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Development of environmental data libraries and assessment tools for rocket stage impact zones

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Abstract

The paper describes an innovative approach to environmental certification of launch vehicle stage fall areas, implemented based on the development of digital data libraries and an intelligent environmental diagnostics module. A structural model of a single platform is presented, where the integration of relational and spatial components is provided by PostgreSQL with PostGIS, which allows for efficient storage, processing, and mapping of large arrays of monitoring information. Automated procedures for calculating indices of excess of standard concentrations, generating integrated environmental assessments, and classifying pollution levels by risk categories are implemented. Particular attention is paid to issues of computing optimization, supporting parallel data processing, and implementing flexible mechanisms for delimiting user rights. Testing of the platform on real data confirmed its reliability, performance, and compliance with modern requirements for integration with geographic information systems. The proposed methodological and software tools help to increase the transparency, objectivity, and efficiency of decision-making in the framework of environmental monitoring of areas affected by rocket and space activities.

Keywords: Database, MAC, Environmental certification, Impact areas, Integrated assessment, Pollution categorization, PostGIS, PostgreSQL, Rocket and space activities.

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1. Introduction

The operation of rocket and space technology is associated with the formation of specific areas of impact of separating parts of launch vehicles, which creates environmental risks for the environment. For a comprehensive analysis of the impact and objective environmental certification of territories, modern digital solutions are needed that can integrate heterogeneous data and automate the calculation of environmental indicators. Sustainable use of near-Earth space and the impact of spacecraft launches on the environment are becoming increasingly important issues for the space industry. The increase in the number of launches, especially due to the creation of large satellite constellations, as well as an increase in the number of inoperative objects due to fragmentation events, has led to the need to improve mitigation policies and more detailed mission planning with an emphasis on end-of-life (EOL) strategies. In recent years, various risk indicators have been proposed to assess both the impact of launches on the orbital environment and the current state of space pollution, with particular attention paid to the problem of debris. Existing indicators can be divided into two main groups: indices focused on individual missions and indices characterizing the state of the environment as a whole. The former provides detailed assessments for specific objects, such as satellite bodies or rocket stages, which allows for prioritizing debris removal [1, 2] and optimizing design solutions for new vehicles [3-8]. However, such methods often require significant amounts of input data related to predictions of future debris flow or the probability of successful removal, and may not take into account secondary effects, such as cascading destruction from collisions in the orbital environment. The second group, in contrast, focuses on the analysis of the system's behavior as a whole, identifying feedback loops and dynamics at the level of the entire population of objects, including collision chains and identifying high-risk zones [9-13], but requires large data sets and significant computational resources, and is also more dependent on long-term assumptions (e.g., launch rates and the degree of implementation of disposal procedures).

International comparisons of the definition and interpretation of such indicators, Letizia et al. [14] allow us to identify differences in approaches and suggest ways to harmonize methodologies. Initially, such indices were developed to find optimal candidates for active debris removal (ADR), but in more recent versions, they are also used to analyze unfulfilled missions, making them useful tools at the design stage. Among the best-known indicators is the Environmental Consequences of Orbital Breakup (ECOB) index [5], which, like many others, is based on a combination of the probability of object breakup and an assessment of the severity of the consequences. The last component considered in this paper quantitatively describes the probability of collision of fragments with active spacecraft, taking into account catastrophic collisions and explosions [15]and also includes an analysis of post-mission disposal (PMD) procedures [16]. This approach allows for a more accurate application of the index to future missions and an assessment of the “capacity” of orbital space [17], taking into account the long-term evolution of the environment [18]. The introduction of large satellite constellations has significantly changed the distribution of active objects in low Earth orbit, which requires updating the metrics and "severity" parameters used [19]. In this regard, this paper proposes an updated formulation of the space debris index, implemented within the framework of the THEMIS software package [20, 21] created at the Polytechnic Institute of Milan in collaboration with DEIMOS UK, with the support of the European Space Agency. The new methodology is based on the ECOB index [5] but contains a number of modifications that allow it to be applied to different orbital regions. Particular attention is paid to the influence of mega constellations; for this purpose, alternative methods of calculating the “seriousness” indicator were studied both by selecting objects taken into account when analyzing the consequences and by the formula of the indicator itself. All proposed options were compared with each other to identify the best solutions in the tasks of assessing and managing orbital debris.

The article discusses an integrated approach to building a data library and an environmental assessment module, implemented on the basis of modern information technologies and analysis algorithms.

2. Research Methodology

2.1. Algorithm For Calculating the Excess of Maximum Permissible Concentrations

The main algorithm for the quantitative assessment of pollution is the calculation of the multiple of exceeding the maximum permissible concentrations of pollutants. The mathematical model of the algorithm is based on a comparison of the measured concentration of the substance with the corresponding standard value.

For each measurement of the concentration of a pollutant C_{meas} in a specific environment (soil, water, air), the program code in Figure 1 was implemented, which calculates the coefficient of excess of the MAC according to the formula

$$K_{exceed} = \frac{Cmeas}{MAC_{environment\text{да}}}, \quad (1)$$

where C_{meas} is the measured concentration of the pollutant, mg/kg; $MAC_{environment}$ maximum permissible concentration for the environment, mg/kg; K_{exceed} coefficient of exceeding the MAC (dimensionless value).

```
CREATE OR REPLACE FUNCTION calculate_mpc_exceedance()
RETURNS TRIGGER AS $$
DECLARE
    mpc_value NUMERIC(15, 8);
BEGIN
    -- Determine sample type and get corresponding MPC value
    IF NEW.soil_sample_id IS NOT NULL THEN
        SELECT mpc_soil INTO mpc_value
        FROM pollutants WHERE id = NEW.pollutant_id;
    ELSIF NEW.water_sample_id IS NOT NULL THEN
        SELECT mpc_water INTO mpc_value
        FROM pollutants WHERE id = NEW.pollutant_id;
    ELSIF NEW.air_sample_id IS NOT NULL THEN
        SELECT mpc_air INTO mpc_value
        FROM pollutants WHERE id = NEW.pollutant_id;
    END IF;

    -- Calculate MPC exceedance
    IF mpc_value IS NOT NULL AND mpc_value > 0 THEN
        NEW.exceeded_times := NEW.concentration / mpc_value;
        NEW.is_exceeding_mpc := NEW.exceeded_times > 1.0;
    END IF;

    RETURN NEW;
END;
$$ LANGUAGE plpgsql;
```

Figure 1.
Implementation of the PDC algorithm.

