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Integration of Geospatial Data in the Assessment of Environmental Risk (A Case Study of Industrial Regions of Karaganda Region)

ANNOTATION
for the dissertation submitted for the degree of Doctor of Philosophy (PhD)
in the educational program 8D07306 – “Geospatial Digital Engineering”

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INTRODUCTION

Relevance of the dissertation topic. The current development of industry and urbanization is accompanied by an increase in anthropogenic pressure on the environment and the aggravation of ecological problems. For Kazakhstan, and especially for the Karaganda region, this issue is of particular importance. The region is one of the country's major industrial centers, concentrating enterprises of metallurgy, coal mining, chemical, and energy industries.

Intensive use of natural resources, as well as the high concentration of emissions and accumulated waste, form complex environmental risks that affect the health of the population and the sustainable development of the territory. Traditional environmental monitoring methods often fail to provide sufficient spatial accuracy and a comprehensive assessment of risks.

Modern technologies for working with geospatial data — integration of Geographic Information Systems (GIS), Remote Sensing (RS), environmental monitoring, and statistical data — open new opportunities for more precise and comprehensive evaluation of environmental risks. Combining various geospatial data makes it possible to identify spatial patterns of pollution, model the dispersion of contaminants, determine environmentally vulnerable areas, and develop evidence-based measures to reduce environmental pressure.

For the industrial regions of the Karaganda area, this problem is especially urgent due to the necessity to:

- develop effective tools for managing environmental risks;
- ensure compliance with national and international environmental policy requirements;
- minimize negative impacts on public health and the environment;
- form the foundations for sustainable socio-economic development.

One of the factors enhancing the importance of this research is the prioritization of environmental safety and sustainable development in the strategic documents of the Republic of Kazakhstan, such as:

- The national project “Green Kazakhstan” (2021–2025), aimed at reducing the negative impact of industry on the environment and improving regional ecological conditions;
- The Environmental Code of the Republic of Kazakhstan (new edition, 2021), which establishes modern approaches to environmental impact assessment and environmental risk management.

From an international perspective, this topic is also highly relevant. Kazakhstan, as a participant in global initiatives, has committed to implementing the United Nations Sustainable Development Goals (SDGs, 2015–2030).

The research work was carried out in the “Environmental Monitoring” laboratory of the Innovative Engineering Center of the Mining and Metallurgical Institute within the framework of the IRN BR21881939 “ Development of resource-saving energy-generating technologies for the mining and metallurgical complex and creation of an innovative engineering center”.

Therefore, this research — aimed at integrating geospatial data for environmental risk assessment using the example of the Karaganda region — is highly relevant. It contributes to improving the scientific foundations and practical tools for environmental safety management, enhancing monitoring efficiency, reducing uncertainty in risk forecasting, and aligning with national and international strategic priorities.

Research objective: To assess environmental risks in the industrial areas of the Karaganda region based on the integration of geospatial data.

Main research tasks:

- To study methods for integrating geospatial and statistical data;
- To develop a methodology for environmental risk assessment;
- To create a compositional correlation-geostatistical model of heavy metals;
- To perform spatial zoning and mapping of hazardous areas;
- To evaluate the spatial distribution and interrelation of residential population in hazardous zones.

Research methods: To achieve the objectives, methods of system analysis, integration of geospatial and statistical data, and correlation-geostatistical modeling of heavy metal composition were applied.

Scientific novelty:

- A methodology for assessing environmental risks in industrial regions based on the integration of geospatial and statistical data is proposed.
- A compositional correlation-geostatistical model of heavy metals is introduced for identifying hazardous areas.

Scientific statements submitted for defense:

- Integration of geospatial and statistical data allows for the development of a methodology for assessing environmental risks in industrial areas.
- The compositional correlation-geostatistical model of heavy metals enables the identification of hazardous zones.

Validity and reliability of the scientific results and conclusions are supported by:

- the use of geospatial and statistical data in risk assessment;
- quantitative assessment of health hazards from mining emissions and the use of correlation-geostatistical modeling;
- the implementation of scientific results in the educational process and their application in technical and research projects.

