Integrated Air-Ground-Space Water Pollution Monitoring Technology: Research Progress and Future Prospects

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Abstract

Water pollution issues have become increasingly severe due to accelerated industrialization, and traditional monitoring methods face challenges such as insufficient coverage and poor timeliness. With advancements in computer technology and the widespread application of high-tech tools like drones, some researchers are exploring integrated air-ground-space monitoring systems for more precise water pollution monitoring and management. This paper systematically reviews the progress in the integrated application of satellite remote sensing, drone sensing, and ground IoT technologies, and analyzes breakthrough directions in key areas such as multi-source data intelligent fusion and dynamic pollution response. Research findings include: Hyperspectral satellites can achieve water quality parameter inversion at a 30m resolution; UAV-mounted LiDAR point cloud density reaches 200 points per square meter, significantly improving pollution source tracing accuracy; edge computing enables accelerated on-site data processing, while digital twin technology supports real-time pollution diffusion simulation, collectively reducing emergency response time to within 20 minutes. Future challenges include the domestic production of micro-sensors and data security in multi-cloud architectures, which will drive the large-scale application of these technologies in water environment governance.

Keywords: water pollution monitoring; integrated air-ground-space system; multi-source data fusion; artificial intelligence; digital twin; edge computing

1. Introduction

In the second quarter of this year, among 3,641 national surface water assessment sections, the proportion of sections with good water quality (Class I-III) was 84.5%, a year-on-year decrease of 0.3 percentage points; the proportion of sections with poor water quality (Class V) was 1.2%, a year-on-year increase of 0.3 percentage points. The main indicators exceeding standards were chemical oxygen demand, permanganate index, and total phosphorus. It is evident that a significant portion of surface water worldwide still faces pollution risks. Water resource security is closely tied to national development and people's livelihoods. While China has abundant total water resources, per capita availability is scarce, far below the global average. Traditional water pollution monitoring methods primarily rely on manual sampling and laboratory analysis, which suffer from limitations such as limited monitoring scope, poor timeliness, and high costs, making it difficult to meet the growing demands of water environment management. Under the disadvantageous conditions of uneven distribution of water resources in terms of time and space, China's water scarcity problem is becoming increasingly severe, gradually becoming an important obstacle to China's economic development. Excessive water pollution and improper treatment further exacerbate the severity of the water scarcity problem. As shown in Figure 1, water quality in China is not good, and there are still river basins with extremely poor water quality. Therefore, conducting timely monitoring of water pollution quality is of great significance for ensuring water resource security.

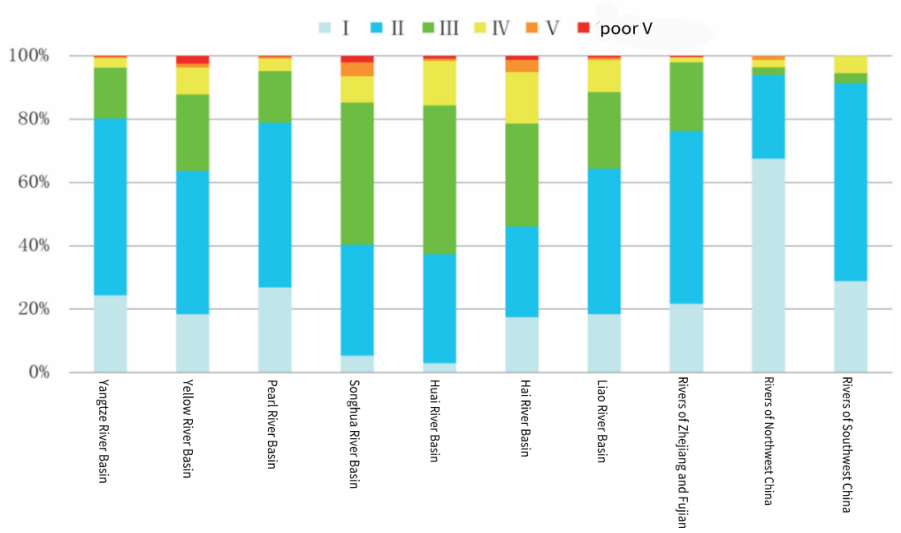

Figure.1 Proportion of water quality categories in major rivers of China's ten major river basins in January 2025

