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DESIGNING A SPATIAL MODEL OF LAND USE IMPACT DYNAMICS CAUSED BY URANIUM MINING USING REMOTE SENSING AND GROUND-BASED METHODS

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***Abstract.:** The paper is dedicated to resolving topical problems related with assessment of the land use impact caused by uranium mining and processing activities. To make such assessment, one should establish in advance land use structure, anthropogenic transformation and its change over the periods before, during and after termination of uranium mining. Aerial and satellite images are becoming increasingly popular as a basic source of such type of information. The major objective of the conducted study is to develop and approbate methodology for designing a spatial model of land use impact dynamics caused by uranium mining. It is based on integrated use of GIS and remote sensing data processing technologies, landscape planning and mapping.*

The proposed methodology was approbated on the territory of the Iskra site located on the land of the Town of Novi Iskur, Metropolitan Municipality. A geodatabase was composed comprising archive panchromatic aerial photos and high-spatial-resolution satellite images for different years (from the periods before, during, and after the end of operation), large-scale topographic maps in scale M 1:5,000, data from terrain studies and measurements, photos, climatic, geologic, and soil data. As a result of the processing and interpretation of aerial photos and satellite images and ground-based data, digital models and thematic maps were created. The specific impacts, their sources and subjects were localized, as well as the peculiarities of their dynamics, intensity, and consequences. This information was used to draw inventory and analytic maps for the periods before, during, and after the end of uranium mining, as well as a map of land use impact dynamics for this area. The designed spatial model may be used by the local self-government authorities to plan and take decisions on reclamation activities of the lands disturbed by uranium mining.

Introduction

The sustainable use of municipal territories suited to ecological and social-economical characteristics is one of the priority lines of modern regional policy. One of the key problems is assessment and control of the territories with land-use impact caused by uranium mining and processing activities. To make such assessment, one should establish in advance land use structure and its change over the periods before, during and after termination of uranium mining. The results from such assessment provide to find a balance between environment and human activity, especially in the areas which have experienced strong anthropogenic transformation. Moreover, the relations between them and the occurring degradation processes are established, which provides for application of adequate reclamation initiatives and modelling of sustainably developing experimental ecosystems, as close as possible to those destroyed in the near past. To design an effective action plan, one should determine very precisely the site's state before restoration. In ecological studies, maps are used as primary and reliable models describing spatially the state of some specific natural systems' components at a given moment. The development and wide application of Geographic Information Systems (GIS) makes it possible to generate new cartographic models. Periodic monitoring of the disturbed territory may be effected by using high-spatial-resolution aerial photographs and space imagery, as well as field measurements. The recent decade witnessed the development of environmental control systems, applying GIS, RS and GPS technologies, in both the USA and the EU. These systems are aimed at establishing regional geoinformation complexes to solve various practical tasks; however, they are still rarely used by the specialists dealing with environment restoration. This contribution aims to compose a geodatabase for the *Iskra* site, encompassing the territory of the *Kourilo* uranium deposit, District of Novi Iskur, Metropolitan Municipality. The major objective of the conducted study is to develop and

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approbate methodology for designing a spatial model of land use impact dynamics caused by uranium mining. To achieve this objective, the following basic tasks should be accomplished:

- Composing a geodatabase for the *Iskra* site with land use information before the uranium deposit's operation, after the termination of the first operation stage and after the mining's termination;
- Identification and comparative analysis of the land use impacts' spatial and time dynamics.

Methodology and Information Background of the Study

The methodology developed for the purpose of this study comprises the following work stages:

1. Collection and analysis of the required information,
2. Selection of data processing methods and monitoring years;
3. Forming a geodatabase;
4. Generating new thematic maps using the raster and vector database;
5. Conducting spatial analyses and assessment of land use impacts.

The activities related with uranium mining and processing are characterized by their complex negative impact on environmental components (soils, water, air), which is a direct consequence of mining technologies. The used uranium mining methods – classical (open or underground) or geotechnological, determine the rate of their impact on environment and land use.

