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Construction of Environmental Management Decision Support System Based on Big Data

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Abstract: Facing increasingly severe environmental challenges, traditional environmental management approaches struggle to address complex ecological issues. Big data technology offers new pathways for environmental management decision-making. This paper systematically discusses building environmental management decision support systems based on big data, analyzing theoretical foundations, application models, technical dimensions, and practical innovations. Research shows that through multi-source data collection, analytical model construction, and decision algorithm optimization, these systems enable real-time monitoring analysis, precise pollution source identification, and environmental risk warning. The paper explores sustainable development paths and emphasizes industry-academia-research collaboration in driving innovation and application. Looking forward, with deeper integration of AI and IoT technologies, big data-based environmental management decision support systems will play increasingly important roles in environmental governance and ecological protection.

1. Introduction

Environmental issues have become a global focus, with climate change, air pollution, and water scarcity threatening sustainable development. Traditional environmental management methods face limitations in comprehensive data acquisition, analytical capabilities, and timely decision-making. The big data era brings revolutionary changes to environmental management, providing unprecedented information foundations through massive, multi-source, heterogeneous environmental data. Environmental management decision support systems based on big data integrate multiple data sources and employ advanced data mining and machine learning algorithms to achieve real-time environmental monitoring, scientific pollution trend prediction, and precise governance planning. This paper explores how big data technology empowers environmental management decisions, systematically explaining construction principles, technical approaches, and application value of these systems, analyzing practical experiences from domestic and international cases, and forecasting future development trends.

2. Theoretical Foundations and Development of Environmental Management Decision Support Systems

Environmental Management Decision Support Systems (EMDSS) originated from decision support system theory in the 1970s, evolving from single-model analysis to multi-dimensional comprehensive assessment. Its theoretical foundation integrates system science, information science, environmental science, and decision theory, focusing on providing scientific decision-making basis through data processing and model analysis [1].

Table 1: Development Stages of Environmental Management Decision Support Systems (EMDSS)

Stage	Period	Key Features	Technologies
Data-driven Stage	1980s-1990s	- Basic database construction - Simple model analysis	Database systems
Knowledge Integration Stage	Early 2000s-2010	- GIS technology integration - Expert systems implementation	GIS, Expert Systems
Big Data Intelligence Stage	2010-Present	- Cloud computing - IoT integration - AI technologies - PB-level data processing	Cloud Computing, IoT, AI, Big Data

Traditional EMDSS relied on limited monitoring data and simplified models, with significant limitations in decision efficiency and accuracy. EMDSS development has undergone three key stages: data-driven stage (1980s-1990s), characterized by database construction and basic model analysis; knowledge integration stage (early 21st century to 2010), introducing GIS technology and expert systems; and big data intelligence stage (2010 to present), integrating cloud computing, IoT, and AI technologies [2]. As shown in Table 1.

Modern EMDSS has evolved from simple data processing tools to comprehensive systems integrating data collection, storage, analysis, visualization, and decision support, capable of processing PB-level environmental data and supporting multi-scale, multi-scenario environmental simulation and prediction. Big data technology has enabled qualitative leaps in EMDSS data processing capacity, analytical depth, and decision precision, laying solid foundations for scientific, refined, and intelligent environmental management [3].

3. Application Models and Technical Dimensions of Big Data in Environmental Management

3.1 Multi-source Data Collection and Integration

Environmental management decision support systems are founded on comprehensive, accurate data collection and integration. In the big data era, environmental data sources are diversified, including fixed monitoring stations, mobile monitoring equipment, remote sensing satellites, and social perception data. These heterogeneous data sources present significant challenges for integration due to differences in temporal resolution, spatial scale, and data formats [4].

Modern systems employ distributed data collection architectures and edge computing for real-time acquisition and preprocessing. For data integration, ETL (Extract-Transform-Load) technology and semantic ontology models establish unified environmental data standards to address heterogeneity issues. Data quality assessment mechanisms ensure reliability through anomaly detection, missing value processing, and consistency verification. Cloud storage and distributed file systems solve massive environmental data storage and management challenges [5].

3.2 Data Analysis Model Construction

In big data environments, environmental management decision support systems require multi-level, multi-dimensional data analysis models to meet various management scenarios. Three main model types are constructed: descriptive analysis models using statistical analysis and data visualization to reveal environmental quality spatiotemporal distribution characteristics; predictive analysis models integrating machine learning and environmental science to build environmental quality prediction systems; and optimization analysis models focused on improving environmental governance solutions [6]. As shown in Table 2.

Table 2: Analysis Model Types in Environmental Management Decision Support Systems

Model Type	Primary Function	Technical Methods	Application Scenarios
Descriptive Analysis	Statistical analysis and visualization	- Data visualization tools - Statistical analysis - Spatial mapping	- Environmental quality distribution - Pollution level assessment
Predictive Analysis	Future trend forecasting	- Machine learning - TensorFlow - Spark MLlib	- Pollution trend prediction - Environmental risk assessment
Optimization Analysis	Solution improvement	- Knowledge graphs - Deep reinforcement learning - Monte Carlo simulation	- Governance planning - Resource allocation

Technically, big data analysis frameworks like Spark MLlib and TensorFlow provide powerful support for complex model construction, while distributed computing technologies solve efficiency issues in large-scale environmental data processing. Knowledge graph technology effectively integrates expert knowledge to enhance interpretability and scientific validity of analysis results.

3.3 Decision Algorithm Optimization and Performance Analysis

The core value of environmental management decision support systems lies in transforming data analysis results into executable decisions through efficient algorithms. Under big data contexts, environmental decision algorithms face challenges in multi-objective trade-offs, uncertainty handling, and real-time response [7].

