution, but in practice, improving detection depth often comes at the cost of reducing shallow resolution. For example, time-domain electromagnetic methods can achieve deep detection of hundreds of meters, but their resolution for shallow media within 30 meters—the key zone for soil and groundwater pollution— is relatively low. Since shallow subsurface is the most directly affected by human activities and the main area of environmental pollution, the insufficient resolution of existing methods severely restricts the accurate characterization of shallow pollution plumes and micro-scale contamination sources.

4.2 Future Development Trends

To address the aforementioned challenges, the future development of geophysical methods in environmental monitoring will focus on the direction of intelligentization, precisionization, networking, and integration, striving to realize the transformation from "qualitative detection" to "quantitative assessment" and from "discrete survey" to "continuous monitoring".

The first key trend is multi-method data fusion and constrained joint inversion. This approach will break through the limitations of single-method detection by integrating heterogeneous data from electrical, seismic, gravity, magnetic, and nuclear geophysical methods, and establishing cross-validation constraints based on geological background and hydrogeological conditions. For instance, combining the high shallow resolution of ground-penetrating radar with the large detection depth of time-domain electromagnetic methods, and using borehole data as hard constraints for inversion, can effectively reduce the multi-solutionality of geophysical anomalies and construct a more accurate and reliable three-dimensional geological-environmental model of the subsurface.

The second development direction is intelligent data processing and interpretation driven by artificial intelligence algorithms. Traditional geophysical data processing relies heavily on manual experience, which is inefficient and subjective. In the future, machine learning and deep learning technologies will be widely applied to the full chain of geophysical data processing—from raw data denoising, anomaly extraction to result interpretation. For example, convolutional neural networks (CNNs) can be used to automatically identify and classify abnormal signals in seismic or radar profiles, while recurrent neural networks (RNNs) can optimize the inversion process and improve the accuracy of parameter estimation. This intelligent transformation will not only significantly improve the efficiency of data processing, but also enhance the objectivity and consistency of interpretation results.

The third important trend is the construction of real-time, online, and long-term monitoring networks based on the Internet of Things (IoT). The development of low-cost, low-power consumption, and miniaturized geophysical sensors will lay the hardware foundation for large-scale network deployment. These sensor nodes—equipped with resistivity, electromagnetic, or seismic detection modules—will be embedded in key contaminated sites, landfill areas, or geological disaster-prone zones, and connected to a cloud platform through IoT technology to realize 24/7 continuous dynamic monitoring. Moreover, the integration of geophysical monitoring data with hydrological, meteorological, and environmental chemical monitoring data will form a multi-source data fusion system, which can realize the dynamic tracking of pollutant migration and the early warning of geological hazards.

The fourth research hotspot will be the innovation of new sensing technologies and detection platforms. On the one hand, the combination of unmanned aerial vehicles (UAVs), unmanned ground vehicles (UGVs), and lightweight geophysical equipment will revolutionize the traditional field survey mode. UAVs equipped with miniaturized magnetometers, gamma-ray spectrometers, and micro-electromagnetic sensors can efficiently complete high-precision surveys in complex terrain areas such as mountainous regions, wetlands, and abandoned industrial sites that are difficult for humans to access. On the other hand, emerging technologies such as distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) based on optical fibers will provide new technical means for underground process monitoring, enabling real-time detection of subtle changes in subsurface stress, temperature, and fluid flow.

Finally, in-depth integration with geographic information system (GIS) and digital twin technologies will be the ultimate direction of development. Geophysical monitoring data will be integrated into GIS platforms to realize the spatial visualization of subsurface environmental information; further, by constructing digital twin models of contaminated sites or ecological zones, the dynamic simulation, prediction, and early warning of pollutant migration, geological hazard evolution, and ecological environment changes can be realized. This integration will transform geophysical monitoring from a "data acquisition tool" to a "decision-making support system", providing a scientific basis for the precise management and sustainable development of the ecological environment.

5. Conclusion

Relying on their advantages of non-invasiveness, high efficiency, and spatial continuity, geophysical methods have been successfully applied in a wide range of environmental fields, from soil and groundwater pollution surveys to geological disaster early warning, and emerging ecological and carbon sequestration monitoring. They make up for the shortcomings of traditional point-scale monitoring, achieving a leap in environmental monitoring capabilities from "2D point-based" to "3D stereoscopic" and from "static snapshot" to "dynamic movie". Although challenges remain in quantification and non-uniqueness of interpretation, through interdisciplinary integration, multi-technology fusion, and the development of intellectualization, networking, and platformization, geophysical technology will surely play an increasingly core role in the future environmental monitoring system. It is not only a "diagnostic instrument" for environmental problems, but also will become a key component of the "early warning system" for ecological environment safety and the "assessor" for remediation and governance effects, providing solid technical support for building a "Beautiful China" and global sustainable development.

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