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Information and Communication Technologies in Environmental Impact Assessment and Environmental Management

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ABSTRACT

The purpose of this study is to systematize, analyze modern information and communication technologies used in the process of environmental assessment, and develop conceptual foundations and their integration into environmental management systems. The methodology is based on a comprehensive analysis of literary sources, a critical assessment of existing technological approaches and conceptual modeling of the architecture of integrated systems. The results of the study include a functional classification of information and communication technologies tools into three categories. Four systemic problems of the current state of information and communication technologies in ecology have been identified, which create contradictions between the means and goals of environmental management, as well as qualification obstacles to the implementation of complex technologies at the regional and local levels. The central scientific result is the developed five-level conceptual model of the architecture of an integrated environmental management system, which includes a level of intelligent data aggregation with automatic format standardization, a level of adaptive processing with self-adjusting algorithms, a level of automated verification to minimize user participation, a level of intuitive management through adaptive interfaces, and a level of intelligent support with built-in learning modules. The model implements the principles of integration through standardized interfaces and provides a gradual transformation of primary environmental data into ready-made management solutions with the possibility of feedback for continuous improvement of the system. The practical significance lies in the possibility of using the developed conceptual principles to create methodological recommendations for the implementation of information and communication technologies in environmental management at different levels. The scientific novelty is due to the first proposed systemic approach to the integration of heterogeneous information and communication technologies into a single multi-level environmental management architecture, which allows overcoming existing technological barriers and creating a synergistic effect from the interaction of various digital tools.

KEYWORDS

information and communication technologies, digitalization, environmental impact assessment, environmental safety, environmental management, geographic information systems, remote sensing, sustainable development.

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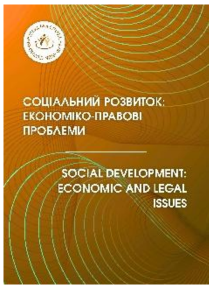

Інформаційно-комунікаційні технології в оцінці впливів на довкілля та екологічного управління

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СТАТТЯ

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АНОТАЦІЯ

Метою даного дослідження є систематизація, аналіз сучасних інформаційно-комунікаційних технологій, які використовуються в процесі екологічної оцінки, та розробка концептуальних засад і їх інтеграції в системи екологічного менеджменту. Методологія базується на комплексному аналізі літературних джерел, критичному оцінюванні існуючих технологічних підходів та концептуальному моделюванні архітектури інтегрованих систем. Результати дослідження включають функціональну класифікацію інструментів інформаційно-комунікаційних технологій за трьома категоріями. Виявлено чотири системні проблеми сучасного стану інформаційно-комунікаційно технологій в екології, що створюють протиріччя між засобами та цілями екологічного управління, а також кваліфікаційні перешкоди впровадження складних технологій на регіональному та місцевому рівнях. Центральним науковим результатом є розроблена п'ятирівнева концептуальна модель архітектури інтегрованої системи екологічного управління, яка включає рівень інтелектуального агрегування даних з автоматичною стандартизацією форматів, рівень адаптивної обробки з самоналаштовуючими алгоритмами, рівень автоматизованої верифікації для мінімізації участі користувача, рівень інтуїтивного управління через адаптивні інтерфейси та рівень інтелектуальної підтримки з вбудованими модулями навчання. Модель реалізує принципи інтеграції через стандартизовані інтерфейси та забезпечує поступове перетворення первинних екологічних даних у готові управлінські рішення з можливістю зворотного зв'язку для безперервного вдосконалення системи. Практична значущість полягає в можливості використання розроблених концептуальних засад для створення методичних рекомендацій щодо впровадження інформаційно-комунікаційних технологій в управління навколишнім середовищем різних рівнів. Наукова новизна обумовлена вперше запропонованим системним підходом до інтеграції різнорідних інформаційно-комунікаційних технологій в єдину багаторівневу архітектуру екологічного управління, що дозволяє подолати існуючі технологічні бар'єри та створити синергетичний ефект від взаємодії різних цифрових інструментів.

КЛЮЧОВІ СЛОВА

інформаційно-комунікаційні технології, диджиталізація, оцінка впливу на довкілля, екологічна безпека, екологічне управління, геоінформаційні системи, дистанційне зондування, сталий розвиток.