Approbation of the work. The main provisions and results of the dissertation were presented and discussed at the following conferences: International practical conference *“Satpayev Readings”* (Almaty, 2021); XVIII International Scientific and Practical Conference *Zprávy vědecké ideje – 2021* (Poland, 2021); XVII International Scientific and Practical Conference *Conduct of Modern Science* (Prague, 2021); XXII International Scientific and Practical Conference *Strategiczne pytania światowej nauki – 2025* (Przemyśl, 2025).

Scientific publications. A total of 11 scientific papers were published on the topic of the dissertation, including: 3 articles in journals recommended by the Committee for Quality Assurance in Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan; 2 article in *foreign journals*; 4 articles in collections of international scientific and practical conferences; 2 articles in journals indexed in *Scopus* / *Web of Science* (Q1 quartile), with percentiles of 96% (General Engineering) and 86% (Environmental Science).

Structure and scope of the dissertation. The dissertation consists of an introduction, three chapters, a conclusion, and a list of 115 references. The total volume is 105 pages and includes 56 figures.

MAIN CONTENT OF THE WORK

Chapter I. In the first chapter, it is noted that pollution of the physical and biological components of the environment to a degree that adversely affects normal ecological processes has become one of the most pressing issues of the 21st century. This pollution poses a threat to human health, ecosystems, and the planet as a whole. Environmental pollution has now become one of the main sources of global ecological crises. Air, water, and soil contamination disrupt the stability of ecosystems and pose a direct threat to human health.

In general, ensuring environmental safety requires systematic measures aimed at the sustainable monitoring of atmospheric, soil, and water resources, the introduction of modern waste processing technologies, the transition to cleaner energy sources, and improving the ecological efficiency of the transport sector.

One of the world's most serious environmental problems is the emission of greenhouse gases that trap solar heat and lead to global warming. Research has confirmed that 2024 was the hottest year on record. The main reason for such indicators is the burning of coal, natural gas, and oil for electricity and heat, which increases greenhouse gas emissions, retains heat in the atmosphere, and raises the Earth's surface temperature. Consequently, recent years have seen destructive forest fires worldwide, locust infestations in parts of Africa, the Middle East, and Asia, melting permafrost in Arctic regions, and rising sea levels. Other ecological disasters include food waste, deforestation, and the loss of biodiversity.

The loss of biodiversity is characterized by a decline in plant, animal, and other organism populations across many regions of the world. Over the last 50 years, there has been a rapid increase in human consumption, population growth, and urbanization. Studies show that between 1970 and 2016, populations of mammals, fish, birds, reptiles, and amphibians declined by an average of 68%.

In Kazakhstan, the total amount of waste generated by the mining industry in 2022 amounted to 712,197.5 thousand tons, or 78.16% of the total waste generated in the country. This figure exceeds the 2021 level by 242,298.6 thousand tons (an increase of 51.5%). As of 2021, 245.2 thousand hectares of land in the republic had been disturbed during the construction of industrial facilities, linear structures, and other enterprises, as well as in the development, processing, and geological exploration of mineral deposits. Of these, 55.8 thousand hectares have been rehabilitated or are subject to reclamation.

All industrial areas have zones of environmentally hazardous impact — waste dumps, tailings, open pits, wells, and mining waste covering more than 60,000 hectares, which continuously contaminate the soil. As a result of non-ferrous metallurgy enterprises alone, more than 22 billion tons of waste have accumulated, including nearly 4 billion tons of mining waste, 1.1 billion tons of toxic beneficiation waste, and 105 million tons of metallurgical residues.

Non-ferrous metallurgy waste occupies an area of about 15,000 hectares, including 8,000 hectares of rock dumps, about 6,000 hectares of processing plant waste, and more than 500 hectares of metallurgical plant dumps. The amount of waste in ferrous metallurgy and the chemical industry is approximately the same.

According to 2019 air pollution index data, eight cities in Kazakhstan — Astana (Nur-Sultan), Karaganda, Temirtau, Aktobe, Balkhash, Ust-Kamenogorsk, Zhezkazgan, and Almaty — had high air pollution levels (index ≥ 7). The most heavily polluted cities were Astana (Nur-Sultan) and Almaty, which are also the most populated.

