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Using geographic information systems to improve the efficiency of healthcare management and ensure the sanitary and epidemiological well-being of the population

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Abstract

Assessing public health risks—shaped by natural, climatic, anthropogenic, socio-economic, and technological factors—demands innovative tools for risk prediction, scenario analysis, and proactive decision-making. Geographic information systems (GIS) have emerged as a transformative technology in healthcare management, enabling spatial analysis of environmental hazards, disease patterns, and demographic trend. Their integration with machine learning (ML) and artificial intelligence (AI) has further enhanced predictive capabilities, allowing for real-time monitoring of epidemiological threats and targeted resource allocation. Implementing such solutions demands substantial investments and regulatory updates, highlighting the need for public-private partnerships to overcome financial and legal barriers.
While the potential application of GIS in public health is immense, practical implementation faces technical, ethical, and operational hurdles. These challenges are exacerbated by the lack of standardized protocols for data sharing and the slow adoption of innovation in bureaucratic systems. Addressing these issues requires not only technological advancements but also systemic changes in policy and governance. This article explores the prospects of GIS in public health, discusses key challenges, and shares insights from developing a geospatial health information system.

1. Introduction

The assessment of public health risks, under the impact of various natural, climatic, anthropogenic, socio-economic factors, biohazards, and factors associated with new technologies, requires innovative technologies for risk assessment, scenario analysis, and forecasting, as well as timely and proactive response.

The rapid implementation of GIS in public health has been driven by three key advantages:

- Computational power. Currently technological advancements and the reduced expense of computational resources allow for the measurement, storage, and compilation of various environmental and health indicators into extensive datasets. Cloud-based platforms and high-performance computing enable processing of large-scale geospatial datasets, such as satellite imagery and IoT sensor networks.

- Interdisciplinary collaboration. Interconnection of environmental science, epidemiology, and urban planning could expand GIS applications, from tracking health impacts related to air pollution to optimizing emergency response.

- Policy integration. Governments increasingly recognize GIS as a tool for evidence-based policymaking. For example, the European Environment Agency utilizes GIS to map climate-related health vulnerabilities (European Environment Agency, 2022), and World Health Organization launches Geolocated Health Facilities Data initiative (WHO, 2022). These examples demonstrate GIS's global relevance, but their success depends on local adaptability and stakeholder engagement.

Beyond these, the growing availability of open-source GIS tools and crowd-sourced data (e.g., from mobile apps) is democratizing access to geospatial analytics. However, this also raises concerns about data accuracy and privacy, necessitating robust validation frameworks.

2. Challenges in Public Health Information Systems

The integration of advanced technologies into public health systems faces significant barriers that hinder effective decision-making and proactive interventions. These barriers are not unique to healthcare; similar challenges exist in urban planning and environmental management. A systemic approach-combining technology, governance, and education is essential for progress. Below is an expanded analysis of key unresolved issues.

2.1 Fragmentation of Databases

Data collected through departmental monitoring systems (e.g., hospitals, environmental agencies) often exist in isolated silos with incompatible formats. This fragmentation mirrors the "silo mentality" prevalent in many organizations, where departments prioritize autonomy over collaboration. Breaking these silos requires incentivizing data sharing, perhaps through policy mandates or funding tied to interoperability standards. This issue leads to situations where crucial information is isolated within different departments, making it difficult to obtain a comprehensive view of the problem. For instance, health data from hospitals may not be integrated with environmental monitoring data, hindering the ability to assess the impact of environmental factors on public health. This disconnect is particularly problematic in regions with high industrial activity, where pollution-related health risks are understudied due to lack of integrated data.

2.2 Lack of Interdepartmental Data Centres and Big Data Tools

The absence of centralized platforms for data sharing and analysis prevents effective collaboration between different government agencies and research institutions. Cloud-based solutions could bridge this gap, but concerns about data sovereignty and cybersecurity often stall their adoption. This gap also includes the lack of advanced analytical tools that could process large datasets in real-time, as highlighted in recent studies on big data in public health management [Dolley, 2018]. Tools like Google Earth Engine offer scalable solutions, but their complexity necessitates training programs for public health professionals to leverage them effectively.