1. Introduction

The existing problems of the global environmental crisis require a fundamental revision in approaches to environmental impact assessment and environmental management systems. According to the World Health Organization (WHO), nine million people die each year due to pollution, a quarter of the total burden of disease in the world. Traditional methods cannot efficiently process large data sets for real-time risk analysis, and hence, there is a need for new monitoring systems that will improve transformation opportunities thanks to rapidly evolving digital technologies. The increase in connected IoT-to, together with the introduction of artificial intelligence algorithms, Geographic Information Systems (GIS) development and remote sensing technology-constitutes the technological foundations for the formation of qualitatively new levels in environmental management. However, modern practice is characterized by fragmented technological solutions, interoperable problems, and the lack of a single architectural concept for integration. Thus, there is a need to develop an integrated model that integrates the different information and communication technologies (ICT) tools into a single environmental management system, aimed at achieving synergies through interaction between digital technologies, as well as overcoming existing technological barriers that block their implementation.

2. Literature Review

Research on the use of ICT in the environmental field has been characterized by active development in recent years. The analysis of the use of artificial intelligence for environmental monitoring shows that machine learning algorithms can increase the accuracy of predicting environmental parameters by 25–40% compared to traditional statistical methods [1].

European researchers are actively developing the concept of a “digital ecological twin” within the framework of the Destination Earth initiative and propose the integration of remote sensing technologies with geographic information systems to create dynamic ecosystem models. The results show that this approach provides a reduction in the time for conducting environmental assessments [2]. Further research confirms that Earth’s digital twins enable the convergence of big environmental data with physical models in interactive computing systems to monitor and predict environmental changes [3]. The practical implementation of digital twins in nature conservation areas demonstrates their effectiveness for monitoring ecosystems and informing management decisions [4].

Research on the development of IoT systems for environmental monitoring substantiates the prospects of using a network of distributed sensors for real-time monitoring of the state of the environment [5]. Further research confirms the effectiveness of wireless sensor networks for monitoring air quality and enabling the development of early detection and warning systems for environmental threats [6; 7].

According to the latest data, blockchain provides accurate monitoring of environmental components to verify environmental data and control natural resources. A number of studies propose a conceptual model for the use of a distributed ledger for the verification of environmental data, as well as transparency in the process of environmental impact assessment, in particular accounting for greenhouse gas emissions [8; 9].

Cloud computing and big data technologies have been significantly developed in the context of environmental management. Research demonstrates that cloud infrastructure provides scalability and cost-effectiveness in processing large amounts of environmental data, while posing challenges in terms of energy consumption and environmental impact [10]. Electricity consumption by data centers is projected to increase to 945 TWh by 2030, which actualizes the need to implement the concept of “green” cloud computing using renewable energy sources [11].

The issue of energy efficiency of ICT systems is of particular relevance in the context of environmental goals. The data show that the ICT sector is responsible for 567 Mt of CO_2 equivalent emissions, which is 1.7% of global emissions [12]. Green computing research offers comprehensive strategies to reduce the environmental footprint of digital technologies, including energy-efficient equipment, software optimization, and implementation of circular economy principles [13; 14].

The problem of interoperability and standardization of data remains critical for the integration of heterogeneous sources of environmental information. The analysis of the studies reveals the need to develop uniform standards for data exchange and semantic interoperability to ensure the effective integration of multidisciplinary environmental data [15]. Modern initiatives, in particular the FAIR (Findable, Accessible, Interoperable, Reusable) principles, are aimed at improving the quality and accessibility of environmental data for scientific research and practical application [16].

The European Copernicus program within the framework of the European Green Deal demonstrates the practical implementation of integrated environmental monitoring systems, providing free access to Earth observation satellite data to support environmental policy and environmental monitoring [17].

Despite significant achievements, the analysis of the literature reveals the lack of comprehensive studies that systematize various ICT approaches and formulate the conceptual foundations of their integration into a single system of environmental management.

3. Problem Statement

It is the modern approach to global challenges in the field of environmental problems that requires a major revision of existing approaches to environmental impact assessment and management. Traditional monitoring methods have limited capabilities in dealing with significant amounts of data, as well as environmental threats, and may not be effective enough when it comes to predicting environmental risk.

