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## ASSESSMENT OF DEFORMATION AND RADIATION SITUATION AT THE SEMIPALATINSK TEST SITE

### Introduction

The Semipalatinsk Test Site (STS) was the test site for 456 nuclear explosions which led to significant deformation of the earth's surface and extensive radionuclide contamination of soil, water and air across large areas [1, 2]. Contaminated lands, along with adjacent areas exposed to radioactive fallout, require continuous monitoring and evaluation to determine their suitability for agricultural, industrial and other forms of economic use.

As portions of the STS are currently being analyzed with a view to commercial land use, a key priority is to carry out comprehensive research and develop measures to ensure safe implementation of economic activities in these areas [3, 4]. An illustration of such activity is development of the Karazhyra coal deposit situated within the Balapan test site, where 106 underground nuclear explosions were conducted in deep boreholes (**Fig. 1**). [5–7].

Near the Karazhyra deposit, the Atomic Lake was formed as a result of an excavation-type nuclear explosion. Geological exploration, coal extraction and subsequent transportation to consumers are currently being carried out at this site. The deposit is developed by open-pit mining, with overburden placed in external and internal waste dumps. Stripping operations disturb the upper soil layer, which contains radionuclide contaminants. During extraction and transport of coal along haul roads, dust is generated directly within the open pit area. In addition, the long-distance transportation of coal beyond the boundaries of the

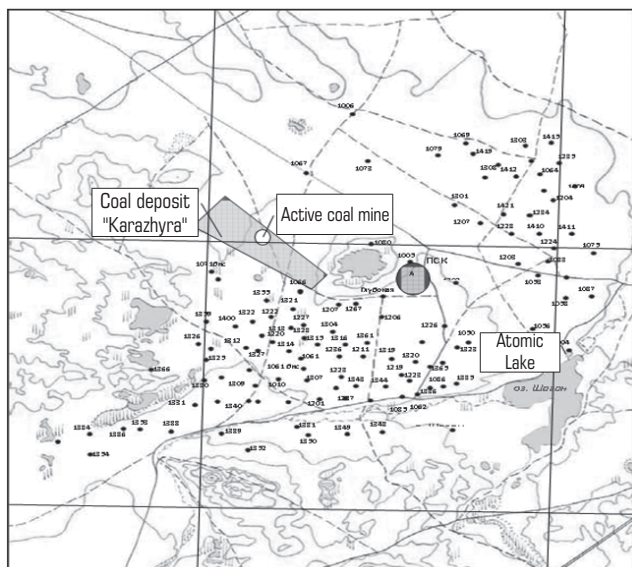
*The article describes the research results obtained by the authors in geodetic monitoring of ground surface deformation with zoning and cadastral valuation of contaminated land. The primary analysis of the geodetic monitoring results is performed in terms of the Balapan site, where subsidence of ground surface reaches 5–6 mm. The findings are used in impact assessment of contamination generated at the Semipalatinsk Test Site (STS), and in development of recommendations on the use of the land in terms of radiation safety. The procedure of creation of a geodynamic test site is proposed, which allows efficient tracing of changes in ground surface deformation and adjusting cadastral valuation of land depending on its contamination level.*

**Keywords:** Semipalatinsk Test Site, Atomic Lake, Karazhyra deposit, geo-information systems, geodetic monitoring, radioecological monitoring, analysis of results, ground surface deformation, radioactive contamination maps

**DOI:** 10.17580/em.2026.01.05

test site contributes to the dispersion of radionuclides, leading to secondary contamination of adjacent area.

The relevance of this research is defined, first, by need to monitor radioactive contamination level in certain areas of the test site, including the Karazhyra deposit, where geodetic and mine surveying operations are underway, and second, by the necessity of applying obtained data to cadastral assessments both within the deposit and in adjacent area, including transport routes. These factors highlight significance of



**Fig. 1. Layout of test wells at the Balapan site, Karazhyra coal deposit and Atomic Lake**

addressing scientific and practical problem of ensuring safe and rational use of land resources in the region [8–10].