2.3 Absence of GIS- and AI-Driven Digital Products

The technologies based on geoinformation technologies, machine learning, and artificial intelligence for the analysis and timely forecasting of potential risks associated with environmental and socio-economic factors could significantly enhance predictive analytics, enabling more accurate forecasting of health risks and facilitating proactive decision-making. For example, AI-driven systems could analyse real-time environmental data to predict pollution-related health risks in specific areas. But the "black-box" nature of AI models often discourages trust among policymakers, underscoring the need for explainable AI techniques.

2.4 Shortage of Interdisciplinary IT Specialists

The lack of professionals who understand both the technical aspects of data management and the specific requirements of environmental and health monitoring creates a significant barrier to implementing advanced digital solutions. This gap is further exacerbated by the rapid evolution of relevant technologies. This skills gap reflects a broader educational disconnect; universities rarely offer hybrid programs in geospatial health analytics. Partnerships between academia and industry, could help cultivate this niche expertise.

2.5 Additional difficulties and possible solutions

Additional difficulties include:

- Inadequate tracking mechanisms for monitoring changes in the levels of harmful factors over specific periods. Current systems often rely on periodic sampling rather than continuous monitoring, leading to potential gaps in data collection and analysis.

- Over-reliance on aggregated reporting forms, primarily annual reports, which do not allow for detailed consideration of data at the local or individual level for health status assessment.

- Technological limitations in data processing and storage capacities, which restrict the ability to handle large volumes of real-time data from various sources efficiently [Dash, 2019].

To address these challenges, several solutions should be considered:

- Developing integrated data platforms that enable seamless data sharing and analysis across different departments and sectors.

- Implementing advanced analytics tools based on machine learning and AI to enhance predictive capabilities and support decision-making.

- Establishing training programs to develop interdisciplinary skills among IT professionals and domain experts.

- Investing in real-time monitoring systems to track environmental and health indicators continuously.

- Creating local-level data dashboards that provide granular insights for targeted interventions and personalized health assessments.

3. Digital platform "Digital Twin of the Human Environment"

To develop a system capable of assessing the impact of environmental factors on health and demographic indicators of the population, a consortium has been established with participation of Kazan State Medical University, the Ministry of Health and Rospotrebnadzor of the Republic of Tatarstan, as well as the development of the digital platform "Digital Twin of the Human Environment" has been initiated".

Rospotrebnadzor (the Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing) is a governmental body in the Russian Federation responsible for oversight and regulation in the spheres of sanitary-epidemiological welfare and consumer rights protection. Its primary objective is to safeguard public health in matters pertaining to the consumption of goods and services, as well as to enforce compliance with sanitary regulations. Due to its institutional focus, Rospotrebnadzor primarily addresses infectious diseases and sanitary monitoring, whereas the surveillance of non-communicable diseases (NCDs) necessitates interagency collaboration, enhanced analytical capabilities, and preventive strategies. A key challenge for Rospotrebnadzor lies in establishing causal relationships between NCDs and environmental determinants.

The Ministry of Health of the Russian Federation serves as the executive authority tasked with formulating and implementing state policy in healthcare, medical services, pharmaceuticals, sanitary-epidemiological welfare, and medical education. Its principal functions include organizing healthcare delivery, patient treatment, disease prevention, pharmaceutical provision, and the training of medical professionals. At present, the Ministry of Health bears the primary responsibility for combating NCDs; however, the effectiveness of interventions remains constrained in the absence of a comprehensive, multisectoral approach.

Challenges in NCD prevention, incidence forecasting, and healthcare resource planning stem from the multifactorial etiology of these diseases. NCDs arise from a complex interplay of determinants, including environmental exposures, occupational hazards, dietary habits, psychosocial stress, and genetic predisposition, complicating the identification of specific causative factors. Furthermore, the lack of longitudinal epidemiological studies - unlike those conducted in the EU or the U.S. - hinders the assessment of environmental influences on population health in Russia.

Kazan State Medical University operates within the sphere of influence of both institutions, as it educates medical professionals for the Ministry of Health and Rospotrebnadzor while also conducting scientific research on environmental health risks. In response to these challenges, we have established a consortium and initiated the development of a digital platform to address these pressing issues.

The characterization of atmospheric air pollution levels will be derived from comprehensive monitoring data on the concentrations of various chemical pollutants, including suspended particulate matter (PM), nitrogen dioxide (NO_2), carbon monoxide (CO), soot, sulfur dioxide (SO_2), formaldehyde, benzene, saturated hydrocarbons, and others, in total 19 pollutants. Since 2014, Rospotrebnadzor has conducted systematic surveillance of hazardous substances in the atmospheric air of the Republic of Tatarstan, utilizing both automated and manual dust analyzers at 43 designated observation stations.