Today, nine million deaths in the world are attributed to ambient air pollution, as evidenced by Global Air's comprehensive analyses of data on air quality and health impacts. It is air pollution that has become the second largest risk factor for death after high blood pressure. In February 2025, the WHO published an updated database, which notes that environmental risks account for a quarter of the total global burden of disease. [18–20]. This highlights how important environmental monitoring is. The IoT Analytics report points to a 13% growth in connected IoT devices to 18.8 billion globally by 2024. New opportunities are opening up for revolutionary changes in environmental monitoring [12].

However, the information and communication technology sector accounts for 1.5% to 4% of total global carbon emissions, which creates a paradoxical situation between technological solutions and environmental goals [12].

This makes it urgent to develop a conceptual model for combining different ICT tools within one environmental management system, for their synergistic work in helping to reduce the negative impact on the environment. In the absence of such a systemic combination, it becomes quite difficult to take full advantage of the opportunities that modern digital technologies can offer.

4. Methods and Materials

The research methodology is based on the application of a set of scientific methods that provide a comprehensive analysis of modern information and communication technologies and the conceptual architectural formation of integrated ecological systems.

For a comprehensive study of scientific publications, the method of analysis and synthesis was applied to the application of the Internet of Things, GIS, artificial intelligence, blockchain technologies and digital twins in environmental assessment and management. The strengths and weaknesses of today's digital solutions, as well as the scientific gaps in environmental assessment and management, have been identified through a critical evaluation of existing technological approaches. The study of the functionality of technologies was carried out by conducting a comparative analysis. Conceptual modeling of the architecture of integrated systems was used to develop a structural model.

Applying the method of systematization and generalization, conclusions were drawn and prospects for the use of digital technologies in processes involving environmental assessment and management were determined.

5. Results and Discussion

The study is aimed at developing conceptual foundations for the introduction of modern information and communication technologies in the system of environmental impact assessment and environmental management.

On the basis of the study of modern technological solutions, the classification of ICT tools by functional purpose is proposed: data collection technologies, processing and analysis technologies, and visualization and communication technologies (Table 1).

Table 1. Classification of ICT tools for environmental assessment

Technology Category	Tools and Methods
Data Collection Technologies	– Remote Sensing – IoT Sensors and Wireless Sensor Networks – Mobile Apps for Public Monitoring – Automated Observation Stations
Processing and Analysis Technologies	– Geographic Information Systems (GIS) – Machine Learning and Artificial Intelligence (AI) – Decision Support Systems – Cloud Computing and Big Data Analytics
Visualization and Communication Technologies	– Geovisualization and Mapping Systems – Web Platforms and Dashboards – Mobile Apps for Stakeholders – Notification and Early Warning Systems

Source: Compiled by the authors.

Data collection technologies constitute the basic level of information support for environmental monitoring. Remote sensing is carried out using satellite observation and aerial photography systems, which provide multispectral information about the state of ecosystems. Modern satellite platforms Sentinel-2 and Landsat provide a spatial resolution of up to 10 meters, which allows you to study in detail the changes occurring with the structure and functions of natural complexes.

IoT forms a technological infrastructure with the provision of sensors and wireless sensor networks that are used to develop an actual distributed system for monitoring environmental parameters. The results of practical experiments have shown high measurement accuracy, which can be achieved by the following systems: ±0.5°C for temperature, ±2% for humidity and ±0.1 for pH [6]. Mobile monitoring applications expand the spatial coverage of observations by involving the public in the processes of collecting primary environmental data.

Processing and analysis technologies support the transformation of primary data into structured information for managerial decision-making. Geographic information systems (GIS) implement the capabilities of spatial environmental analytics and synthesis of heterogeneous information for complex modeling of the state of the environment. Systems based on ArcGIS software allow mathematical modeling of pollutant distribution processes, as well as quantitative assessment of environmental risks.

The application of machine learning algorithms and artificial intelligence methods demonstrates a statistically significant improvement in the accuracy of predicting environmental parameters by 25–40% compared to traditional statistical methods [1]. Deep learning algorithms are very useful for analyzing time series of environmental data and for discovering hidden patterns in the dynamics of natural processes.