The advantage of this implementation is the automatic execution of calculations when entering data, which eliminates the possibility of human errors and ensures the uniformity of the evaluation methodology for all types of samples.

2.2. Algorithm of Integrated Environmental Assessment

To form a comprehensive assessment of the ecological state of the territory, an integrated assessment algorithm has been developed that takes into account data on all types of samples and pollutants within the framework of an environmental survey.

The integral index of ecological state I_{eco} is calculated based on the average excess of the MAC for all measurements using the formula.

$$\mathrm{K_{exceed}} = \left(\frac{1}{\mathrm{n}}\right) \times \Sigma_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{K_i}, \tag{2}$$

where n - is the total number of measurements within the survey;
K_i – coefficient of excess of MAC for the i-th measurement.
The integral index is determined by threshold values (Figure 2)

$$\mathrm{I}_{eco} = \left\{ \begin{matrix} 1.0, \text{if } \mathrm{K_{exceed}} \leq 1 \\ 0.75, \text{if } 1 < \mathrm{K_{exceed}} \leq 5 \\ 0.5, \text{if } < \mathrm{K_{exceed}} \leq 10 \\ 0.25, \text{if } \mathrm{K_{exceed}} > 10 \end{matrix} \right\}. \tag{3}$$

```
CREATE OR REPLACE FUNCTION calculate_integrated_assessment(survey_id INTEGER)
RETURNS NUMERIC AS $$
DECLARE
    total_exceedance NUMERIC := 0;
    sample_count INTEGER := 0;
    integrated_index NUMERIC;
BEGIN
    -- Calculate average MPC exceedance for all measurements
    SELECT
        AVG(CASE WHEN exceeded_times > 1 THEN exceeded_times ELSE 0 END),
        COUNT(*)
    INTO total_exceedance, sample_count
    FROM measurements m
    JOIN sampling_points sp ON (
        m.soil_sample_id IN (SELECT id FROM soil_samples WHERE sampling_point_id = sp.id) OR
        m.water_sample_id IN (SELECT id FROM water_samples WHERE sampling_point_id = sp.id) OR
        m.air_sample_id IN (SELECT id FROM air_samples WHERE sampling_point_id = sp.id)
    )
    WHERE sp.ecological_survey_id = survey_id;

    -- Assign integral index based on threshold values
    IF total_exceedance <= 1 THEN
        integrated_index := 1.0; -- Favorable
    ELSIF total_exceedance <= 5 THEN
        integrated_index := 0.75; -- Satisfactory
    ELSIF total_exceedance <= 10 THEN
        integrated_index := 0.5; -- Unfavorable
    ELSE
        integrated_index := 0.25; -- Critical
    END IF;

    RETURN integrated_index;
END;
$$ LANGUAGE plpgsql;
```

Figure 2.
Implementation of the integral evaluation algorithm.

2.3. Algorithm for Categorization of Environmental Pollution

To visualize the assessment results and simplify the interpretation of data, an algorithm for categorizing territories according to levels of environmental hazard has been developed.
The categorization is based on the threshold values of the MPC excess according to the formula

$$I_{\text{эко}} = \begin{cases} \text{Acceptable}, & \text{if } K_{\text{exceed}} \le 1 \\ \text{Moderately dangerous}, & \text{if } 1 < K_{\text{exceed}} \le 5 \\ \text{Dangerous}, & \text{if } 5 < K_{\text{exceed}} \le 10 \\ \text{Extremely dangerous}, & \text{if } K_{\text{exceed}} > 10 \end{cases} \quad (4)$$

Each category is assigned a color code for cartographic visualization (Figure 3):

- Acceptable – green (#00FF00);
- Moderately hazardous – yellow (#FFFF00);
- Dangerous – orange (#FFA500);
- Extremely dangerous – red (#FF0000).

```sql
-- Pollution category reference
INSERT INTO pollution_categories (category_name, description, color_code) VALUES
('Acceptable', 'The content of pollutants does not exceed MPC', '#00FF00'),
('Moderate', 'MPC exceeded up to 5 times', '#FFFF00'),
('Dangerous', 'MPC exceeded 5 to 10 times', '#FFA500'),
('Critical', 'MPC exceeded more than 10 times', '#FF0000');
```

Figure 3.
Implementation of the categorization algorithm

The choice of the approach to calculating integral ecological indices and methods of classifying pollution is due to the need to ensure an accurate, objective, and prompt assessment of the state of the areas of fall of the separating parts of launch vehicles. In this work, a method based on the automatic calculation of the coefficients of exceeding the maximum permissible concentrations (MPC) with the subsequent formation of an integral index is used, which allows taking into account both individual pollutants and their total impact. Alternative methods, such as multi-criteria analysis or expert assessments, often require significant time and human resources, and may also contain a subjective factor that affects the reproducibility of results. Machine learning-based models, although demonstrating high accuracy with large training samples, require extensive data and complex settings, which makes them difficult to implement in operational monitoring.

