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INTEGRATED MONITORING-BASED ASSESSMENT OF DEFORMATION AND RADIATION SITUATION OF TERRITORIAL DOMAINS

The article describes integrated monitoring (space, geodetic, radioecological) in the area of earlier underground explosion at Semipalatinsk Test Site (STS). The data of space monitoring of the territory and the experience of the data integration into the geographic information system (GIS) are analyzed.

The primary analysis of geodetic monitoring results is performed as a case-study of Balapan and Telkem sites where ground surface subsidence is up 5–6 mm. Based on the integrated monitoring, the dynamic maps of temperature and ecological characteristics of the test site territory are obtained. The results are used for additional assessment of pollution consequences at STS and to work out recommendation on the use of the lands in the context of radiation safety.

Keywords: *underground nuclear explosion, geographic information systems, space monitoring, geodetic monitoring, radioecological monitoring, analysis, temperature anomaly, ground surface deformation, radioactive contamination maps.*
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Introduction

Eco-systems in Kazakhstan feature weak resistance to anthropogenic impact. About 75% of the territory of Kazakhstan (Aral Sea, Semipalatinsk Test Site (STS), the coast of the Caspian Sea, desert and semi-desert land ranges in Central and Southern Kazakhstan, etc.) are subject to an increased risk of environmental disruption. STS had been used as the main site for nuclear tests for 40 years [1, 2].

By the decree of the President of the Republic of Kazakhstan N. A. Nazarbayev, the test site was closed on August 29, 1991, with internal and adjacent contaminated areas left behind. That circumstance caused intensive researches of the nature and pollution level of test site territory with the aim to determine the nuclear explosions after-effects and and for monitoring of radiation-hazardous objects.

For the timely indication of further changes, assessment of the rates and areas of the natural environment degradation, for the impact prevention and situation stabilization, the operational control of these regions is necessary. Considering the vast territory of Kazakhstan, hardness of many areas and limited funding in modern conditions, such control can be only effective based on the integrated research (satellite monitoring and ground investigations).

Description of Semipalatinsk Test Site

STS is located at the intersection of three regions of Kazakhstan: Pavlodar, Karaganda and East Kazakhstan, and covers 18 thousand km^2. During the operation of STS (1949–1989), 456 nuclear tests were conducted on its territory, including 86 air tests, 340 underground tests and 30 contact tests. Here, the first in the USSR nuclear (1949) and the world's first hydrogen (1953) bombs were tested.

As the result of nuclear explosion in 1965, more than 10 million tons of ground was thrown to a kilometer height and a funnel with a diameter of 430 m and depth of 100 m was formed. This funnel is called the Atomic Lake. As a result of the tests, radioactive decay residues – radionuclides covered STS territory [3].

Methods and results

Ample research had been devoted to the territory of the former STS [4-6]. However, the research had no common information basis, which would allow moving from theory to solving practical problems.

In this case, creation of GIS is the most effective way, which allows not only preserving the available and readily accessible data but also enables simulation, the results of which can be combined with the geographical and space images of the region under study [7, 8].The main tool that combines subsystems into integrated GIS is the ArcInfo package. It is one of the most powerful tools for creating geographic information systems.

Cartographic data ‘pour’ into the subsystem of remote sensing, i.e. participate in gridding of geo-referencing space images. In turn, space images are the source of the geographic information database. Geographical data and remote sensing data are inputs for the modeling subsystem.

Space monitoring. During the space image processing, a number of interesting results, including detection of temperature anomalies in STS area, were obtained, which had a large resonance both inside the country and abroad. Methods for reconstructing the surface temperature from the Earth remote sensing (ERS) data are based on separation of the surface radiation data (taking into account absorption and atmosphere radiation). These methods are well approved for homogeneous surfaces, in particular, surfaces of sea and oceans, for which there are reliable temperature recovery techniques.