Additionally, data from 10 monitoring stations operated by the Federal State Budgetary Institution "Department of Hydrometeorology and Environmental Monitoring of the Republic of Tatarstan" will be incorporated to account for meteorological variables, including weather conditions, wind patterns, humidity, and atmospheric pressure in the study areas. Long-term health effects—such as mortality rates and the primary incidence of chronic non-communicable diseases—will be assessed using annual average and maximum pollutant concentrations. Conversely, short-term health impacts, including hospitalization episodes and acute health conditions, will be evaluated based on daily average and peak concentrations of harmful substances and aerosols.

Key factors influencing the relationship between air quality and public health include climatic and geographical conditions, urban density, land use characteristics, vehicular traffic load, co-exposure to multiple air pollutants, and individual risk factors. Data on urban planning and land use will be sourced from the Institute of Spatial Planning of the Republic of Tatarstan, while traffic load assessments will rely on information from the automated traffic management system maintained by the State Budgetary Institution "Road Safety".

Within a 1-kilometer radius of air quality monitoring stations, epidemiological data will be collected on:
- newly diagnosed cases among adults (18–65 years),
- hospital admissions of individuals (≥18 years) for: respiratory diseases (upper respiratory tract infections, pneumonia, chronic obstructive pulmonary disease, respiratory neoplasms, acute respiratory viral infections), cardiovascular diseases (acute coronary syndrome, cerebrovascular accidents), endocrine disorders (diabetes mellitus, obesity, thyroid diseases).

These health records will be extracted from the Republican Medical Information and Analytical Center (RMIAC) database (https://rmiac.tatarstan.ru), part of the Republic of Tatarstan’s Ministry of Health. Case data are generated through physician entries in the Medical Information System (MIS) upon patient consultations or confirmed diagnoses. The MIS database contains anonymized patient demographics (age, sex, residential microdistrict), social and occupational status, medical history, treatment records, and comorbidities. For geospatial linkage to air quality monitoring points, residential microdistrict data will be retained while ensuring patient confidentiality.

3.1 Platform structure

The platform includes the following main components: Information-Analytical System "Data Aggregator", Information-Analytical System "Environment and Public Health", Digital Educational Platform.

3.1.1 Information-Analytical System "Data Aggregator": This system will have the following modules.

Data import module (Data Ingestion)

This module is responsible for receiving, parsing and primary processing of data from various sources. It provides flexibility by supporting multiple formats and protocols, as well as reliability due to validation and failure recovery mechanisms.

It is planned to import to various data sources:
- files: CSV, JSON, XML, Excel, Parquet,
- databases: SQL (PostgreSQL, MySQL), NoSQL (MongoDB, Elasticsearch),
- API and web services: for example, weather API, transport services,
- medical systems: electronic medical record data.

Currently, a file loader of various formats has been implemented for the following data for any time period: air quality analysis data for harmful substances and suspended particles, death cases, infectious and non-infectious disease cases, hospitalization cases (Figure 1.).

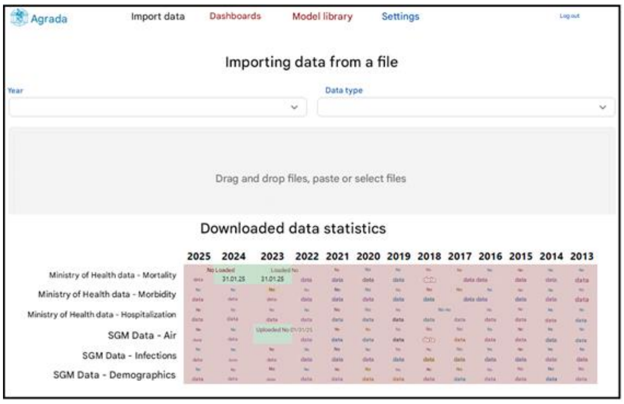

Figure 1. Example of working with the Data import module

The module is also responsible for data parsing and normalization: automatic data structure detection, conversion to a single internal format, processing of nested structures (e.g. medical reports with a hierarchy). At this stage, the information must be validated and error-handled: checking for compliance with the schema (e.g. mandatory fields in medical data), logging and notifications about problematic data, the ability to manually correct it through the administrative panel. It is mandatory to implement saving information about the source, download time, and version of the data.

