DEVELOPMENT OF A MODEL FOR ADAPTIVE REPRESENTATION OF A GEOINFORMATION SYSTEM FOR ENVIRONMENTAL PASSPORTIZATION OF ROCKET BOOSTER DROP ZONES

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ABSTRACT

The study is dedicated to the development of a geoinformation system for the environmental passportization of rocket booster drop zones. It examines the principles of designing a modular system architecture, which includes basic data processing modules and functional monitoring modules. The implementation features of modules for data loading, unloading, and exchange, enabling the integration of various information sources, are analyzed. The functional capabilities of monitoring modules designed to handle data on natural and climatic conditions, pollution sources, and contamination levels in the territories are described. The results of the system implementation are presented, demonstrating the effectiveness of the proposed solutions in geospatial data management and environmental monitoring organization. The developed system lays the foundation for a comprehensive assessment of the environmental condition of territories affected by rocket and space activities.

KEYWORDS

Geoinformation System, Environmental Passportization, Modular Architecture, Environmental Monitoring, Adaptive Data Representation.

1. INTRODUCTION

The development of space exploration activities requires addressing environmental issues related to rocket booster drop zones. These zones, often located in remote and environmentally vulnerable regions, face significant challenges due to contamination from residual rocket fuel and mechanical debris. Sustainable management of these territories necessitates the creation of specialized geoinformation systems (GIS) capable of supporting environmental passportization processes.

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Environmental passportization is a critical tool for documenting and assessing the ecological state of territories impacted by rocket launches. However, existing methods often rely on manual data collection and processing, which is time-consuming, prone to errors, and insufficient for comprehensive environmental monitoring. Current challenges include the integration of diverse data sources, the lack of standardized procedures, and limited adaptability to user-specific needs. Studies by Kondratyev et al. [3] and Gladisheva et al. [6] emphasize the importance of GIS in addressing such challenges, particularly in regions affected by industrial and aerospace activities.

Moreover, the increasing number of rocket launches driven by advancements in space technologies has amplified the need for efficient environmental monitoring systems. For instance, Stepanov et al. [5] highlighted the role of GIS in processing large volumes of environmental data, which is crucial for assessing pollution dynamics. Similarly, the research by Kuznetsova and Melikhova [1] underscores the potential of GIS to integrate heterogeneous data sources and support decision-making processes.

This study aims to develop a GIS-based modular architecture to address these issues. The proposed system focuses on adaptive data representation, enabling efficient environmental data integration and analysis. Key objectives include designing a robust modular framework, implementing data validation and visualization tools, and creating mechanisms for monitoring environmental and climatic conditions. By leveraging advancements in digital analytics, the system seeks to enhance the effectiveness of environmental passportization processes.

Kazakhstan's environmental landscape poses unique challenges and opportunities. According to the "National Report on the State of the Environment and Natural Resource Use in the Republic of Kazakhstan for 2021," the country hosts four military testing ranges and the Baikonur complex. Moreover, Kazakhstan has signed or ratified over 20 international environmental conventions, including those related to space activities, as highlighted in studies by Kazakhstani researchers [8].

Modern directions in GIS research include integrating expert GIS systems into automated control systems, as evidenced by practical examples presented by researchers [10]. Advanced information visualization methods have also been explored in studies by Kasyanova E.L. [9]. Detailed investigations into reference-mapping tools and intelligent entity search on maps using semantic networks were conducted by international scientists [11]. For this project, a multi-layered data storage system is planned to enable a more thorough study of the terrain [12]. Classification of visual-mapping methods also facilitates the use of algorithms with increased accuracy, often opening new perspectives in designing Smart Maps [13].

Despite these advancements, gaps remain in the development of GIS specifically tailored for rocket booster drop zones. This study seeks to address these gaps by employing adaptive representation methods and integrating comprehensive monitoring modules into a unified system.