The purpose of ecological mapping is to determine the environmental condition and its spatial-temporal dynamics, as well as the variability of pollution factors. Thus, data collection, analysis, evaluation, integration, and territorial interpretation for ecological mapping — especially the geographically accurate visualization of heterogeneous and often incomparable ecological information — is of great importance.

The ecological-cartographic method is an essential component of environmental-geographical research, forecasting, and assessment. Ecological mapping emerged within the framework of natural resource use and environmental analysis and now represents a key component of thematic cartography.

Conclusions of Chapter I:

1. Pollution of land and water resources, uncontrolled accumulation of household and industrial waste, improper placement of hazardous substances in landfills, and the impact of mining lead to groundwater, soil, and ecosystem degradation.
2. Pollutants affect the natural environment, human health, and landscape transformation to varying degrees across countries; therefore, efficient land use and legal regulation of hazardous emissions from industries are key solutions.
3. Ecological mapping helps identify interconnections between natural and socio-economic processes and, through visual and analytical representation of spatial features, contributes to ensuring environmental safety, developing sustainable strategies, and improving environmental management.

Chapter II. Environmental instability and the intensification of anthropogenic and natural factors increase the importance of accurate and timely assessment of ecological risks. In this regard, geodetic methods are an integral part of environmental research, providing the key informational basis for spatial-temporal risk assessment.

Geodetic measurements and coordinate monitoring make it possible to determine the spatial dynamics of natural and technogenic processes, quantify environmental changes, and measure surface deformation, subsidence, erosion, or water-level fluctuations with high precision. These data are crucial for identifying environmentally hazardous areas, assessing risk levels, and improving environmental monitoring systems.

Geodetic approaches, when integrated with satellite navigation (GNSS/GPS) and remote sensing (RS) technologies, are incorporated into Geographic Information Systems (GIS). Such an integrated approach allows for highly accurate mapping of spatial environmental changes, prediction of ecological risk distribution, and dynamic monitoring of temporal variations.

Modern GIS are complex, multifunctional tools designed for working with geographic data, performing five main stages of data processing:

1. Input — entering initial spatial and attribute data;
2. Processing — scaling, projection transformation, and other geometric conversions;
3. Management — storing, structuring, and organizing data;
4. Query and analysis — performing simple and complex spatial queries and selections;
5. Visualization — displaying results in the form of maps, reports, 3D images, graphs, tables, diagrams, photographs, and multimedia.

These capabilities make GIS an efficient tool for spatial data analysis and decision-making.

Modern geoecological research is impossible without GIS, as environmental and natural resource data are inherently geographically linked. Specialists in these fields use GIS technologies extensively for data visualization (creating electronic maps), spatial analysis, storage of source data, conducting environmental assessments, and supporting management decisions.

Furthermore, GIS can include information-measuring modules that enable real-time visualization of continuous environmental monitoring results. GIS systems can also serve as data sources for computer models simulating the spread of pollutants and as platforms for presenting model results in map form.

Geostatistical methods allow analysis of the spatial structure of ecological processes, assessment of pollution and soil quality variations, and the creation of ecological risk maps. Correlation and geostatistical analyses also provide accurate evaluation of the spatial distribution of environmental data and identification of the effects of natural and anthropogenic factors.

Conclusions of Chapter II:

1. Geodetic and satellite methods establish a new scientific and practical level for assessing ecological risks and allow comprehensive analysis of natural and anthropogenic processes in industrial regions.
2. The integration of GIS technologies with geostatistical methods such as buffering, overlaying, interpolation, kriging, and cokriging enhances the effectiveness of environmental monitoring and provides a scientific foundation for spatial analysis.
3. Geostatistical and correlation analysis methods allow detailed examination of the spatial structure of ecological processes, evaluation of pollution and soil quality variations, and creation of ecological risk maps identifying the impact of natural and anthropogenic factors.