Currently, water quality monitoring is primarily conducted through traditional methods such as manual inspections, data reporting, and data processing. This requires staff to conduct river inspections on foot and visually monitor conditions, which has significant drawbacks: 1. Insufficient spatial coverage: The density of manual sampling points is extremely low, making it impossible to accurately, efficiently, and quickly reflect the extent of river pollution. 2. Low temporal resolution: A single sampling process involves the steps of "on-site collection → laboratory transportation → chemical analysis," with an average cycle that is too long to provide real-time data, making it impossible to capture the dynamic spread of pollution or respond quickly. 3. Significant human error: Issues such as sampling location shifts and variations in preservative agent addition reduce data reliability. 4. Wasted human resources: Inspection personnel must perform repetitive tasks with a heavy workload, and the data obtained through this method is difficult to process efficiently and monitor comprehensively, resulting in poor regulatory effectiveness.

Compared to traditional water quality monitoring technologies, the use of drones, satellites, and shore-based stations in combination for water quality monitoring offers numerous advantages, significantly outperforming traditional methods in terms of coverage capability and data timeliness, as summarized in table1 below.

Table 1: Comparison of Traditional Manual Inspections and Integrated Air-Ground-Space Collaborative Monitoring

Dimension	Traditional manual inspections	Integrated air-ground-space collaborative monitoring
Coverage capability	Point-based discrete monitoring	Holistic three-dimensional sensing (air-ground-space)
Data timeliness	Significant delay	heoretically capable of second-level early warning
Decision-making mechanism	Experience-driven	AI model simulation
Economic efficiency	High implicit costs (pollution losses + safety risks)	Marginal costs approach zero after large-scale application
Scalability	Difficult to integrate new parameters (e.g., microplastics)	heoretically supports the integration of cutting-edge technologies such as eDNA and quantum sensing

2. Necessity of Application

2.1 Inherent Limitations of Single Technologies

Existing environmental monitoring technology systems all exhibit significant inherent limitations when addressing complex river and lake pollution issues:

Satellite remote sensing technology: Possesses unparalleled advantages in large-scale, periodic wide-area monitoring. However, its revisit cycle is relatively long, making it difficult to effectively capture sudden, transient pollution events. More critically, domestic high-spectral satellite resources are currently relatively scarce, and the spectral coverage of mainstream payloads (such as the hyperspectral imager on the HJ-1A satellite) is primarily limited to the visible to near-infrared wavelength range (451–950 nm). This results in significant shortcomings in accurately quantifying pollution gases (such as SO_2 and NO_2) in the mid-infrared wavelength range where their characteristic absorption peaks are located, as well as in precisely determining certain fine water quality parameters (such as specific dissolved organic matter and nutrients). In summary, satellite remote sensing is limited by its revisit cycle and spectral band coverage.

UAV monitoring technology: Known for its high mobility and spatial resolution advantages, it is suitable for rapid localization and detailed investigation of pollution sources. However, its application effectiveness is strictly constrained by battery endurance, making it difficult to support continuous monitoring over long periods and large areas (such as entire river basins). Additionally, airspace restrictions (such as no-fly zones and restricted-fly zones) significantly limit their routine deployment in critical areas. In summary, UAV monitoring is constrained by battery life and airspace restrictions.

Shore-based fixed monitoring stations: These can provide real-time, in-situ, high-precision continuous monitoring data for key water quality parameters (such as turbidity, pH, dissolved oxygen, and flow rate). However, their deployment locations are constrained by factors such as shoreline topography, power supply, and communication conditions, typically resulting in sparse distribution. The data obtained exhibits significant “point-like” characteristics, making it difficult to comprehensively and accurately characterize the continuous spatial distribution patterns and migration/diffusion patterns of pollutants. In summary, shore-based stations are constrained by sparse deployment, leading to insufficient spatial coverage.

2.2 Urgent need for river and lake management businessization

As the “river chief system” moves from “full establishment” to “full effectiveness,” two core bottlenecks need to be overcome:

First is the challenge of cross-regional coordination: the typical contradiction of “upstream pollution and downstream treatment” is becoming increasingly prominent, and there is an urgent need for objective, traceable evidence to determine pollution responsibility. Second, the lack of dynamic monitoring capabilities: Traditional reliance on manual patrols suffers from low efficiency, limited coverage, and inability to respond around the clock.

In this context, establishing an integrated air-ground-space monitoring system has become an inevitable choice. This system can integrate data from different spatial scales, temporal frequencies, and monitoring dimensions, providing an efficient “one-map” perception capability for the entire watershed's pollution status, thereby offering robust data support for pollution tracing, cross-regional coordinated enforcement, and precise regulation.