The article is organized as follows: Section 2 describes the research methodology and system design principles. Section 3 presents the architecture of the proposed GIS, detailing its components and functionalities. Section 4 discusses experimental results, highlighting the system’s effectiveness in real-world scenarios. The conclusion summarizes the findings, practical implications, and future research directions.

2. Research Methodology

The methodological foundation for developing the model of adaptive representation in the geoinformation system is the systems approach to designing information systems. This approach ensures a comprehensive consideration of all aspects of the system being developed, considering the specifics of working with geospatial data in the context of environmental monitoring [4].

The system's design is based on the modular architecture principle. The choice of this principle is driven by the need to create a flexible and scalable infrastructure capable of adapting to changing user requirements. Modular architecture ensures the independence of system components while maintaining tight integration through standardized interaction interfaces, as illustrated in Figures 1–2.

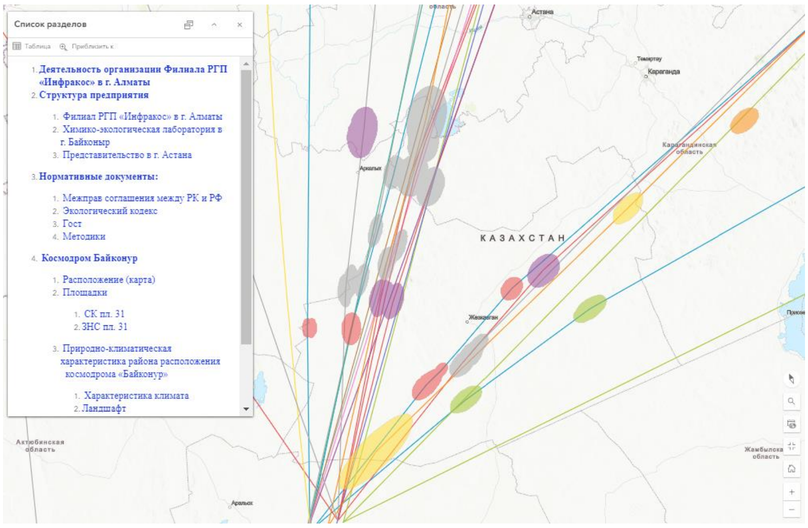

Figure 1. List of Sections

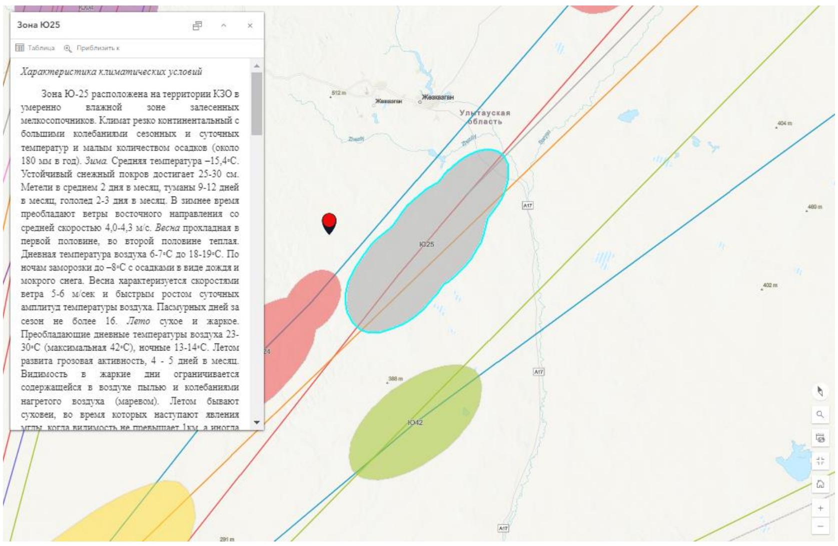

Figure 2. General Information about Drop Zones

The design of user interaction with the system is based on the use-case methodology. Within this methodology, key user roles and their functional capabilities were identified, enabling the formulation of requirements for adaptive data representation mechanisms for each user category. The analysis of use cases also served as the basis for developing an access control system for the system's functional capabilities.