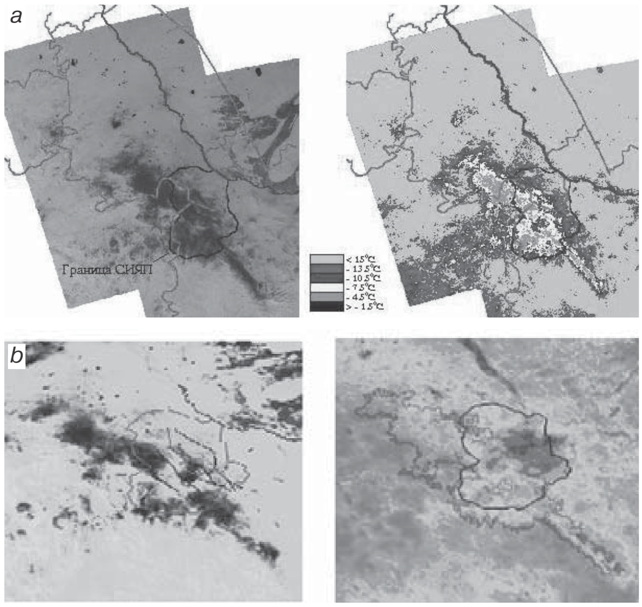
The task of temperature recovery of land surface is more complex due to additional difficulties connected with surface relief. This complicates the use of simple models to determine relationship between brightness and physical temperature. It is possible to recover temperature of the earth’s surface truly only for homogeneous areas: steppe, desert, snow cover, etc. The territory of Kazakhstan satisfies this condition. In such cases, the temperature recovery algorithms developed for the temperature recovery of surface of seas are used, as a rule. In this field, the algorithm developed by McClain [9] to find the temperature of the earth’s surface from space has found wide application. The main factors affecting surface temperature measurement accuracy using the data from space are: air temperature, air humidity, wind speed, cloudiness, vegetation cover, surface features, etc. Taking into account the specificity of STS, the maximum accuracy of water measurement is 0.5 C°, earth surface – 1 C°.

To process the obtained temperature fields in GIS environment, they must be reduced to the cartographic form and combined with the topographic base of the studied territory. The corresponding technology was tested in mapping of the temperature dynamics of the underlying surface in STS area. In 1998 to 2008 STS territory was studied using various earth satellites rockets (ESR), but ERS data were not available in those years.

At present, during processing of space images, including detection of temperature anomalies in STS area, a number of interesting results have been obtained. Snowless areas during winter period (**Fig. 1**) and areas without vegetation in the summer were identified. On the temperature maps within the spot, the areas of high temperature (to 8–9 °C) are clearly distinguished [10]. The mapping results of the temperature fields from the data surveys in 2000 confirmed the presence of temperature anomalies in this region (See Fig. 1a).

It is also necessary to note the similarity of the configuration of the snowless zones in winter with the areas without vegetation in summer (Fig. 1b).

The analysis of the remote sensing data indicates a stable connection between the location of snowless areas and summer drought focuses in STS area, and they are confined to test sites. The foregoing facts could have been caused by an accidental combination of weather conditions or local terrain features (relief, hydrothermal regime, etc.) that contribute to the denudation of the snow cover and, as a result,



Map of snow cover on January 15, 2015

Vegetation map as of June 10, 2015

Fig. 1: (*a*) Snow cover in infrared (IR) range temperature field in STS area according to the data of the US satellite NOAA (March 7, 2000); (*b*) Vegetation in STS area

more intensive heating of bare areas of the earth by the sun rays.

On the other hand, temperature increase could be the consequence of the activation of tectonic processes caused by numerous nuclear explosions [11]. The fact is that several deep faults pass through the territory of the test site. It is well known that, as a result of underground explosions, cardinal changes take place in geological environment and hydro geological conditions [12–14]. Our estimates have shown that powerful explosions can lead to the development of abnormally extended cracks in the zone far from the explosion, which can be channels for the penetration of harmful substances into rock mass [15–17]. Despite more than 25 years since the last tests in STS were carried out, the region is still an ecologically dangerous zone, and the natural environment of STS territory is covered by waste of radioactive decay – radionuclides.

Geodetic monitoring. At many sites, underground nuclear tests have led to deformation of the day surface in their epicentral zones.