Systems address these challenges through innovative algorithms: improved Analytic Hierarchy Process (AHP) and fuzzy comprehensive evaluation methods for multi-objective decisions; Bayesian networks and Monte Carlo simulations for uncertainty handling; and incremental learning algorithms and approximate computing techniques for real-time decision-making. Algorithm performance is evaluated through multi-dimensional metrics including computational efficiency, prediction accuracy, and decision effectiveness. Deep reinforcement learning-based decision algorithms demonstrate excellent performance in complex environmental problem-solving.

4. Big Data Innovation Practices and Case Analysis in Environmental Management Decision-making

4.1 Management Innovation and Model Innovation

Big data technology has improved environmental management technical means and driven innovative transformations in management models, shifting from end-of-pipe treatment to wholeprocess control, from single pollutant control to comprehensive environmental quality management, from experience-based judgment to data-driven decision-making, and from compartmentalized to collaborative management.

China's River Chief System exemplifies this by integrating water quality monitoring, polluting enterprise data, and watershed ecological data into a digital management platform for coordinated governance. In corporate environmental management, the "environmental big data + IoT" model transforms passive compliance into proactive management. In government supervision, the "Internet + environmental protection" model has shifted environmental monitoring from manpower-intensive approaches to intelligent supervision.

4.2 Functional Innovation and Typical Application Cases

Big data technology has brought functional innovations to environmental management decision support systems in intelligent environmental monitoring, precise pollution source tracing, real-time risk warning, and personalized governance solutions.

Internationally, the U.S. EPA's Community Multi-scale Air Quality (CMAQ) system exemplifies big data application by integrating meteorological data, emission inventories, and satellite remote sensing data. The European Union's Water Framework Directive (WFD) data platform integrates water quality monitoring data from 27 member states.

In China, the Ministry of Ecology and Environment's "Blue Sky Defense" decision support system successfully integrates data from over 1,500 air quality monitoring stations, satellite remote sensing, and meteorological data. Zhejiang Province's "Five Waters Governance" information platform integrates water quality monitoring, discharge outlet monitoring, and rainfall/water condition data for multi-level water environment management.

4.3 Effect Assessment and Challenges

Big data-based environmental management decision support systems have achieved significant results while facing numerous challenges. Positive changes include improved environmental supervision efficiency, optimized resource allocation, and improved environmental quality, as shown in Table 3.

Table 3: Major Challenges in Big Data-based Environmental Management Systems

Challenge Category	Key Issues	Impact
Data Quality	- Insufficient accuracy - Limited coverage - Inconsistent standards	Affects reliability of decision-making
Technical	- Complex system simulation - Heterogeneous data fusion	Limits system effectiveness
Mechanism	- Departmental data barriers - Inadequate information sharing	Hinders collaborative management
Talent	- Shortage of interdisciplinary professionals - Limited expertise	Affects system implementation

However, systems face four major challenges: data quality issues including insufficient accuracy, limited coverage, and inconsistent standards; technical challenges such as insufficient simulation precision for complex environmental systems and difficulties in multi-source heterogeneous data fusion; mechanism challenges including departmental data barriers and inadequate information sharing; and talent challenges with shortages of interdisciplinary professionals. These challenges constrain the application depth and effectiveness of environmental big data systems.

5. Sustainable Development and Practical Application of Environmental Management Decision Support Systems

5.1 Sustainable Optimization Strategies and Performance Prediction

For long-term development, environmental management decision support systems must continuously improve in technology, management, and application. Technologically, systems should follow principles of self-adaptation, self-learning, and self-evolution, using federated learning and transfer learning to address model adaptability differences across regions and environments. Managerially, closed-loop optimization mechanisms comprising data, models, decisions, and feedback should be established. In application, systems should transition from single environmental element management to multi-element collaborative management.

5.2 Industry-Academia-Research Integration for Technological Innovation and Application

Environmental management decision support systems will achieve significant progress in prediction accuracy, response speed, and decision intelligence over the next five years. Continuous innovation and promotion depend on deep integration of industry, academia, research, and users. Universities and research institutions provide technological innovation sources, enterprises serve as technology application entities, and government departments identify needs and implement results.

Establishing joint laboratories and industry-academia-research innovation alliances effectively promotes the transition from laboratory research to practical application. Project cooperation and talent exchange facilitate technology transformation and application, as exemplified by Tsinghua University's collaboration with a provincial ecology and environment department to develop a watershed water environment management decision support system.

6. Conclusion

6.1 Technology Development Trends

Environmental management decision support systems based on big data are transitioning from data-driven to intelligence-driven approaches, with three major trends: increasing intelligence through deep integration of AI technologies with environmental science; accelerated multi-technology fusion of IoT, blockchain, and edge computing with big data; and expanding application scenarios from single environmental element management to holistic ecosystem management. The core driving force will be cross-innovation between environmental science and data science.

6.2 Future Optimization Directions

Future optimization of environmental management decision support systems must target four key directions: significantly improving data quality through enhanced environmental monitoring networks and data quality control systems; promoting cross-domain knowledge integration by breaking disciplinary barriers and integrating ecology, environmental engineering, economics, and data science; ensuring transparent decision processes by strengthening model interpretability and decision traceability; and optimizing user experience through personalized decision support tools based on different environmental managers' needs. These measures will enable more precise and efficient operation of big data-based environmental management decision support systems in service of ecological civilization construction and harmonious human-nature coexistence.

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