2.3 Challenges in Precise Identification of Complex Pollution Scenarios

Water body spectral signals are complex responses to the combined effects of multiple environmental factors, with suspended sediment concentration and algal chlorophyll content being the primary sources of interference. Single remote sensing monitoring methods are highly susceptible to interference in complex scenarios such as turbid water bodies or algal blooms, leading to misjudgments of pollutant concentration or type. Therefore, it is essential to rely on in-situ measurement data (primarily from shore-based stations) to effectively calibrate and validate remote sensing physical models, thereby significantly enhancing the accuracy and reliability of pollutant information extraction (especially quantitative concentration).

3. Basic Approach and Technical Synergy Logic

3.1 Hierarchical Technical Synergy Architecture

To achieve complementary advantages and overcome the limitations of single technologies, a hierarchical collaborative monitoring architecture is constructed:

Space-based platform (satellite remote sensing): responsible for large-scale periodic surveys. Core objectives include: spatial distribution inversion of key water quality parameters (water temperature, pH, chlorophyll a, etc.). Regional monitoring of atmospheric pollutant gas (SO_2, NO_2) column concentrations.

Technical Implementation Path: Primarily relies on hyperspectral satellite data (e.g., historical Hyperion data, Sentinel-2 MSI, etc.), utilizing radiation transfer principles or empirical/semi-empirical methods to construct physical models, enabling the inversion and mapping of pollutant concentration spatial distributions.

Airborne Platform (UAVs): Responsible for detailed surveys of key areas and emergency response tasks. Measures are primarily targeted at the following issues:

Detection of thermal anomalies at suspected pollution discharge points (indicating illegal discharges). Identification and quantification of floating debris (garbage, oil spills) on water surfaces. Rapid detection and evidence collection of illegal activities (e.g., sand mining). Technical Implementation Pathway: Equipped with hyperspectral imagers, thermal infrared cameras, or multispectral cameras, these platforms rapidly acquire high-resolution orthophotos and 360° panoramic imagery of target areas, enabling precise identification and quantitative tracking of pollution source types, spatial extent, and dynamic changes.

Ground-based platform (shore-based station): Responsible for on-site verification and real-time monitoring tasks. Core objectives include:

Continuous, real-time, on-site collection of key water quality parameters (turbidity, pH, dissolved oxygen, conductivity, ammonia nitrogen, etc.).

Providing ground-based “true value” data for space-based and airborne remote sensing inversion models to support model calibration and accuracy verification.

Technical implementation path: Based on embedded microcontroller systems such as STM32, integrate multiple water quality sensor modules to construct intelligent monitoring terminals. Adopt a solar power supply system to address energy issues for long-term field operations and use wireless communication modules (based on the TCP/IP protocol stack) such as GPRS/4G to achieve near-real-time, high-reliability (error rate approaching zero) remote transmission of monitoring data to the central management platform.

3.2 Multi-source Data Fusion Process

The core of systematic collaboration lies in establishing standardized data flow and fusion processes, with the general process outlined below:

Satellite-based preliminary screening: Utilize satellite remote sensing data for regular large-scale scanning and analysis to identify areas with abnormal water body reflectance spectra, which serve as potential pollution target zones.

Aerial detailed investigation: Deploy drones to conduct rapid and precise aerial detailed investigations of the abnormal target areas identified by satellites, confirm the type of pollution (such as discharge outlets, floating objects, algal blooms, etc.), precisely delineate the pollution area, quantify the pollution severity, and obtain on-site imagery evidence.

Ground-based verification and calibration: At pollution areas or representative points confirmed by drones, real-time in-situ water quality parameter data is collected using shore-based stations (or mobile monitoring devices when necessary). This field data is used to verify drone observation results and provide critical ground calibration parameters for satellite remote sensing inversion models, significantly enhancing the models' regional adaptability and quantitative accuracy.

Comprehensive Analysis and Decision-Making: Integrate satellite survey results, UAV detailed survey information, real-time monitoring data from shore-based stations, and any other auxiliary data (e.g., meteorological, hydrological, topographical) into a Geographic Information System (GIS) platform. Through spatial overlay analysis and spatio-temporal correlation mining, generate pollution distribution thematic maps, source tracing analysis reports, and

comprehensive assessment reports to provide scientific basis for river chief system management decisions (such as pollution source localization, responsibility determination, governance effectiveness assessment, and emergency response).