This indicates that over the focal cavities, as a result of earlier conducted underground nuclear explosions, several decades later, various geodynamic processes occur. An example is Glubokaya well site, where ground surface subsided 15 years after the test [18, 19]; at present the crater has a diameter of 110 m and a depth of 17 m.

This phenomenon poses danger to mineral mining practices in the immediate vicinity of these objects. It must be avenged that sinkholes can also be triggered by seismic vibrations during blasting operations. To solve this problem, it is necessary to carry out a set of high-precision geodetic measurements directly in the wellhead areas of emplacement holes.

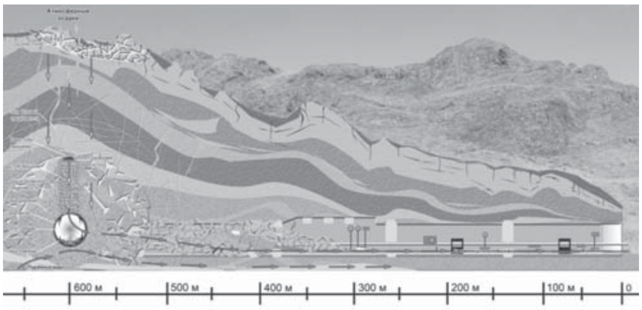


Fig. 2. Location of nuclear object in test site

Since the 1990s radioecological, geoecological, geological, geophysical and topographic-geodetic studies of areas exposed to nuclear tests began. The energy of underground explosions in the form of seismic vibrations is caused destruction in the thickness of enclosing rocks. The radius of the impact zone can reach several kilometers. The force of seismic action in underground nuclear explosions depends on the power of the charge and geological conditions (tectonic faults, fracture of rocks, etc.) of the test site [20, 21]. Semipalatinsk test site is composed of robust rocks of granite origin. Granites have low absorption properties of elastic seismic vibrations. Therefore, underground explosions were accompanied by significant tremors. Totally 343 underground explosions were conducted, each of them led to earth movement. Large destruction in rock mass caused subsidence and sinking on ground surface. **Figure 2** shows the vertical section of an underground tunnel, where nuclear object is located in the last box.

At present, in the test site territory, Karazhyra coal deposit is being developed, salt is extracted from Zhaksytuz Lake, geological survey is carrying out, cattle is pastured and hay is prepared. Such activities, firstly, contribute to the transfer of radioactive contamination inside the test site and beyond it; secondly, it is connected with the additional risk of workers, for the population of the region as a whole and for consumers of products.

Mineral exploitation carried out without notice of radioactive situation or hydro geological mapping of radioactive contamination can lead to loss of deposit – for hundreds and even thousands of years, the territory, soils and minerals themselves may be contaminated.

Therefore, it is vitally important to investigate comprehensively STS territory. The object of the research is the natural environment: soil and vegetation cover, water and air mediums, fauna. Radioecological monitoring is also integrated within GIS, where it is possible to integrate terrestrial geodetic methods with space ones. It increases the reliability and accuracy of measurements and monitoring.

Underground nuclear explosions (UNE) in Balapan area were carried out in 105 emplacement holes. At many sites, underground nuclear tests have led to deformation of ground surface in their epicentral zones. This indicates that over the focal cavities, due to previously conducted underground nuclear explosions, several decades later, various geodynamic processes occur.

Since 2015, comprehensive monitoring has begun on the territory of Telkem sites. As a result, the nature of change in ground surface is determined as uplift and subsidence, which may indicate various processes occurring over focal cavities of nuclear explosions. Satellite instrument was used to locate points in geographic coordinate system. Coordinates of survey network points were entered into GPS receiver and determined on site in the navigation mode.

In 2017 and 2018 at Telkem-2 site, topographic survey was carried out, as a result of which dimensions and relief of crater were determined. Ten reference points were selected along the edge of the funnel. For installation of geodetic and environmental instruments and efficiency of measuring operations, we have developed permanent benchmark, installed at reference point during monitoring, where upper part of the center is equipped with table for forced centering [22] (Fig. 3c). Telkem-2 crater map, created from data collected during field work in August 2018, clearly shows access road location to the southeastern shore of Lake (**Fig. 3**), location of observation wells in the dump of funnel, observation pipes in the Lake, road access and soil sampling points.