### The subject and methods

The test subject is the area of the Semipalatinsk Test Site (STS). The scope of the study embraced: 1) geological and hydrogeological conditions; 2) ground surface deformation; 3) waste rock and coal dumps; 4) snow, soil and plants. Samples were collected in accordance with GOST standards and methodological recommendations. Field research was conducted in the impact zone of the Karazhyra coal deposit located 130 km southwest of the city of Semey in the Abay region of the Republic of Kazakhstan.

To monitor land deformations, it is proposed to create a geodynamic test site with local networks for tracking changes on ground surface and minimizing the impact of radiation on environmental components.

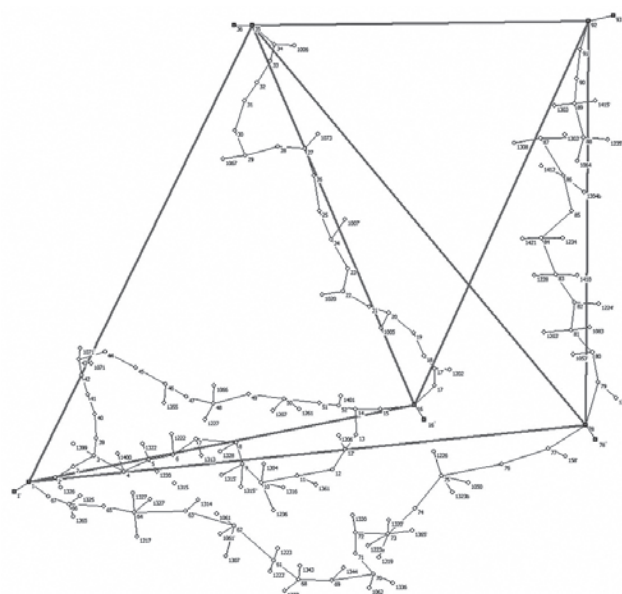
The experimental data were processed using variational statistical methods in Microsoft Excel. In this context, the most effective approach is the development of a geoinformation system (GIS), which enables not only storage and convenient retrieval of existing data, but also modeling spatial processes. The resultant models can then be integrated with geographic and satellite imagery of the study area.

### Results

Integrated approach to zoning and determining cadastral value of contaminated land plots represents an important tool for managing areas affected by radioactive pollution. Its significance is determined by the factors listed below.

1. Identification of different contamination level zones. The use of geoinformation systems (GIS) makes it possible to analyze spatial data and delineate zones of different levels of radioactive contamination, thereby facilitating informed and targeted management and remediation decisions.

2. Economic incentives for rehabilitation. Determination of cadastral value in accordance with contamination level can motivate land users and stakeholders to undertake reclamation, environmental restoration and



■ – GNSS points  
○ – points of the planning and high-altitude justification  
— – leveling traverses (polygonometric)  
- - - satellite change vectors

**Fig. 2. Layout of geodynamic test site and local networks**

risk-reduction measures.

3. Mitigation of environmental and health risks. Zoning enables prioritization of areas with critical contamination levels, which contributes to reducing potential adverse impacts on ecosystems and human health.

4. Prediction of changes. Integration of monitoring data with modern analytical technologies, including artificial intelligence and predictive modeling, allows more accurate forecasting of changes in land condition and enhances effectiveness of long-term land management strategies.

5. Geodetic monitoring. To monitor deformation processes within STS area, it is proposed to create a geodynamic test site for the continuous observation of changes on ground surface while minimizing radiation exposure of personnel.

The geodynamic test site includes local networks of leveling benchmarks designed to record variations in surface elevation. The benchmarks are installed at a depth of not less than 2 meters to ensure long-term stability and high accuracy of measurements, as well as to reduce direct exposure to radionuclide contamination during surveying operations [11]. This geodetic network provides a reliable framework for analyzing deformations and predicting changes of ground surface (Fig. 2).