3.3 Key Technological Breakthroughs

The effective operation of this collaborative system primarily relies on the support and breakthroughs of the following key technologies, which should also be continuously improved and updated.

High-precision physical model inversion: Focus on developing spectral uncoupling models tailored for complex water bodies (high turbidity, eutrophication), deeply exploring the physical mechanisms linking pollutant concentrations to their spectral response characteristics, effectively reducing interference from background factors (especially suspended sediments) on the quantitative inversion of target pollutants (such as chlorophyll a, CDOM, and specific chemical pollutants), and enhancing the accuracy of remote sensing data extraction.

Reliable data communication assurance: Based on mature cellular network technologies such as GPRS/4G, design and implement low-power, high-stability remote data transmission modules. By optimizing TCP/IP protocol stack applications and data compression/verification mechanisms, ensure the integrity and near-real-time transmission of monitoring data from shore-based stations in complex field environments (with extremely low measured error rates, meeting operational requirements).

Long-term energy supply solution: For shore-based monitoring points far from the power grid, an innovative approach combines high-efficiency solar photovoltaic panels with a large-capacity energy storage battery system (such as lithium-ion batteries) featuring intelligent charge/discharge management. This completely resolves the energy bottleneck issue for monitoring equipment operating in remote, off-grid areas, enabling long-term, stable, unmanned operation.

4. Practical Achievements and Application Value

4.1 Significant Improvement in Monitoring Efficiency

Drone river patrols demonstrate a significant efficiency advantage over traditional manual inspections. Empirical evidence shows that drones can complete a typical 3,000-meter river patrol task in approximately 8 minutes, achieving an efficiency more than 10 times that of manual inspections, significantly expanding regulatory coverage and response speed [3].

4.2 Effective Validation and Improvement of Monitoring Accuracy

By incorporating real-time in-situ monitoring data from riverside stations into the calibration process of satellite remote sensing inversion models, the regional adaptability and accuracy of the models have been significantly improved. Practical application verification shows that the inversion results of water quality parameters (such as chlorophyll and turbidity) after calibration can control errors within 5%, achieving a high level of quantification and meeting the requirements of refinement management [4-7].

4.3 Optimization and Upgrading of Management Efficiency

The integrated air-ground-space monitoring model provides strong technical support for the efficient, precise, and dynamic management of the river chief system:

According to literature [4], in large-scale application cases such as the Pearl River Estuary, this system successfully identified and quantified the distribution of over 2,562 square kilometers of heavily polluted water areas, providing precise targeting for regional pollution prevention and control.

According to literature [2], in local practices such as Shangyu District, it has successfully achieved precise identification, range quantification, and dynamic monitoring of shoreline encroachment behaviors (such as illegal construction, unauthorized planting, and illegal wharves), significantly enhancing the spatial control capabilities of river and lake shoreline areas.

The integrated air-ground-space river and lake pollution monitoring model establishes a three-tiered collaborative technical system with clear hierarchical structure and complementary functions by scientifically coordinating the wide-area periodic scanning of space-based satellites, the mobile targeted verification of air-based drones, and the on-site real-time validation of ground-based shoreline stations. This model fundamentally overcomes the inherent limitations of

single monitoring technologies in terms of coverage, spatio-temporal resolution, monitoring accuracy, and response speed, successfully achieving a closed-loop management process encompassing "large-scale periodic surveys → detailed inspections of key suspect areas → precise identification and control of pollution sources."

Practice has proven that this model is the core technical pathway for significantly enhancing the operational capabilities and scientific decision-making of river and lake pollution monitoring. Its core value lies not only in improved monitoring efficiency and accuracy but also in providing methodological support: the developed multi-source spectral inversion model based on physical mechanisms offers a scientific methodological framework for high-precision extraction of pollution information in complex environments. It also establishes a data foundation: the IoT-enabled, intelligent shore-based station design addresses the key bottleneck of long-term in-situ monitoring, providing stable, reliable, and real-time ground verification and calibration data source for the collaborative system.

Therefore, the integrated air-ground-space collaborative monitoring system not only demonstrates significant application effectiveness but also, through its underlying technical logic and methodological innovations, lays a solid technical and data foundation for constructing an intelligent, precise modern water environment regulatory system.

5. Conclusion

This paper systematically explores the application of integrated air-ground-space technology in water pollution monitoring. By integrating multi-source data from satellite remote sensing, UAV sensing, and shore-based stations, a hierarchical collaborative monitoring system has been established. The study demonstrates that this technology significantly enhances the accuracy of pollution monitoring.

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