The ground surface deformation behavior (subsidence and uplift) is reflective of the continuing geodynamic processes after an explosion, which necessitates cause-and-effect monitoring.

Radioecological monitoring. The radioecological researches conducted in STS territory in 2014 and 2015 revealed areas of significant radioactive contamination with nuclear materials. The main part of radionuclides formed during explosions fell directly inside actual testing grounds (Experimental field, Balapan, Degelen, Sary-Ozen).

To identify manmade objects in Balapan area, space images were studied, which allowed detecting a number of objects, including large epicenters. Then field visits were conducted to inventory the manmade objects and assess the degree of induced disruption of natural landscape.

The first stage included identification of radioactively contaminated sites, drawing up survey networks by different steps: 200×200; 100×100 and 40×40 m. Then, pedestrian gamma survey was carried out, including MED

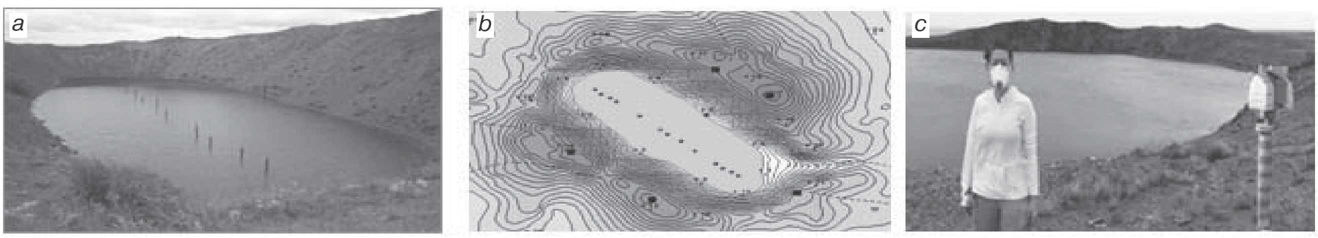


Fig. 3. (*a*) Telkem-2; (*b*) topographic map and (*c*) observation at the Atomic Lake

measurement at nodal points using dosimeter-radiometer Radiagem 2000.

The second stage was the study of vertical distribution of radiation in epicentral zones of sites. It consisted in selection of soil and water samples at various distances from the epicenter [23].

The low-water Shagan River is the longest surface watercourse on the territory of Semipalatinsk test site, its main waterway. As a result of nuclear tests at the STS, the valley of the Shagan River has been exposed to radioactive contamination to one degree or another. Basically, radioactive components contamination of the river's ecosystem is concentrated near the Atomic Lake, where excavation nuclear explosion was carried out in well No. 1004, and pollution was caused by underground nuclear tests in the emplacement holes of Balapan site.

The Lake Chagan is included by the government of Kazakhstan in the list of areas especially badly affected by nuclear tests. Some species of fish still live in the Lake, but eating them is highly discouraged. Water in the Lake is not suitable for drinking and irrigation of agricultural land. Level of radioactive substances contained in it, especially tritium (^3H) is hundreds of times higher than the permissible levels.

The main danger to humans is represented only by soil heap zone around the Atomic Lake, with a radius of 3–4 km, which should be considered as serious potential source of secondary pollution of environmental objects (water, vegetation, air).

As a result of researches in 2016–2018, high concentrations of ^{3}H were revealed in the waters of the Shagan River at a distance of 5 km downstream of the Atomic Lake revealed (**Fig. 4**).