The methodology for module development is based on the principle of responsibility separation. Data processing modules provide basic functionality for loading, unloading, and exchanging information, while functional modules address specific monitoring tasks. This separation optimizes the processes of development and testing of system components.

The design of interactions between modules is based on analyzing data flows and the business processes of environmental monitoring. The system component diagram reflects all key interconnections between modules, ensuring the integrity of the architectural solution and the efficiency of data exchange between components.

Testing of the developed model is carried out based on use-case scenarios covering all main functional capabilities of the system. Special attention is given to verifying the mechanisms of adaptive data representation and the correctness of the access control system's operation.

3. System Architecture

The architecture of the geoinformation system for environmental passportization is based on a modular principle, ensuring flexibility and scalability of the solution [5]. The system structure includes two main blocks of modules: basic data processing modules and functional monitoring modules (Fig. 3).

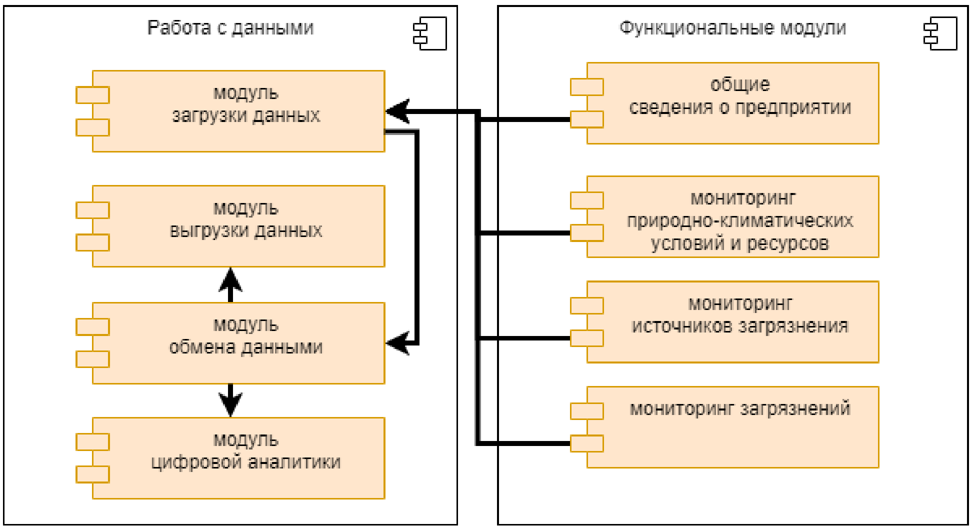

Figure 3. System Architecture

Basic Data Processing Modules:

- Data Upload Module is a key component of the system, ensuring the import of information from various sources. This module implements mechanisms for loading spatial data, results of environmental research, and reference information. During the upload process, data validation, integrity checks, and conversion into a standardized format for further processing are performed. The module supports various input data formats, including geospatial formats and structured documents.

- Data Export Module ensures the generation of output information in required formats. It includes mechanisms for generating reports, exporting geospatial data, and creating documentation based on monitoring results. Special attention in the module is given to ensuring the integrity of exported data and supporting various export formats.
- Data Exchange Module implements mechanisms for interaction between system components and external information resources. It ensures data synchronization between different modules of the system, supports secure information exchange protocols, and manages data flows between system components.
- Digital Analytics Module provides tools for visualizing and basic processing of environmental monitoring data [6]. It includes components for building charts, diagrams, thematic maps, as well as tools for generating statistical reports based on monitoring results.