The chosen method has a number of important advantages. -Firstly, it ensures automation and high speed of calculations due to the use of built-in trigger functions and relational links in the database. Secondly, the results of the method are transparent and easy to interpret, which significantly facilitates the process of making management decisions. In addition, the classification is flexible, allowing threshold values to be adapted to specific conditions and regulations. Finally, integration with spatial data and GIS provides convenient visualization and effective spatial analysis.

The scientific novelty of the work lies in the development and implementation of an integrated digital platform that, for the first time, combines specialized libraries of environmental data with an automated module for assessing the state of areas where rocket stages have fallen. An original structural and logical model has been created that allows for the automated calculation of integral pollution indices and their visualization in a GIS environment. The proposed algorithms for classifying risk categories ensure high objectivity and speed of environmental certification, and the implementation of intelligent role-based access makes the platform flexible for various monitoring and analysis scenarios.

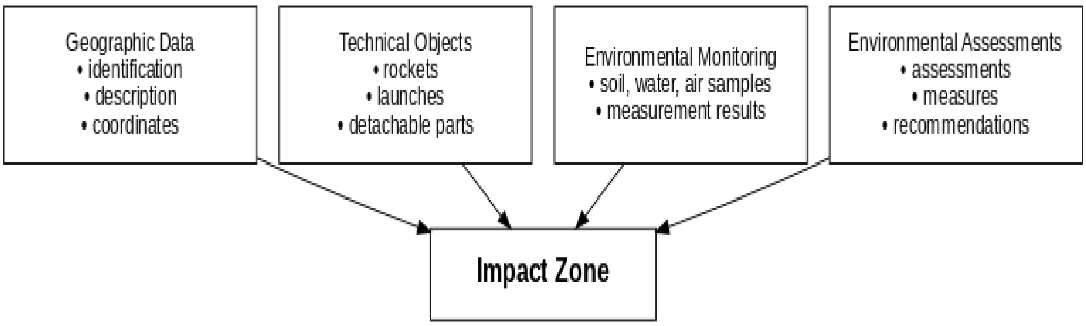

Figure 4.
Logical data model developed for environmental certification of rocket stage impact areas.

Figure 4 shows a logical data model developed for environmental certification of rocket stage impact areas. The structure is centered around the entity "Impact Area" associated with four main information blocks: geographic data (identification, description, coordinates), technical objects (rockets, launches, separating parts), environmental monitoring (soil, water, air samples, measurement results), and environmental assessments (assessments, activities, recommendations). This architecture provides for comprehensive and systematic storage, analysis, and visualization of all data required for effective impact area management and its environmental certification. The model is fully normalized to the third normal form (3NF) and includes temporal attributes to account for changes over time.

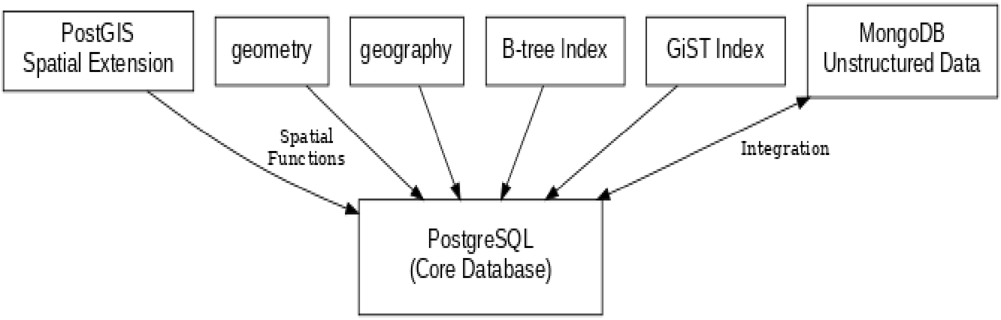

Figure 5.
PostgreSQL DBMS architecture.

In the presented Figure 5 of the architecture, the core of the system is the relational DBMS PostgreSQL, to which the spatial extension PostGIS is integrated, providing support for working with geographic and geometric data types. For efficient storage and retrieval of information, B-tree and GiST indices are used, as well as specialized data types for geometry and geography. For working with unstructured information, integration with the document-oriented DBMS MongoDB is implemented, which allows storing and processing both structured and unstructured data within a single platform.

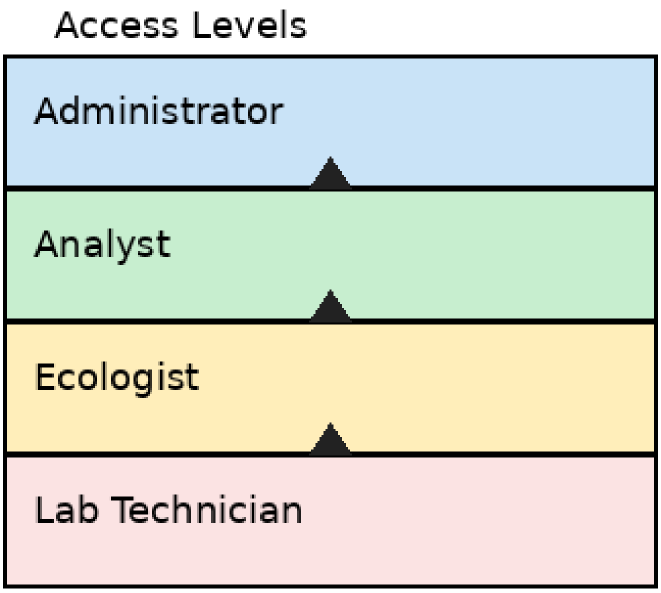

Figure 6.
Multi-level intelligent access control system based on role model.