The horizontal and vertical photo-control must be designed in such a way that its points are placed in areas with the lowest possible levels of radioactive contamination, as well as in zones where no underground nuclear explosions were conducted. The survey network is developed using dual-frequency satellite receivers and total stations. Modern electronic and laser-based geodetic instruments were employed to carry out monitoring and to evaluate the current condition of the territory (GPS receiver, total station, laser scanner, laser level).

Data obtained from the Leica TCR 1201 total station can be seamlessly integrated into standard geodetic data processing workflows. Field measurements can be transferred for processing and adjustment

into a wide range of specialized software packages, including Liscad, CREDO-DAT, RGS, and AutoDesk Survey [12, 13].

In addition to establishing reference geodetic network, the use of various leveling techniques is recommended to ensure accurate monitoring of deformation processes across land plots. In particular, the geometric and trigonometric leveling methods.

*Geometric leveling* is used for areas with minimal radiation contamination and allows changes to be recorded with high accuracy.

*Trigonometric leveling* is applied in areas with elevated radiation backgrounds, where it is necessary to minimize the time personnel spend in hazardous zones. In such conditions, a fan-shaped trigonometric leveling scheme with short sight lines is used.

In 2023 and 2024, topographic surveys were carried out in the Atomic Lake area. To support installation of geodetic and environmental monitoring equipment and to ensure efficient execution of measurement operations, a permanent benchmark was designed and installed at the monitoring site. The upper part of the benchmark is equipped with a forced-centering platform, which ensures precise and repeatable placement of geodetic instruments during repeated measurement cycles [14].

*Radioecological monitoring.* Areas of significant radioactive contamination associated with nuclear materials were identified within the STS during 2014–2015. Many radionuclides released during tests were deposited directly at the primary test locations, including Test Field, Balapan, Degelen and Sary-Uzen.

To identify anthropogenic features within the Balapan area, high-resolution satellite imagery was analyzed, which allowed detection of several man-made structures, including key explosion epicenters. Subsequent field surveys were conducted to take stock of these features and to assess the degree of anthropogenic disturbance caused to the natural landscape.

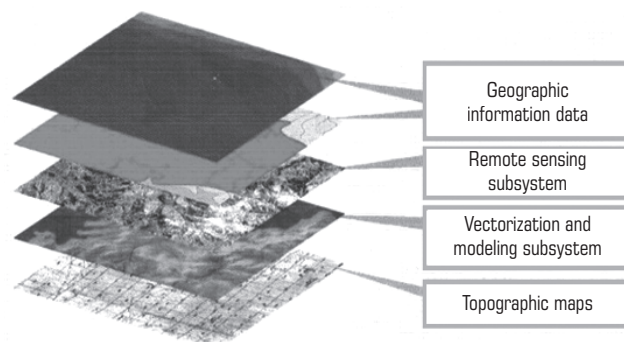
The first stage of the study involved identifying areas of radioactive contamination and producing survey maps at different spatial resolutions (200×200, 100×100 and 40×40 meters). A pedestrian gamma survey was subsequently performed, which included measuring the ambient dose equivalent rate at key observation points using a Radiagem 2000 dosimeter-radiometer.

The second stage focused on examining the vertical distribution of radioactive contamination within the epicentral zones. For this purpose, soil and water samples were collected at varying distances from the explosion epicenters to determine radionuclide concentration profiles and assess the depth of contamination spread. Primary radiological hazard to humans is associated with the soil mound zone surrounding Atomic Lake, within a radius of approximately 3–4 km. This area should be regarded as a significant potential source of secondary contamination of environmental components, including water, vegetation and air [15, 16].

A lot of research has been devoted to studying the area of the former STS. However, this work has not been based on a unified information framework that would allow transition from scientific research to practical problem-solving.

The most effective approach in this case is the creation of geographic information system (GIS), which not only allows storage of existing data and easy access to it, but also enables modeling, the results of which can be combined with geographic and satellite imagery of the region under study. All components of the STS GIS, shown in **Fig. 3**, are interconnected [17–20].