The *Kourilo* uranium deposit is located on the territory of the District of Novi Iskur, Metropolitan Municipality. The ore's good uranium composition, high uranium extraction factor during the ore's processing, as well as the proximity of the deposit to the *Bouhovo* Chemical Metallurgical Plant facilitated the mine's normal production activity during the period 1955–1990. Uranium mining at the *Kourilo* deposit featured two operation periods:

1. Mining after the classical method - 1955–1963. The deposit's operation started in 1955 using the quarry method by constructing a quarry on the territory of Brezi Vruh, and later - by horizontal mining exploitations at seven hypsometric levels.

2. Mining after the geotechnological method (underground mining) - 1984-1990, by drilling oxidizing boreholes to the level of the ore body, processing the ore with sulphuric acid solution and extracting this enriched solution to the surface.

The *Kourilo* deposit's technical liquidation and biological reclamation was undertaken in accordance with Decree No.56 of 29.03.1994 on closing uranium mining in Bulgaria, and is still ongoing.

To compose the geographic database, design a model of land use impact dynamics caused by uranium mining and make subsequent analyses and assessments, the following materials were used:

- Archive aerial photographs shot in 1940 and 1982;
- High-spatial-resolution satellite images from QuickBird taken in 2007;
- Economic (topographic) maps in scale M 1:5,000;
- Data and results from ecological studies carried out during the period 2000–2002 [1, 2, 3];
- Stock material and scientific literature.

During this study, a complex of modern methods and technologies was used: GIS; remote sensing methods; temporal analysis; conventional methods for ground-based study of the state of the individual environmental components; and mathematical-statistical methods.

One of the essential elements in designing the spatial model of land use impact dynamics is the selection of classification indicators. They must be selected in such a way as to reveal adequately the nature and type of impact sources. The major characteristics used to draw the series of impact maps are shown on Table 1., and are considered in details in [4].

The selection of the years for cartographic monitoring is mainly determined by the available archive of aerial photos and satellite images for the studied territory and the two operation periods of the deposit. The smallest size of the mapped areas of the studied territory provided for by these images is equal to 1 ha. The chosen baseline year is 1940. This is the year of the first taken aerial photos of the territory when the geologic prospecting and operation activities related with uranium mining had not begun yet. To determine the rate of land use impacts resulting from the deposit's operation, the year 1982 was chosen. At this time, the deposit's operation after the quarry manner had been terminated, partial reclamation had been carried out, and activities related with the preparation of the second operation stage – uranium mining after the geotechnological manner, were underway. To determine the current state of the territory after the termination of uranium extraction when technical liquidation and biological reclamation of the deposit was underway, the year 2007 was chosen.

A geodatabase for the territory of the *Iskra* site was composed using ArcGIS software, which contains spatial and attributive data for the conducted monitoring. The geodatabase is structured in two modules: information module comprising raster and vector submodule, and analytical module. Using the information and analytical module, the following types of maps for the territory of the *Iskra* site were created: land use maps for the years 1940, 1982, and 2007; analytical map of land use impact rate for the years 1940, 1982, and 2007; analytical map of land use impact rate caused by uranium mining and transport for the year 2007; and map of land use rate dynamics for the year 2007 compared to 1940 (Fig. Fig. 1., 2., 3., 4., 5.).

***Table 1**. Classification Indicators and Their Characteristics*

CLASSIFICATION INDICATORS	CHARACTERISTIC
Source of impact	industry, transport, minerals mining, tourism, other human activities etc.
Land use categories as impact subject	forests, natural meadows, pastures, perennial plants, fields, water bodies, streams, hydro-melioration equipment, transport and infrastructure territories, residential and industrial built-up lands, disturbed lands
Occurrence of impact	initial date of source working
Manifestation of impact	Illegal forests clearance, wildfire, pollution etc.
Development duration of impact	long time period, short time period
Development stages	initial, active, attenuating
Development trends	ascending, descending
Degree of impact	low, middle, forced
Border character	distinctive, indeterminate
Shape of the layout contours	areal, linear
Impact groups	result from legal and illegal activity
Undertaken measures to resolve impact	yes, no