Data Preprocessing Module

This module cleans, transforms, and enriches data before loading it into storage. It is critical to ensure the quality and consistency of the data. Main functions: removing duplicates (e.g. repeated records from sensors), filling gaps (median value, interpolation), filtering anomalies (statistical methods, ML models).

Geospatial Processing Module

Provides work with geodata. Designed for geocoding and reverse geocoding: converting an address to coordinates (and vice versa) via open APIs. The module should be able to perform the following spatial operations: searching for objects within a radius (e.g. places of residence of people near a pollution source), routing (the shortest route taking into account traffic jams), clustering (identifying "hot spots"). Integration with GIS should be provided to implement visualization at subsequent stages.

Data Storage Module

This is a unified storage for all types of data with support for fast access and scalability. The main requirements for this module: using structured data (SQL), replication and backup of data in the archive.

These 4 modules form the core of the system, providing flexible data collection, cleanliness and consistency, spatial context, and secure storage. This system will feature an expandable architecture capable of importing new data, geoinformation referencing, an interactive user interface, as well as modules for data preprocessing, query formation, dataset generation, preliminary analysis using known frequency and neural network algorithms.

3.1.2 Information-Analytical System "Environment and Public Health": The Information-Analytical System (IAS) "Environment and Public Health" is a data-driven, platform designed to assess, predict, and mitigate environmental health risks through advanced computational modeling. By integrating real-time environmental monitoring, health registries, and geospatial analytics, the system enables evidence-based decision-making in public health, environmental policy, and urban planning.

Core Components of the System

1. Risk Assessment Models. Purpose: Quantify the impact of environmental factors (air/water/soil pollution, noise, radiation) on population health.

Models will be based on the following methodology:

Exposure-Response Modelling: Uses geocoded health and pollution data to estimate disease risks (e.g., asthma from PM2.5, cancer from benzene).

Population Vulnerability Scoring: Identifies high-risk groups (children, elderly, chronic patients) using demographic and medical data.

Toxicological & Epidemiological Integration: Combines dose-response curves with real-world exposure data.

We have begun using the first models to assess mortality and morbidity in a specific area of the Republic of Tatarstan and the relationship with concentrations of individual pollutants in the air (Figure 2).

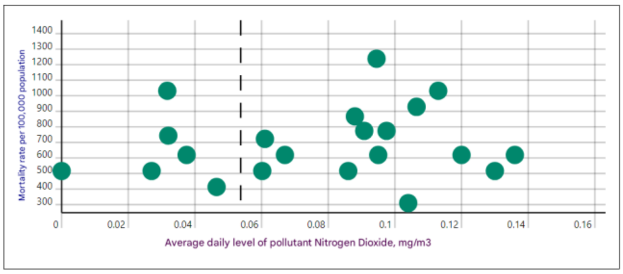

Figure 2. Example of visualization of the results of the model for mortality risk assessment

2. Scenario Analysis & Forecasting

What-if Simulations: Tests policy impacts (e.g., "How would a 20% reduction in industrial emissions affect respiratory disease rates?").

Climate Change Adaptation: Models long-term shifts (e.g., heatwave mortality, vector-borne disease spread).
Machine Learning Predictions: Forecasts outbreaks (e.g., COPD hospitalizations during smog seasons) using time-series analysis.

3. Model Training & Validation

Continuous Learning: Retrains algorithms with incoming data (e.g., new pollution sensors, EHR updates).

Bias & Uncertainty Quantification: Ensures robustness across diverse populations.

Benchmarking: Compares predictions against historical outcomes for accuracy checks.

4. Decision Support Systems (DSS)

Policy Optimization: Recommends interventions (e.g., traffic rerouting, green space allocation) based on cost-benefit analysis.

Early Warning Alerts: Flags emerging risks (e.g., toxic spills, pollen peaks) for preemptive action.

Urban Planning Tools: Evaluates health impacts of infrastructure projects (e.g., factories, highways).

The IAS "Environment and Public Health" transforms raw data into actionable intelligence, bridging the gap between environmental science and public health practice. By automating risk detection and policy testing, it empowers leaders to proactively safeguard communities—turning reactive crisis management into preventive, precision public health.