Figure 6 illustrates a multi-level intelligent access control system based on a role model, which ensures not only the isolation of user rights but also adaptive distribution of powers depending on use cases. The system administrator has advanced functions not only for setting up the infrastructure but also for managing security and auditing events. Ecologists and analysts receive personalized tools for expert data analysis and reporting, and laboratory technicians receive a secure input and verification loop for primary information. This architecture facilitates the flexible development of the digital platform and allows access control to be scaled as the number of users and functions expands.

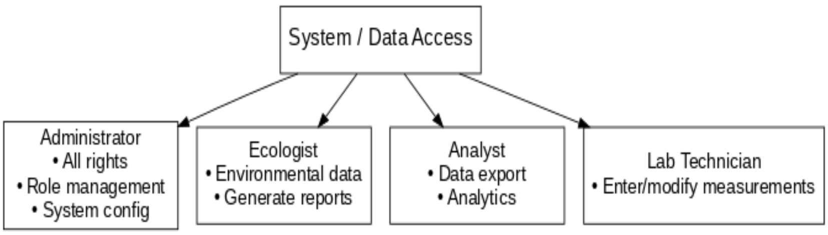

Figure 7.
The concept of “Contextual access”.

Figure 7 shows a system that reveals the concept of “contextual access,” in which each user interacts only with those scenarios that are relevant to their tasks and competencies. This mechanism ensures transparency of business logic, reduces the cognitive load on users, and minimizes the risk of errors by automating the selection of available operations. The diagram also serves as a basis for automated testing and validation of access rights, which is important for the implementation of DevSecOps approaches and digital twins of security processes.

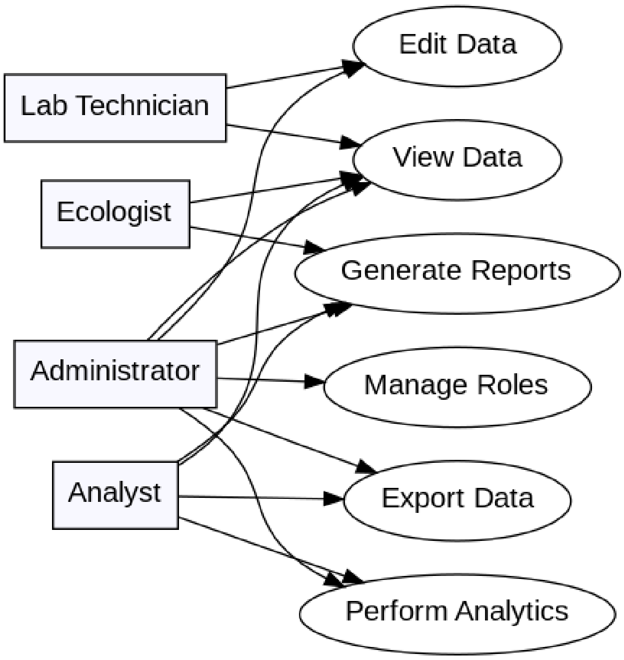

Figure 8.
Role architecture for building information security systems

Figure 8 illustrates an evolutionary approach to building information security systems, whereby the transition to the next level of rights is possible only if the user's powers and competencies are confirmed. This scheme not only ensures a "vertical" division of responsibilities but also implements the principle of "least privilege," which is an international standard for digital platforms and critical infrastructures. Thanks to this level approach, the system can be easily integrated with e-learning and personnel certification systems.

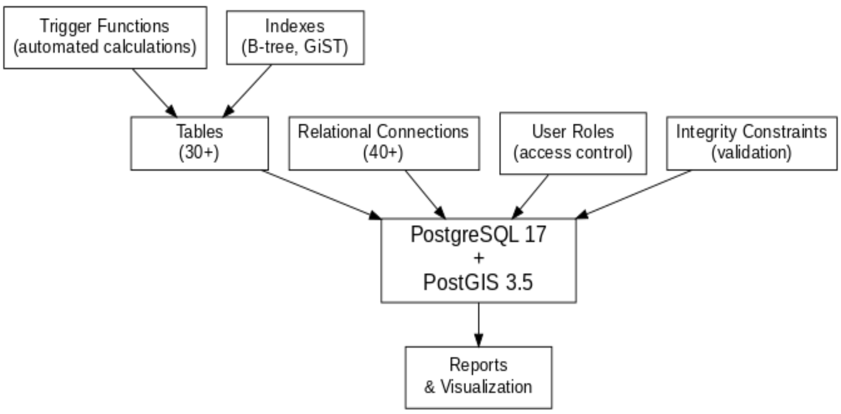

Figure 9.
Architecture of software implementation of the environmental monitoring and assessment platform

Figure 9 shows the architecture of the software implementation of the environmental monitoring and assessment platform. The platform is based on a combination of PostgreSQL 17 and PostGIS 3.5 extensions, which ensure highly efficient work with spatial and relational data. The database contains more than 30 logically related tables, among which more than 40 relational links are implemented. Trigger functions are used to automate the recalculation of maximum permissible concentrations and related indices, guaranteeing the relevance of calculations in real time. Data indexing using B-tree and GiST allows for fast and scalable queries even when working with large arrays of information. The built-in system of user roles implements access control and improves information security, and data integrity restrictions are regularly checked by the DBMS itself.