Spatial Analysis and Assessment of Land Use Impact

To establish the rate of land use impact available before starting uranium mining on the studied territory, analytical map for the year 1940 was created. Because of the nature of impact sources, the degree of disturbance and anthropogenic transformation is different and is based on qualitative-quantitative expert ratings. Typical impact sources during this time were agriculture, stock-breeding, and logging. The most common negative consequences of unregulated human activities were forest fires, which resulted in nearly total degradation of forest vegetation occupying 31.77% of the territory and its replacement by deciduous forest-bush, bush, and grass vegetation. During this period, the natural paragenetic landscape self-restoration circuits were suppressed by constantly acting factors, such as unregulated cuttings for household needs, charcoal production etc., as well as by grazing and haymowing. It is well known that grazing results in a number of negative changes in the type composition of grass and forest vegetation. Goat-breeding which was practiced during this period was a significant factor acting continuously on the whole studied territory, which destroyed forest outgrowth, reducing forest self-restoration processes, accordingly. The areas occupied by meadows and pastures amounted to 42.63%. Problems of this sort are not a rare event in our times, too. An example of indirect changes caused by direct human intervention is landscape degradation resulting in the formation of incomplete Natural Territorial Complexes (NTCs), such as badlands and bare rocks – 3.25%. As a result of activated erosion and denudation processes, strongly eroded soils now occupy 22% of the studied territory.

To establish the rate of impacts caused by uranium mining at the *Iskra* site, analytical map for the year 1982 was created. In the beginning of the 80-ies of the 20th century, uranium mining after the classical method was terminated and preparation of the terrain was undertaken for uranium mining after the geotechnological method. During the quarry (open) uranium mining, mineral masses with increased content of radioactive elements were brought to the site's surface, the local landscape was changed, the ecological equilibrium was disturbed and prerequisites were established for pollution and erosion of the pertaining territories. New types of land use were introduced, related with bringing to the surface of great amount of rock materials, which occupy large territories, as well as with the direct disturbance of soil cover integrity on small areas located near to the shafts' openings. These materials are an improper substrate for growing cultivated plants and present a threat for the uranium ore residues contained in them. The major facilities constructed during this period were the spoil heaps, the shafts and the drainage systems, as well as the tailings pond and the premises of the *Redki Metali (Rare Metals)* State Economic Group. Technological roads and shaft waste water channels were also laid.

A positive initiative was the planting of the southern macroslopes of Sofia Mala Planina with black (*Pinus nigra*) and white (*Pinus silvestris*) pine which, though not growing in their natural optimal ecological environment, create preconditions for accumulation of humus and natural self-restoration of the forest.

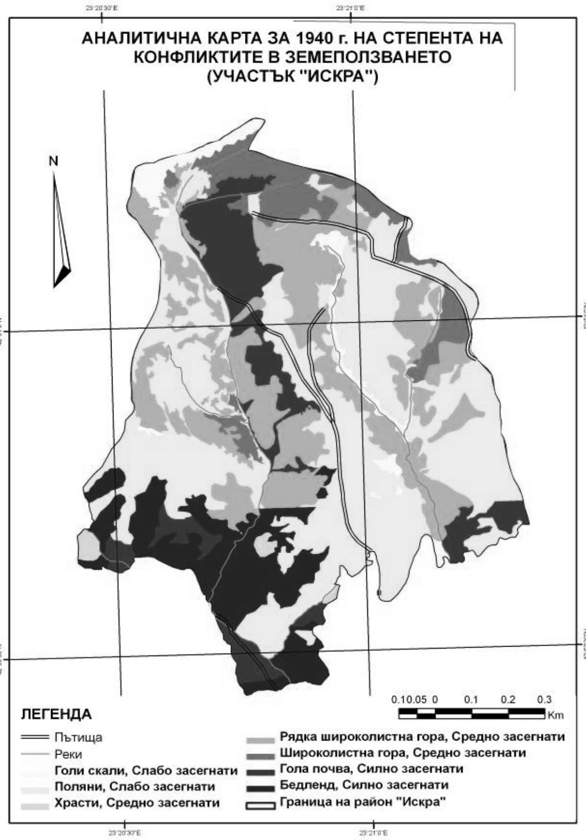

Fig. 1. *Analytical map of the rate of land use impact at the Iskra site for the year 1940*