The STS geoinformation system includes:  
—geographic and information databases;



**Fig. 3. Geoinformation system of STS**

—remote sensing subsystem;  
—modeling subsystem;  
—results visualization subsystem.

The ArcInfo package is the primary tool that integrates subsystems into a single GIS. It is one of the most powerful tools for creating geoinformation systems.

Cartographic data are integrated into the remote sensing subsystem, where they are used for the georeferencing of satellite imagery. In turn, satellite images serve as a source of spatial information for geographic information database. Both geographic and remote sensing datasets are subsequently transferred to the *Modeling* subsystem.

As a result of the analysis of the implemented research findings, information was obtained on the current condition of the ecosystem components of the Balapan site. It was determined that radioactive contamination of soils and bottom sediments with man-made radionuclides was confined to the Atomic Lake craters and the Balapan site. There is no doubt that the subsurface of the earth where the adits and boreholes were tested contains large quantities of radioactive products, including long-lived ones. Such areas, which are not subject to economic development, must be protected for a long time, preventing human access.

Based on available data on the radiation situation at the test site, the government developed a plan for a phased survey of the Semipalatinsk Test Site by 2021, aimed at fundamentally addressing the problems of the former Semipalatinsk Test Site by the 35th anniversary of the Republic of Kazakhstan's independence [18].

The results of radioecological studies conducted at the Semipalatinsk Test Site from 2010 to 2024 revealed areas of significant radioactive contamination with nuclear materials (**Fig. 4**).

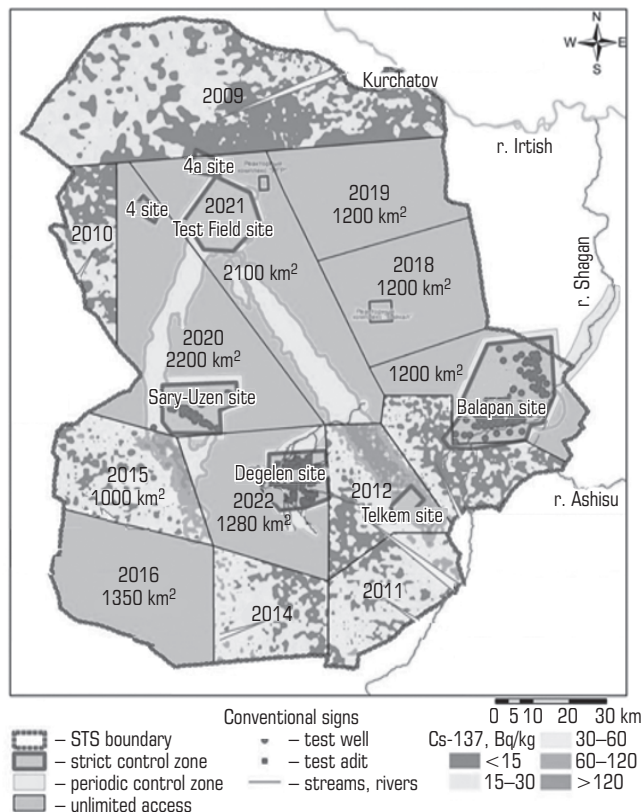
Nuclear explosions produce several hundred different radionuclides, among which the most persistent and long-lived are cesium-137 and strontium-90. Most radionuclides generated during testing were deposited directly at the primary test sites, including Balapan and Atomic Lake. Since 2023, comprehensive monitoring of the so-called “combat” boreholes has been carried out at the Balapan and Sary-Uzen sites. These observations have revealed surface deformation patterns, such as uplift and subsidence, which may reflect ongoing geomechanical and geochemical processes above the focal cavities of underground nuclear explosions (UNE). Such processes can pose potential hazards not only within the test site boundaries but also at considerable distances from them, highlighting the need for continuous monitoring and assessment.