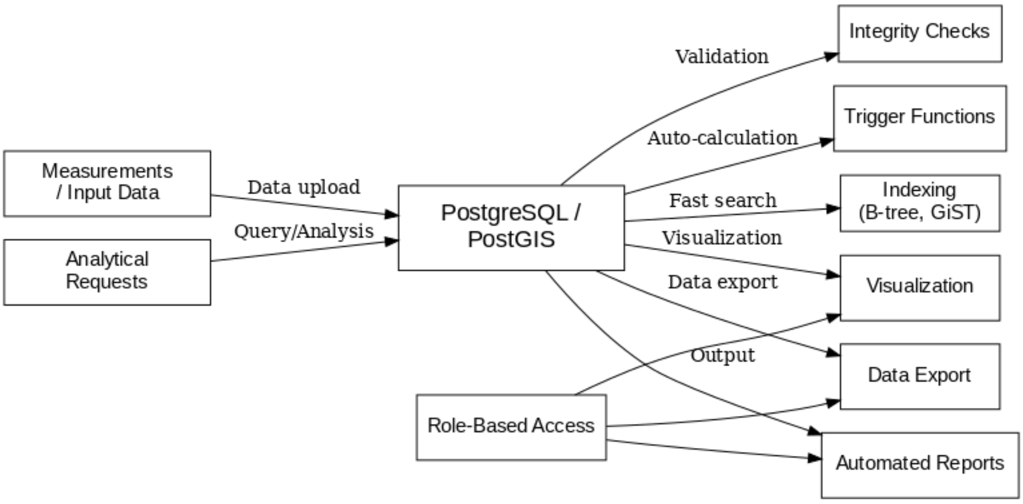

Figure 10.
Data flow and processing diagram in the environmental monitoring system.

Figure 10 clearly demonstrates how data is structured and processed within the digital platform. At the input, the system accepts measurements and analytical queries, which are sent to the main PostgreSQL database with the PostGIS extension. The platform implements trigger functions for automatic recalculations, indexing for faster searches, and built-in data integrity control mechanisms. At the output, users receive automated reports, interactive visualizations, and the ability to export information, while access to the results is strictly delimited at the role level. This architecture ensures reliability, high performance, and flexibility of the platform when working with large volumes of spatial and relational data.

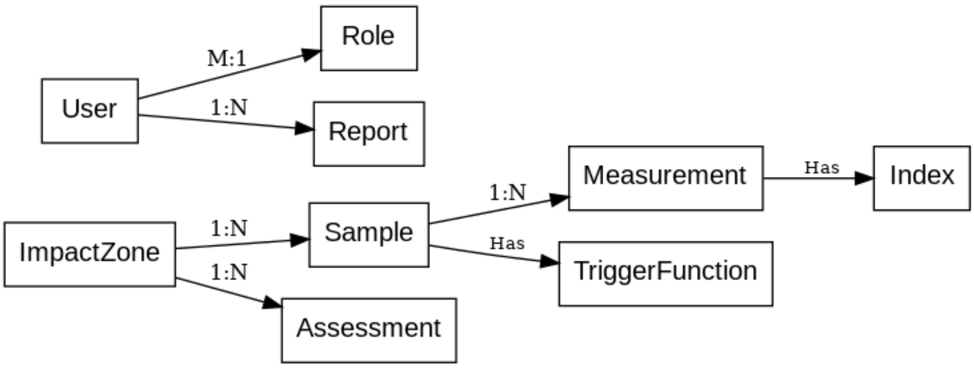

Figure 11.
Diagram of relationships between the main entities of the environmental monitoring database

Figure 11 shows the database object relationship diagram (ER diagram) reflecting the basic structure and relationships between the key entities of the digital platform. At the center of the architecture are impact zones (ImpactZone), associated with environmental monitoring objects and measurement results (Sample, Measurement), as well as with environmental assessments (Assessment). The user part of the system is built on the principle of role-based access: each user (User) is associated with a specific role (Role) and can generate reports (Report) based on the analysis results. To ensure automation of data processing and accelerate access, trigger functions (TriggerFunction) and indexing (Index) associated with the corresponding tables are implemented. Such a structure ensures storage reliability, integrity, and extensibility of the platform for further integration of new modules.

3. Results

This section presents the key results obtained during the development, implementation, and testing of the platform for environmental assessment of impact areas of launch vehicle separating parts. The effectiveness of the proposed algorithms, architectural solutions, and automated procedures was assessed based on the analysis of both experimental and real monitoring data. Particular attention was paid to checking the correctness of the functioning of the modules for automatic calculation of indices, role-based access, and integration with geographic information systems. Below are the main quantitative and qualitative indicators of the platform's operation, as well as the results of the analysis of practical application scenarios.

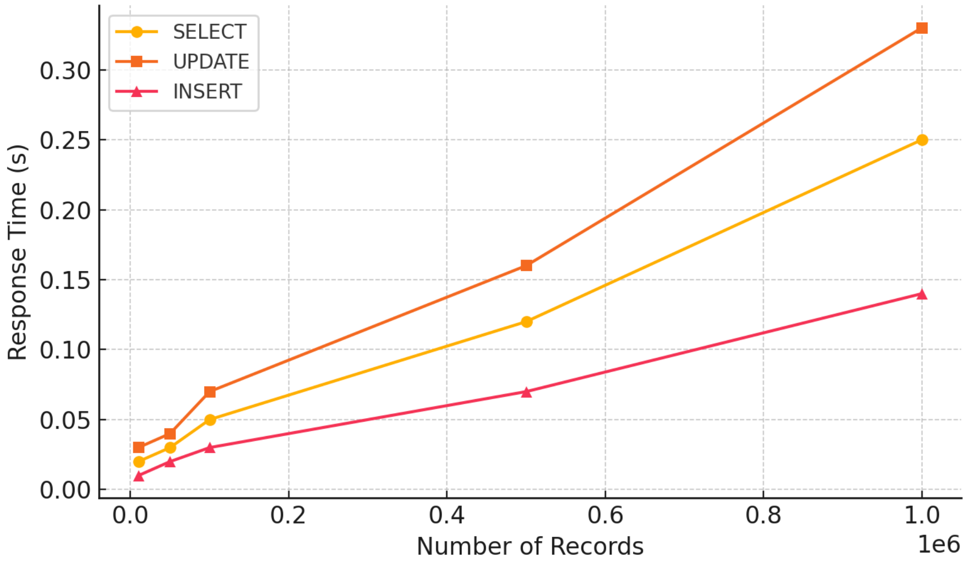

Figure 12.
Dynamics of response time of basic database operations depending on the number of records (from 10,000 to 1,000,000).