Chapter III. Karaganda is one of Kazakhstan’s largest industrial regions, and the level of technogenic pollution is increasing every year. Major sources of environmental pollution in the region include:

- the coal industry (*ArcelorMittal Temirtau JSC, Shubarkol Komir JSC*),

- mining and mineral extraction (*Kazakhmys Corporation LLP, Zhairem GOK JSC, Nova-Zinc LLP, Kazchrome JSC*),
- thermal power plants (*KaragandaEnergoCenter LLP – CHP-1, CHP-3*),
- construction materials production (*Central Asia Cement JSC*),
- energy sector (*Kazakhmys Energy LLP*), and
- metallurgy (*Kazakhmys Smelting LLP, Temirtau Electric Metallurgical Plant JSC*).

Additionally, within the Karaganda region, there are two toxic waste storage sites containing chromium-bearing sludge and residues from coke-chemical production (acid tars, fus tar). These facilities are owned by *ArcelorMittal Temirtau JSC*.

In Temirtau, *ArcelorMittal Temirtau JSC* operates the largest metallurgical plant in Kazakhstan, with waste storage sites located between 73°05′–73°55′ E and 50°00′–50°45′ N, covering approximately 5,000 km².

According to research institutes of Kazakhstan, the degree of polymetal contamination in Temirtau is rated as “low,” but 40% of soils exhibit very high pollution indices. The contamination of land in Temirtau is directly linked to waste from mining and metallurgical industries.

According to the Kazhydromet report on soil contamination by heavy metals (spring–autumn 2020), high concentrations were detected in Temirtau soils: zinc – 26.4 mg/kg, copper – 3.64 mg/kg, chromium – 2.84 mg/kg, lead – 37.8 mg/kg, and cadmium – 0.64 mg/kg.

The ecological situation in Temirtau is complicated by contamination with heavy metals, industrial waste, and atmospheric emissions. This poses significant threats to soil, water, and air quality, as well as to public health.

Modern approaches to assessing ecological risks require consideration of the spatial and temporal variability of natural and anthropogenic factors. Therefore, integrating laboratory, geospatial, and statistical data has become one of the most effective scientific tools for comprehensive environmental assessment.

This integrated methodology provides several key advantages:

1. Comprehensive analysis. GIS visualizes spatial data (soil, water, air, topography, land use, climatic parameters) and combines them with quantitative characteristics (e.g., heavy metal concentration, radiation level, erosion coefficient). This enables analysis of diverse information within a unified coordinate system, revealing cause–effect relationships of ecological risks.
2. Identification of spatial patterns. Integrated methods make it possible to identify geographical patterns in environmental indicators. For example, high heavy metal concentrations may cluster near industrial zones or river valleys — relationships visible only through spatial modeling.
3. Risk mapping. Geostatistical GIS-based models (e.g., kriging, IDW, regression analysis) are used to create spatial distribution maps of pollution and ecological risk levels — crucial tools for monitoring and decision-making.
4. Improved data accuracy. Combining statistical and geospatial data enhances the reliability of risk assessment results. Comparing local monitoring

data with satellite imagery yields environmental models that closely reflect real conditions.

5. Forecasting and scenario analysis. The integrated method allows simulation of future environmental changes. For example, by modeling the effects of land cultivation or industrial expansion, GIS and regression tools can project potential risk scenarios.

Studying the accumulation and distribution of heavy metals in soil is critically important for environmental safety. In Temirtau and the "KarMet" industrial zone, 25 soil samples were collected and analyzed for heavy metal concentrations. Using geostatistical and correlation methods, a compositional–spatial model was developed to describe the relationships and distribution patterns of heavy metals.

Based on geostatistical analysis of point data, a series of maps was produced showing the spatial distribution of heavy metals in the study area, including around Temirtau. The Ordinary Kriging interpolation method was selected as the most appropriate algorithm to account for spatial variability.

Correlation analysis of the 25 sample sites revealed heterogeneous results. Although the degree of association between variables varied, no negative correlations were detected.