When zoning land plots, the levels of soil, groundwater and air pollution are considered. A radiation risk category is determined for each

**Table 1. Proposed reduction factors**

Radiation risk zones	Soil cover	Water resources	Air, dust smoke	Reduction factors*, %
Extreme radiation risk	Pollution	Pollution	Pollution	100 (60–80) reserve lands
Maximum radiation risk	Pollution	Pollution	Pollution	70–80 (50–60)
Increased radiation risk	Pollution	Pollution	Norm	40–60 (30–50)
Minimal radiation risk	Pollution	Norm	Norm	10–30 (10–20)
Natural background (are with preferential socio-economic status)	Norm	Norm	Norm	0

\*Comment: The coefficients for defense, national security, and nuclear safety areas are given in parentheses



**Fig. 4. Zoning of the STS area by radiation contamination level (based on monitoring results in 2010–2024)**

plot, which is used to develop reduction factors for cadastral valuation. This is important for the precise evaluation of contaminated plots and determination of their suitability for future use [19].

Type of contamination is important factor in land valuation. The following types of contamination are considered:

- Soil pollution** is the most common type of contamination, affecting feasibility of agricultural activities in a given area.
- Groundwater pollution** is a critical factor when assessing land for construction, industry and water-related economic activities.
- Air and atmospheric pollution** affect the safety of living and working in areas adjacent to test wells, as well as the feasibility of locating industrial facilities.

*Reduction Coefficients for Cadastral Valuation.* To ensure objective assessment of cadastral value of land, reduction coefficients have been proposed, which are applied depending on the level of land contamination.

**Table 2. Frequency of adjustment of cadastral value of land**

Radiation risk zones	Frequency, years
Natural background	Once every 5 years
Minimal risk	Once every 3 years
Increased risk	Once every 2 years
Maximum risk	Annually
Extreme risk	Annually

These coefficients vary depending on the type of land use and the radiation risk zone (Table 1).

These coefficients take into account the degree of contamination and are used to determine market value of land plots for economic use.

Lands exposed to radiation contamination require regular cadastral value revisions depending on the level of contamination and the dynamics of changes. The frequency of cadastral assessments is proposed in Table 2.

These data make it possible to adapt the cadastral valuation to the changing conditions of the contaminated area and consider possible changes in the level of radiation contamination, which may affect the market value of the land [20].

There are several examples of successful management of radiation-contaminated areas worldwide, such as the Chernobyl Exclusion Zone and the Fukushima Daiichi Nuclear Power Plant site. These areas employ similar methods of pollution monitoring and control, and conduct zoning and cadastral assessment of contaminated lands. The experience of such international projects could be useful for adapting these methods to the STS context.

One of the key factors in the effective management of radiation-contaminated areas is the systematic monitoring of soil, water and atmospheric conditions. It is important to recognize that radioactive contamination has long-term and evolving consequences, meaning that zoning schemes and cadastral value adjustments must reflect temporal changes over extended periods. A geodynamic test site provides accurate and reliable data for predicting land surface changes and supporting informed management decisions, thereby helping to minimize environmental and radiological risks associated with the use of contaminated lands.

**Conclusions**

- Studying the consequences of long-term nuclear tests at the former Semipalatinsk Test Site (STS) and assessing the radioecological state of the soil cover are among the most pressing issues in the region. To objectively assess the impact of nuclear explosions on the environment at the site, taking into account the overall radiation situation

there, a comprehensive monitoring methodology has been developed to determine the main deformation and environmental impacts of STS operations.

2. Based on the developed comprehensive environmental monitoring methodology, a man-made geodynamic testing ground has been created for land monitoring at the STS, representing an important step in the management of radiation-contaminated areas. This system not only allows tracking changes in earth surface deformations but also enables adjusting land cadastral valuations, facilitating the safe and rational use of the areas.

3. The results of geodetic observations allow substantiation of recommendations for improving the operation of local networks and the creation of a regional STS network based on them. This will allow us to further study geodynamic processes and construct maps of modern crustal movements for the entire territory of the Semipalatinsk test site.

### Acknowledgements

The study was supported by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan AP23489269.

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