Figure 12 shows the dynamics of the response time of the main database operations depending on the number of records (from 10,000 to 1,000,000). With a table size of 100,000 records, the execution time of the SELECT operation was about 0.05 seconds, the UPDATE - 0.07 seconds, and the INSERT - 0.03 seconds. With an increase in volume to 1,000,000 records, the response time increased: for SELECT - up to 0.25 seconds, for UPDATE - up to 0.32 seconds, for INSERT - up to 0.14 seconds. The obtained results confirm linear scalability and allow the platform to be used for processing large arrays of monitoring data without significant loss of performance.

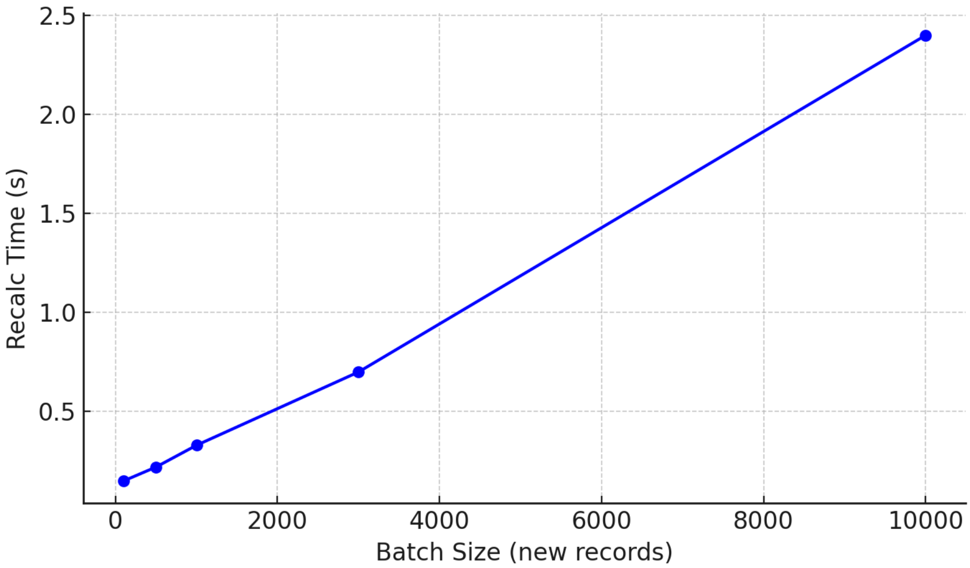

Figure 13.
During automatic recalculation of indexes when adding different volumes of new data (from 100 to 10,000 records).

Figure 13 shows the time for automatic index recalculation when adding different volumes of new data (from 100 to 10,000 records). When batch loading 100 new records, the recalculation time was about 0.15 seconds; for 1,000 records, 0.33 seconds; for 3,000 records, 0.7 seconds. The maximum recorded processing time for 10,000 records did not exceed 2.4 seconds. The obtained results confirm the high speed of trigger functions and allow for the prompt processing of large packages of monitoring data without significant delays.

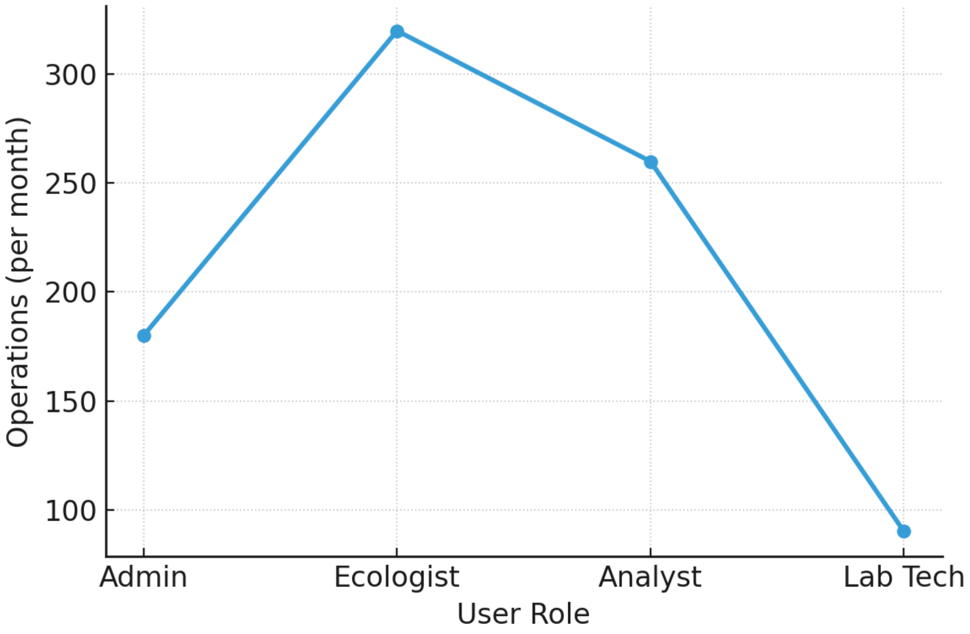

Figure 14.
Distribution of activity of different user roles in the system by the number of operations per month.