3.1.3 Digital Educational Platform: The digital educational platform is designed to foster the development of comprehensive educational modules and advanced digital simulators, equipping learners with critical competencies in utilizing information resources related to sanitary and epidemiological well-being. Beyond foundational knowledge, the platform integrates cutting-edge disciplines such as geoinformation technologies (GIS), machine learning (ML), and artificial intelligence (AI), enabling users to develop sophisticated algorithms and computer programs tailored to public health applications.

Key Features and Innovations:
Interdisciplinary Competency Development.
The platform goes beyond traditional training by incorporating predictive analytics and risk assessment tools, allowing users to analyze environmental and socio-economic factors that influence public health. By leveraging big data and AI-driven modelling, the system facilitates timely forecasting of potential epidemiological threats, empowering future specialists to make data-informed management decisions.

Full-Cycle Human Resource Development.
A unique aspect of this initiative is its "full-cycle" approach to cultivating IT potential in the field of public health. The platform not only trains end-users in digital literacy but also nurtures software developers and data scientists capable of creating specialized tools for epidemiological monitoring and response. This dual focus ensures a sustainable pipeline of professionals who can bridge the gap between public health expertise and technological innovation.

Advanced Professional Training Programs.
As part of the project, two specialized professional programs will be implemented:
"Digital Technologies for Analyzing the Sanitary and Epidemiological Well-Being of the Population" – Focused on applying AI, GIS, and statistical modelling to track disease spread, assess environmental risks, and optimize preventive measures.
"Digital Technologies for Analyzing Big Data" – Designed to equip professionals with skills in handling large-scale health datasets, integrating IoT (Internet of Things) devices, and deploying predictive algorithms for early warning systems.
Practical Applications and Societal Impact

The platform's simulations and real-world case studies will enable users to test hypotheses, refine decision-making strategies, and develop scalable solutions for global health challenges.

Potential applications include:
- AI-powered disease outbreak prediction models.
- Geospatial mapping of contamination risks (e.g., waterborne diseases, air pollution effects).
- Automated reporting systems for regulatory compliance and public health surveillance.
- Collaboration and Scalability.

To maximize impact, the platform could incorporate partnerships with government agencies, research institutions, and private-sector tech firms.

Future expansions might include:
Virtual labs for collaborative research.
Integration with global health databases (e.g., WHO, CDC).
Gamification elements to enhance engagement in training modules.

Long-Term Benefits:
By merging public health expertise with advanced digital skills, this initiative will not only enhance individual career prospects but also strengthen national and global capacities in epidemic preparedness and response. The project sets a precedent for interdisciplinary education, fostering a new generation of professionals capable of harnessing technology to safeguard population health in an increasingly complex and data-driven world.

3.2 Key advantages

The cornerstone of our methodology lies in its highly granular, individualized approach to linking environmental exposures with health outcomes. Unlike traditional ecological studies that rely on broad regional averages, our model establishes precise connections between pollution levels and specific cases of disease or mortality by leveraging geospatial precision. By analyzing patients' residential addresses within a 1 km radius of air quality monitoring stations, we minimize exposure misclassification and enhance the accuracy of our assessments.
The main strengths of the approach are as follows.

Geospatial Precision in Exposure Assessment

Residential proximity to pollution sources is a critical determinant of health risks. Our method ensures that environmental data is not just generalized but tied to exact individual locations, reducing the "ecological fallacy" common in population-level studies.

Advanced GIS (Geographic Information Systems) mapping could further refine this by incorporating factors like wind patterns, urban heat islands, and traffic density to adjust exposure estimates.

Dynamic and Real-Time Demographic Data

Instead of relying on static annual health reports, we integrate real-time demographic and medical data from electronic health records (EHRs) and national health registries. This allows for temporal alignment between pollution spikes and health events, capturing acute effects that might be missed in yearly aggregates.

Future enhancements could include AI-driven predictive modeling to identify high-risk populations before adverse outcomes manifest.

Comprehensive Pollution Monitoring

Our analysis utilizes state-sanctioned air quality data, ensuring regulatory compliance and methodological consistency. However, we recognize that official monitoring networks may have gaps—particularly in rural or underserved areas.

Supplementing with low-cost sensor networks, satellite-derived AOD (Aerosol Optical Depth) data, or mobile monitoring units could improve spatial coverage.