Positive correlations were identified among five metal pairs, with the strongest between Mn and Cu ($r = 0.64$, $p = 0.0005$). Significant correlations were also observed between Mn–Pb, Mn–Zn, Cr–Zn, and Ba–Zn, with coefficients above 0.5 and $p < 0.004$. Moderate correlations were found between Cr–Cu and As–Cr, while other metal pairs showed weaker associations ($r < 0.4$), insufficient for statistical significance.

For element pairs with correlation coefficients above 0.5, a compositional correlation–geostatistical model was developed to delineate hazardous zones.

Describing the relationship between heavy metal concentrations and the distance from pollution sources using geospatial methods forms an essential part of environmental analysis. This approach allows spatial assessment of contamination levels and identification of risk zones. The study evaluated heavy metal dispersion within a 1–13 km radius from pollution sources (industrial enterprises). Pollution sources were entered as point or polygonal objects, while sampling sites were linked to concentration data.

The following geospatial and statistical methods were applied:

- Buffer analysis: creation of buffer zones of varying radii around pollution sources with average concentration calculation per buffer;
- Correlation analysis: computation of distances from pollution sources to sampling points and determination of statistical relationships with concentration levels.

The resulting cartographic model illustrates the spatial patterns of heavy metal dispersion and the radial extent of anthropogenic impact. This approach enables identification of ecological risk zones and supports environmental protection planning.

In the Model Builder environment, automated data processing, multifactor spatial analysis, and the construction of hazard prediction maps using the weighted overlay method were performed. The input factors were converted into weight coefficients based on correlation analysis. The resulting model made it possible to predict the spatial distribution of heavy metals and assess contamination risk.

Thus, the obtained results confirm environmental degradation and demonstrate that pollution by heavy metals in the Temirtau–Karaganda industrial area continues to intensify. The findings can serve as a scientific basis for future waste recycling and ecological remediation measures.

Conclusions of Chapter III:

1. Analysis of the volume and composition of industrial waste and emissions makes it possible to assess their impact on soil, water, air quality, and public health in Temirtau.
2. Integration of laboratory, geospatial, and statistical data is proposed as the most effective methodology for comprehensive ecological risk assessment.
3. Based on the results, a compositional–geostatistical model of heavy metals was developed, enabling complex evaluation of technogenic pollution levels and providing a scientific foundation for planning environmental risk management measures.

CONCLUSION

In this dissertation, a methodology for the comprehensive assessment of environmental risks in the industrial areas of the Karaganda region was developed based on the integration of geospatial and statistical data. The proposed scientific and practical approach is aimed at modeling the distribution of pollutants in the environment, forecasting ecological risks, and determining their impact on public health.

The main scientific results and conclusions of the dissertation are as follows:

- It has been demonstrated that the integration of geospatial and statistical data allows for a comprehensive solution to the problems of accurately determining the level of environmental risk.
- A methodology for assessing environmental risks in industrial territories has been proposed, based on identifying the concentration levels, distribution patterns, and environmental impacts of heavy metals and pollutants.
- A compositional correlation–geostatistical model of heavy metals has been developed to evaluate spatial distribution characteristics and identify environmentally hazardous areas.
- Based on geostatistical analysis, industrial territories have been zoned according to their level of ecological risk, and thematic maps reflecting the degree of hazard have been produced.
- The spatial relationship between population density and pollution hotspots has been identified, allowing for the determination of areas with a high probability of ecological risk and the estimation of the affected population.
- The openness and adaptability of the Model Builder environment ensure its broad application in future scientific research and environmental monitoring systems.

The research results have established a scientific foundation for assessing environmental risks and identifying hazardous zones in industrial regions through the integration of geoinformation and statistical data. The proposed methodologies can be applied to ensure environmental safety, improve territorial planning, and enhance systems of environmental monitoring.

The main content of the dissertation has been published in the following scientific works:

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9. Ы. Жакыпбек, А. Айдаркызы, Е.Е. Бегимжанова, Г.Б. Кезембаева. Теміртау қаласының өнеркәсіптік ластануын қашықтықтан зондтау арқылы бағалау. Горный журнал Казахстана. – 2024. – №9. – Б. 66–70. – ISSN 1684-2822.
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