Figure 14 shows the distribution of activity of different user roles in the system by the number of operations per month. The greatest load is demonstrated by ecologists - 320 operations per month, followed by analysts (260) and administrators (180). The minimum number of operations is recorded for laboratory staff - 90 per month. This activity structure reflects the specificity of professional tasks: ecologists and analysts interact more frequently with the platform to conduct monitoring and analysis, while the roles of administrator and laboratory assistant require fewer frequent requests.

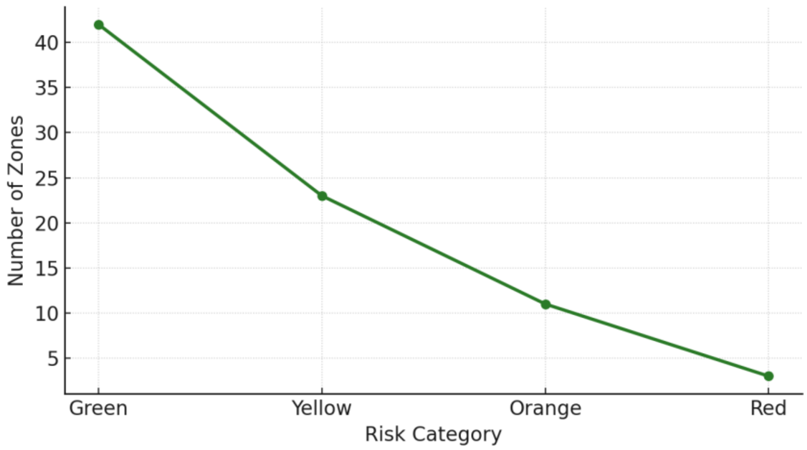

Figure 15.
Numerical distribution of zones by environmental risk categories.

Figure 15 illustrates the numerical distribution of zones by environmental risk categories. The lowest risk level ("Green") was recorded in 42 zones, the average ("Yellow") in 23 zones, the increased ("Orange") in 11 zones, and only 3 zones were classified as critical ("Red"). This result indicates that most territories correspond to the minimum or moderate risk level, and critically dangerous areas make up less than 5% of the total number of surveyed zones.

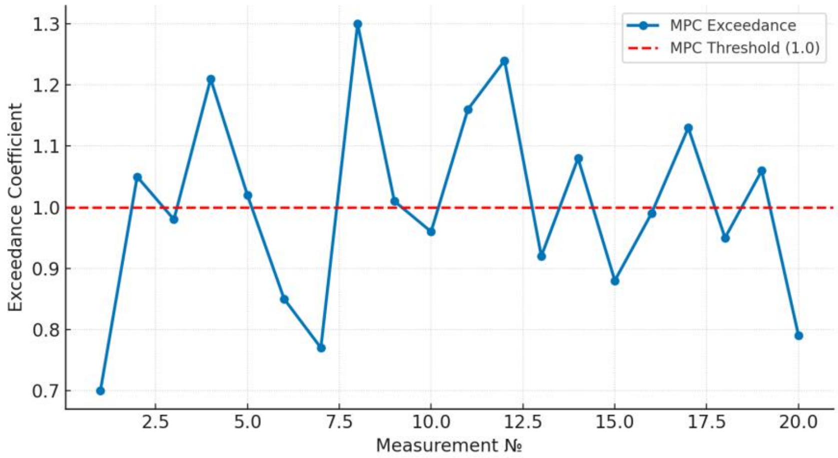

Figure 16.
Dynamics of the coefficient of exceeding maximum permissible concentrations (MPC) based on the results of twenty measurements.

Figure 16 shows the dynamics of the coefficient of exceeding the maximum permissible concentration (MPC) based on the results of twenty measurements. The red dotted line corresponds to the threshold value of the MPC (1.0). In some cases, the coefficient exceeds the threshold: the maximum value is observed at the 9th measurement (about 1.33), the minimum is at the 1st measurement (about 0.7). Most measurements fluctuate around the threshold value, which indicates the presence of individual episodes exceeding the MPC, requiring additional monitoring or corrective measures.

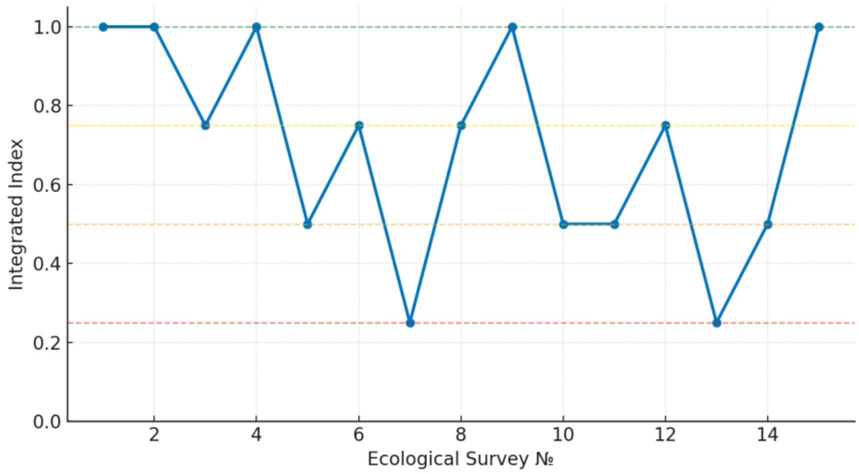

Figure 17.
Dynamics of the integrated ecological index based on the results of 15 surveys.