Cloud computing technologies and big data analytics allow you to process vast amounts of environmental data while maintaining scalability and cost-effectiveness.

Verification and management technologies represent the information plus technological cycle of environmental management at its last stage. Geovisualization and mapping systems present the results of environmental monitoring in a visual way, expressed in terms understandable for making a management decision.

Blockchain technologies guarantee cryptographic immutability and transparency of environmental data, which is especially important in the field of accounting for greenhouse gas emissions and verification of environmental reporting [8; 9]. Early warning systems combine information from various sources to automatically identify and report potential environmental threats.

A critical analysis of the current state of ICT application in the field of environmental monitoring reveals a number of systemic limitations. It is these limitations that do not allow you to effectively use potential opportunities.

In particular, the fragmentation of technological solutions is understood as the lack of integration between individual ICT platforms. Existing systems mostly work as standalone solutions with minimal interoperability with other existing solutions. This leads to the creation of isolated information arrays and does not allow for the effective use of available resources. The situation is even worse when there is no unified architectural concept for the construction of integrated environmental information systems.

The compatibility problem lies in the lack of common standards for data exchange between different ICT platforms. This is manifested in differences in data formats, information transfer protocols and program interfaces. Thus, there are serious technical obstacles to building complex systems based on environmental management. This requires the development of more levels of adaptation, and therefore makes technological solutions more complex and expensive.

The energy paradoxes of ICT systems also consist of the significant energy consumption of modern digital technologies, with the main share being machine learning systems and distributed ledgers. According to experts, it is likely that the functioning of ICT infrastructure can nullify all positive effects on the environment when it is used, creating a conceptual contradiction between its means and environmental management objectives.

It is impossible to ignore the qualification obstacles associated with the great technological complexity of modern ICT solutions, which require high professional competence from their users. This becomes an obstacle to the widespread practical implementation of innovative technologies in environmental management at the regional and local levels of government.

Based on the analysis of functional categories and the identified system limitations, a conceptual model is formulated, which consists of five interacting architectural levels (Table 2)

Table 2. Structural diagram of the multi-level system of integration of information and communication technologies for environmental assessment

Level	Description
Level 1	Intelligent data aggregation with automatic standardization of formats and information exchange protocols
Level 2	Adaptive processing and analytics, where algorithms self-adjust to the specifics of user tasks
Level 3	Automated verification, minimizing user involvement in the data validation process
Level 4	Intuitive management and visualization via adaptive interfaces that automatically assess the user's technical proficiency
Level 5	User support system with integrated training and consulting modules

Source: Compiled by the authors.

The basic level (Level 1) of the architecture carries out the basic processing and unification of heterogeneous flows of environmental information. The main function of this level is to overcome the problem of fragmentation of technological solutions through the development of a single information space.

Intelligent aggregation is carried out by automatically determining types and constructing input facts regardless of their basic form. The setup can process satellite observer information, IoT sensor data, lab test results, meteorological data, and field research details.

Automatic standardization of formats ensures that all information is brought to common technical standards, so there are no compatibility issues between different data sources. Information exchange protocols are optimized to ensure reliable and fast data transfer between system components.

The level contains mechanisms for quality control of primary data with automatic detection and correction of typical measurement errors, which increases the overall reliability of the information base of the system.

The analytical layer (Level 2) provides intelligent processing of normalized data with the automatic selection of the best analysis methods according to the nature of the tasks to be performed and the characteristics of the available information.

The adaptability of processing is expressed in the ability of the system to automatically select those analysis algorithms that are most successful, depending on the type of environmental task, the amount of information available, requirements for the accuracy of results and time constraints. The system can use a range of analytical methods, ranging from simple statistical calculations to complex machine learning models.

Query history, user activity profile, and domain features determine how algorithms can be configured automatically. The system optimizes work for different categories of users and gradually studies their needs. Among them are scientists, heads of environmental protection agencies, and representatives of industrial enterprises.

Here, there is an automatic detection of trends, anomalies and patterns in environmental data, which creates predictive models and assesses the probability of various scenarios for the development of the environmental situation.