Expanding beyond classic pollutants ($PM2.5$, NO_2, SO_2) and using measurements of a large number of air pollutants provides a more holistic risk assessment.

Broader Implications for Public Health Policy

By demonstrating direct links between localized pollution and individual health outcomes, our approach provides actionable insights for policymakers:
Targeted interventions (e.g., stricter emission controls near high-risk residential zones).

Health equity considerations—identifying vulnerable populations (children, elderly, low-income groups) for prioritized protection.
Cost-benefit analyses for environmental regulations, quantifying healthcare savings from pollution reduction.

In summary, our method represents a paradigm shift in environmental epidemiology, moving from correlational to causal insights by harnessing high-resolution geospatial and medical data. Future integration with big data analytics, IoT sensors, and AI could further revolutionize how we understand and mitigate the health impacts of pollution.

3.3 Platform development plans

The project aims to develop innovative technologies for preventive population medicine, including decision support systems, to promote active and healthy longevity by creating competency-based, organizational, infrastructural, and methodological conditions. An additional outcome of the project will be the establishment of a "full-cycle" system for developing IT-personnel competencies in the field of sanitary and epidemiological well-being, encompassing both digital competencies. The digital educational platform will include the development of educational modules and digital simulators to facilitate the acquisition of competencies in the use of information resources and the creation of algorithms and computer programs.

Our approach involves collaborating with AI specialists to train the analytical platform using existing datasets. The predictive AI models will be developed based on extensive historical data pertaining to air quality and population health indicators. A key challenge in constructing such models lies in ensuring data quality and addressing methodological complexities associated with the acquisition of primary data [Bellinger, 2017]. Given that our analysis relies on long-term, real-world air quality measurements and primary health records, we posit that this foundation offers substantial advantages and enhances the potential for the broader application of the analytical system.

4. Limitations and problems

From the very beginning of our work, we have encountered a number of problems and limitations that make the creation of a full-fledged analytical system a complex and lengthy process. While ambitious, its success hinges on data quality and stakeholder buy-in. For example, "Smart City" data can enhance precision, but only if municipalities standardize data formats and update sensors regularly.

The main feature is the personalized linking of environmental data to health outcomes. This approach mirrors precision medicine but introduces ethical and technical dilemmas—e.g., how to handle data for communities with limited healthcare access in low income countries? Ethical guidelines must evolve alongside the technology. The main issues are described below.

4.1 Fragmented Data

Medical and epidemiological data are scattered across incompatible systems (hospitals, labs, regional databases), making integration nearly impossible. Lack of standardized formats or protocols for data sharing between institutions exists. There are limited tools for aggregating and analyzing heterogeneous data (e.g., text, lab results, imaging).

4.2 Patient Privacy and Legal Barriers

Strict laws (e.g., Russia's Federal Law on Personal Data) require complex anonymization processes, which can delay research and reduce data utility. Risks of re-identification even after anonymization, raising ethical and legal concerns should be concerned. Inconsistent enforcement of cybersecurity standards across institutions increases vulnerability to breaches.

4.3 System Conservatism and Bureaucracy

Healthcare authorities often rely on outdated practices, resisting digital transformation due to fear of disruption or lack of expertise. Regulatory frameworks lag behind technological advancements. For example, AI-driven diagnostics or predictive analytics lack clear legal approval for widespread use. Limited funding for IT infrastructure upgrades in public healthcare institutions and in environment monitoring institutions is a problem as well.

4.4 Lack of Collaboration

Poor coordination between governmental agencies, research institutions, and private-sector innovators exist. Initiatives often remain isolated "pilot projects" without scaling due to bureaucratic hurdles.

5. Conclusion

This project will not only enhance sanitary and epidemiological well-being but also influence demographic and urban development policies, support the implementation of "smart city" initiatives, and contribute to the socio-economic growth of regions. A key benefit is the early detection and analysis of critical public health trends, enabling timely interventions.

The project's outcomes are expected to be applied in the following areas:
Scalable deployment – Expanding the use of developed digital solutions across Russian regions.
Data-as-a-service – Offering cloud-based data center capabilities on a subscription model.
Policy support – Generating analytical reports and actionable recommendations for federal and regional authorities.
R&D partnerships – Conducting customized research and development for external stakeholders.

By addressing these priorities, the project will serve as a catalyst for data-driven decision-making and long-term public health resilience.

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