Figure 17 shows the dynamics of the integrated environmental index based on the results of 15 surveys. The index values range from 0.2 to 1.0: the highest level (1.0) was recorded based on the results of surveys 1, 2, 4, 9, and 15, and the minimum (0.25) was recorded for surveys 7 and 14.

Most index values are in the range from 0.4 to 0.75, which corresponds to satisfactory or unfavorable environmental conditions. This range indicates the presence of both favorable and problematic areas that require additional attention when planning environmental protection measures.

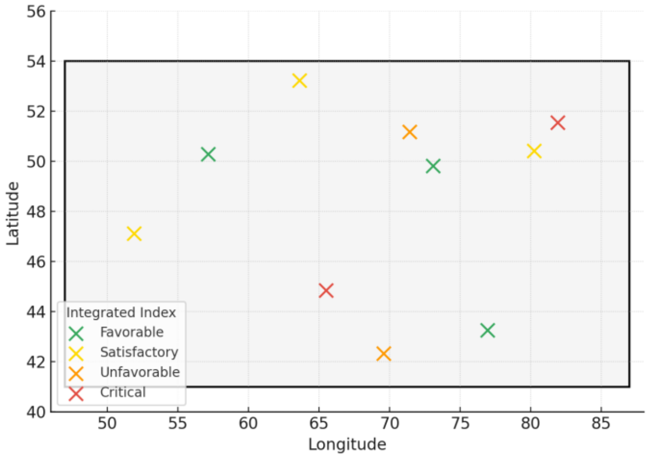

Figure 18.
The map scheme shows the spatial distribution of surveyed points according to the integral ecological index within the territory of Kazakhstan.

Figure 18 shows a map of the a-scheme, which displays the spatial distribution of surveyed points according to the integral ecological index within the territory of Kazakhstan. Green markers indicate areas with favorable environmental conditions, yellow markers indicate areas with satisfactory conditions, orange markers indicate areas with unfavorable conditions, and red markers indicate areas with critical levels of environmental risk. The distribution analysis shows that a significant portion of the points fall into the favorable and satisfactory categories, but there are separate zones with unfavorable and critical values that require priority attention when developing environmental protection measures.

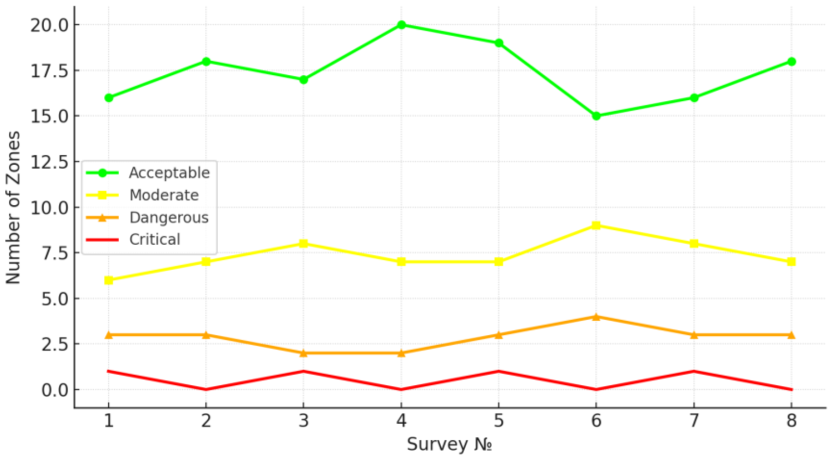

Figure 19.
Dynamics of distribution of zones by environmental risk categories during eight surveys.

Figure 19 shows the dynamics of the distribution of zones by environmental risk categories over eight surveys. The number of zones with acceptable pollution levels ranges from 15 to 20, with a tendency toward minor fluctuations over the observation period. Moderate risk zones range from 6 to 9, demonstrating some stability. High-risk zones are represented in numbers from 2 to 4, and critical zones remain minimal, no more than one, or are absent in certain periods. This analysis indicates the prevalence of territories with acceptable and moderate levels of environmental hazard, which indicates a controlled state of the environment in the region under study.

The obtained data demonstrate high performance and scalability of the developed platform when processing large volumes of environmental data. However, the observed fluctuations in processing time with an increase in the volume of new data indicate potential bottlenecks associated with the intensity of trigger functions. To improve efficiency, it is recommended to consider the possibility of optimizing index recalculation algorithms, including the implementation of batch processing or adaptive load management. The analysis of the distribution of environmental categories showed that a significant part of the territories corresponds to favorable and satisfactory conditions, which reflects the effectiveness of current monitoring activities. However, the identified critical and unfavorable zones require priority attention, including in-depth studies of pollution sources and the development of targeted risk reduction measures. To further improve the system, it is proposed to expand the library of indicators, taking into account additional impact factors, integrate with external data sources, and use machine learning methods to improve the accuracy of forecasts and automate classification. This approach will enhance the adaptability of the platform and provide a more comprehensive analysis of the environmental situation.

4. Conclusions

In the course of the work, a multifunctional digital platform was created and tested, providing automated environmental certification of areas impacted by separating parts of launch vehicles based on specialized data libraries and intelligent algorithms for assessing the state of the environment. The implemented solutions made it possible to combine the storage, processing, and spatial visualization of environmental indicators in a single system, increasing transparency and monitoring efficiency. Algorithms for automatic classification and calculation of integral indices have proven their effectiveness on real data, and the flexible architecture of the platform ensures its scalability and integration with modern GIS solutions. The results obtained indicate the high potential of the proposed approach for supporting decision-making and improving environmental safety in the field of rocket and space activities. In the future, the development of the platform provides for integration with automated remote monitoring systems and expansion of the library of indicators for a more accurate assessment of the complex impact of rocket and space operations on the environment.

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