In order to understand the process of tritium transfer, we divide graph (See Fig. 4) into four sections and deduce dependencies for each of them:

1) tritium concentration increases according to the formula:

$n = 1000 \cdot 10^{0.242L}$ Bq/m^3, over $0 < L \leq 5$ km, (1)

where n – specific activity of tritium Bq/m^3; L – distance from the Atomic Lake, km;

2) tritium concentration practically unalters and is equal to:

$n = 16200$ Bq/m^3, over $5 < L \leq 20$ km; (2)

3) tritium concentration decreases according to the formula:

$n = 1620 \cdot 10^{0.054(L-20)}$ Bq/m^3, over $20 < L \leq 70$ km; (3)

4) tritium concentration slowly increases according to the formula

$n = 31{,}6 \cdot 10^{0.005\,(L-70)}$ Bq/m^3, over distance >70 km; (4)

It should be noted that in theory, migration of tritium should stabilize in the fourth section, but the research (2016–2018) shows a slow increase in concentration. Perhaps this is the transfer of manmade radionuclides by wind, as well as washing away by atmospheric precipitation both on the surrounding area and into the Shagan River channel with further transfer of radionuclides by surface water flow. In any case, this is a topic for further research [24, 25].

Thus, only at distance of 40 km from the Atomic Lake along the river bed, the limited residence zone of population ends and the zone of relatively satisfactory radiation situation begins, where concentration of ^{3}H in air is <140 Bq/m^3. It is worth noting that the limited stay zones of population and dangerous radiation situation are small in width – a few tens of meters. So, already at a distance of 50 m from the channel,

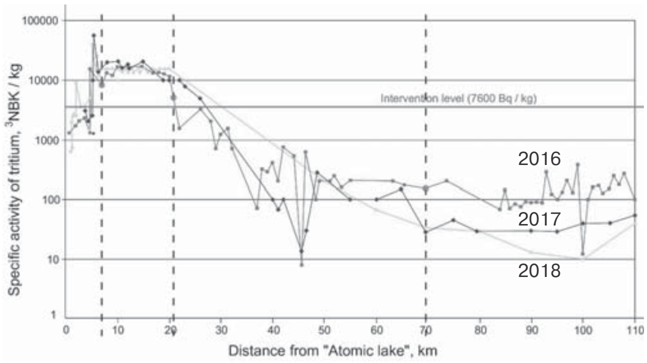


Fig. 4. Concentration of tritium (^{3}H) in the Shagan River versus distance from the Atomic Lake

the content of ^{3}H in the air is safe for humans along the whole Shagan River.

The studies provided the information on current state of ecosystem components of Balapan site. Radioactive contamination with manmde radionuclides of soil and bottom sediments of the territory is confined to the funnels of the Atomic Lake and Telkem. There is no doubt that the earth interior contains large number of radioactive products, including long-lived ones which were tested in galleries and wells. Such places, which are not subject to development, have to be guarded for long time, excluding people's access there.

Based on the available data on the radiation situation in the area, the plan of stepped inspection of STS until 2021 was developed by the government with the aim to solve cardinally the problems of the former STS to the 30th anniversary of the Independence of the Republic of Kazakhstan.

Conclusions

1. Based on the above facts, it can be confidently asserted that STS area is located in the zone of stable climatic anomaly characterized by the earlier snow cover, increased surface temperature in the winter–spring period and by the reduced volume of green biomass in the summer. These facts provide sufficient grounds for the conclusion that nuclear explosions are involved in the temperature anomalies in STS area and emergence of drought focus in this region.

2. To prevent secondary distribution of radioactive substances, the most acceptable approach is the integrated monitoring (space, geodetic and radioecological) of STS territory. The key task of integrated monitoring is to create a common information space that can be formed on the basis of use of modern geoinformation technologies [26–29].

3. The results obtained by geodetic monitoring make it possible to substantiate recommendations for improving the local networks operation and creating on their basis a regional geomonitoring network in STS. In the future, this will allow studying geodynamic processes and build maps of modern movements of the earth's crust for entire territory of the test site. The *radioecological* monitoring results made it possible to offer scientifically reasoned recommendations for the state bodies of the Republic of Kazakhstan on development of assessment criteria for ecological situation in territorial domains, and to optimize comprehensive environmental

study of STS territories with the aim of their further transfer to the national economy within the framework of Kazakhstan State Program: STS Radiation Safety.

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