The validation layer (Level 3) is designed to ensure high reliability of analysis results by implementing automated mechanisms for verifying data and processing results without the need for constant user intervention.

Auto-verification involves a multi-level control system: checking input data for compliance with physical laws and environmental patterns, cross-checking the results with various analytical methods, as well as comparing with historical data and reference values.

Minimizing user participation is achieved by implementing expert systems that automatically assess the reliability of information based on accumulated experience and accepted quality criteria. The system itself identifies possible errors, inconsistencies, as well as dubious results and informs the user only those cases that require an expert decision.

This layer provides documentation at all stages of the verification process to be able to track the verification process and verify the quality of the results. Mechanisms for the versioning of data and analysis results are also implemented so that changes can be tracked and be able to return to previous states.

At the interface level (Level 4), effective interaction of users with the system is ensured by automatically adjusting the complexity of the interface to the level of technical training and professional needs of a particular user. The implementation of intuitive control takes place in natural forms of interaction: graphical interfaces with drag-and-drop elements, voice commands, gesture control, and auto-completion of requests. The system tries to minimize the number of technical operations that need to be performed to obtain the desired result.

According to user behavior, by the frequency of use of a particular function, by typical errors and methods, and by how well the work is done, the systems present a simplified interface for beginners with step-by-step instructions for using the system. For experts who may wish to never see such annoying interfaces, adaptive systems provide all the advanced features that help you get quick access to professional tools.

Analysis of the speed of execution of operations, the use of complex functions, understanding of terminology, as well as the interpretation of the results automatically assesses the level of technical training. Based on this, the system automatically adjusts the level of detail of the information to be provided, the complexity of the tools that may be available, and even the amount of reference information.

Visualizing the results automatically selects the best ways to display information: maps, graphs, charts, 3D shapes, and videos. The setting looks at how different people see things and what information about the environment exists for the most informative visual display.

The User Support System (Level 5) provides complete assistance to the user by mixing training materials, consulting services, and expert help systems directly in the stages of using the system.

The support system works like a smart assistant that always monitors what the user is doing, detects possible problems, and provides assistance even before it is asked. Help comes right in the center of the task at hand, without distracting from the main work.

Training modules are built into apply the concept of continuous professional development by combining the content of education with the work process. The system automatically detects gaps in the user's knowledge and learning materials, including interactive lessons, practical tasks, and thematic webinars.

Consulting modules unlock expert knowledge through multiple channels: automatic answers to frequently asked questions, access to a knowledge base of best practices, and the ability to connect with experts in real time. The system stores its consultation history and thereby creates a personal knowledge base for each user.

This level involves the establishment of feedback mechanisms that would constantly update the support system based on the user's experience and any changes noticed in the subject area. Tools for self-assessment of competencies and tools for planning professional development have been introduced.

The proposed five-level architecture acts as one whole system, where each layer receives the results of the previous one and passes the processed information to the next. This setting ensures a continuous improvement in both the quality and value of information at every step of processing.

Standardized interfaces and data exchange protocols ensure vertical integration of layers. Quality control at each transition between levels and verification of processing results accompany every step taken. Horizontal integration allows information to be exchanged between all components within any given level for a synergy effect that optimizes the overall performance of the system. The proposed architecture supports this principle, whereby feedback from higher-level decision-makers can be used to optimize the performance of lower-level decision-makers. This will make this architecture dynamic with respect to continuous improvement.

6. Conclusions

The conducted research made it possible to systematize modern information and communication technologies of environmental assessment, as well as to develop conceptual foundations for their integration into environmental management systems. A functional classification of ICT tools into three main categories has been developed, which provides a structured approach to the selection of technological solutions in accordance with the specifics of environmental tasks.

A conceptual model of a five-level architecture of an integrated environmental management system is proposed, which provides the transformation of raw environmental data into ready-made results of a management decision using intelligent aggregation, adaptive analytics, automated verification, intuitive control, as well as intelligent user support. Further research prospects in this direction include the development of appropriate interaction standards for different ICT platforms, the improvement of artificial intelligence methodologies, the study of energy efficiency in information technology, and the study of ethical aspects of the application of artificial intelligence within the framework of environmental management.

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