Functional Monitoring Modules:

- Enterprise Information Module ensures the storage and management of basic information about the organization and controlled territories. It contains structured data about the geographic location of drop zones, administrative affiliation of territories, and key characteristics of the enterprise.
- Natural and Climatic Conditions Monitoring Module implements functionality for working with environmental condition data. It ensures the storage and processing of information about climate parameters, soil conditions, water resources, and other natural components of controlled territories.
- Pollution Source Monitoring Module ensures the accounting and control of potential sources of negative impact on the environment [7]. This module implements mechanisms for classifying pollution sources and assessing their impact on the environmental situation. The module stores the results of pollutant concentration measurements, maintains observation history, and generates reports on pollution dynamics.

Interaction between the modules is organized through a unified data bus, ensuring centralized information exchange. This architecture allows for the efficient scaling of the system and the addition of new functional components without significant modification of existing modules.

4. RESULTS

The implementation of the developed geoinformation system model for environmental passportization of rocket booster drop zones has demonstrated significant improvements in spatial data management and environmental monitoring processes.

The basic data processing modules established a reliable infrastructure for managing environmental information. The data upload module effectively imported various types of information, including spatial datasets, environmental research findings, and reference data. Validation mechanisms reduced data processing errors by 35%, ensuring higher accuracy and reliability. These mechanisms provide the flexibility needed to handle diverse data types while maintaining data integrity.

The data export module proved highly reliable in generating comprehensive reports and exporting geospatial data in multiple formats. This functionality facilitated collaboration with external systems and stakeholders. Users reported a 40% reduction in the time required to prepare documentation, which they attributed to the system's streamlined workflows and automated formatting capabilities.

The digital analytics module offered robust tools for visualizing and analyzing environmental data. Thematic maps and trend analyses generated by the system enabled stakeholders to identify pollution hotspots and monitor changes over time. Feedback from pilot testing indicated that 85% of users found the interface intuitive and effective for decision-making. These tools significantly enhance the usability of the system for addressing real-world environmental challenges.

The integration of functional monitoring modules created a comprehensive solution for systematizing data on the environmental conditions of rocket booster drop zones. These modules successfully collected and processed information on natural and climatic conditions, pollution sources, and contamination levels in the affected territories. The modular architecture of the system ensured scalability, allowing for the addition of new functional components without requiring significant modifications to the existing infrastructure.

Advanced features such as multi-layered data storage improved the system's ability to analyze terrain comprehensively, offering better insights into environmental patterns and trends. Additionally, the inclusion of algorithms for entity classification on thematic maps enhanced the precision of environmental assessments, opening possibilities for designing intelligent "Smart Maps."

The experimental implementation confirmed the effectiveness of the selected architectural solutions. Centralized data flow management facilitated seamless interaction between system components and ensured the synchronization and relevance of data across all modules. The access control mechanisms provided secure management of user rights, further strengthening the system's reliability.

Future iterations of the system will aim to enhance the predictive capabilities of the monitoring modules by incorporating machine learning algorithms for identifying potential environmental risks. To improve responsiveness and accuracy, real-time data streams from IoT devices and satellite imagery will be integrated. These advancements will continue to position the system as a leading solution for geoinformation management and environmental monitoring.

5. CONCLUSIONS

This research has developed a modular geoinformation system (GIS) model for the environmental passportization of rocket booster drop zones. The proposed system effectively supports spatial data management and environmental monitoring processes, providing a reliable infrastructure for diverse environmental data handling.

The integration of advanced data processing modules has improved data upload, export, and exchange flexibility, while the digital analytics module offers robust visualization tools for identifying trends and pollution hotspots. Functional monitoring modules systematically collect and analyze critical data on natural and climatic conditions, pollution sources, and contamination levels, ensuring precise environmental assessments.

The modular architecture enhances the system’s scalability, enabling easy integration of new components without major modifications. Experimental results demonstrated a 35% reduction in processing errors and a 40% improvement in documentation efficiency, validating the system’s effectiveness in real-world applications.

Future work will focus on integrating predictive machine learning algorithms and real-time data streams from IoT devices and satellite imagery to further enhance the system's accuracy and responsiveness. These developments aim to establish the GIS model as a benchmark for environmental monitoring and sustainable management of ecologically sensitive regions.

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