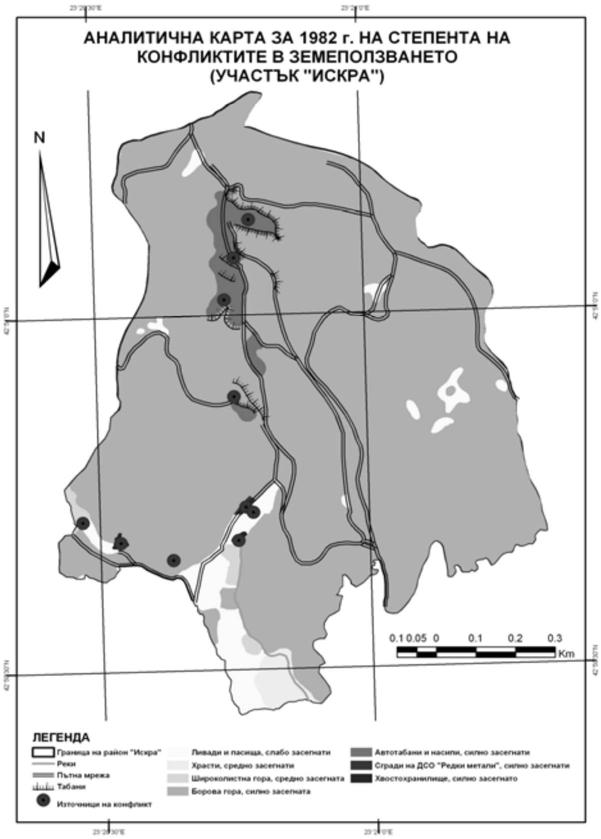

Fig. 2. *Analytical map of the rate of land use impact at the Iskra site for the year 1982*

To establish the current state of the territory, analytical map of land use impact rate for the year 2007 was

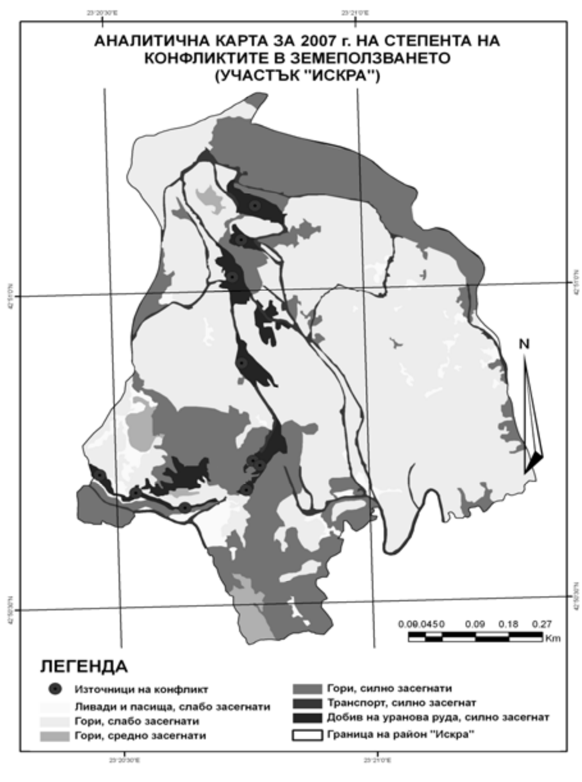

Fig. 3. *Analytical map of the rate of land use impact at the Iskra site for the year 2007*

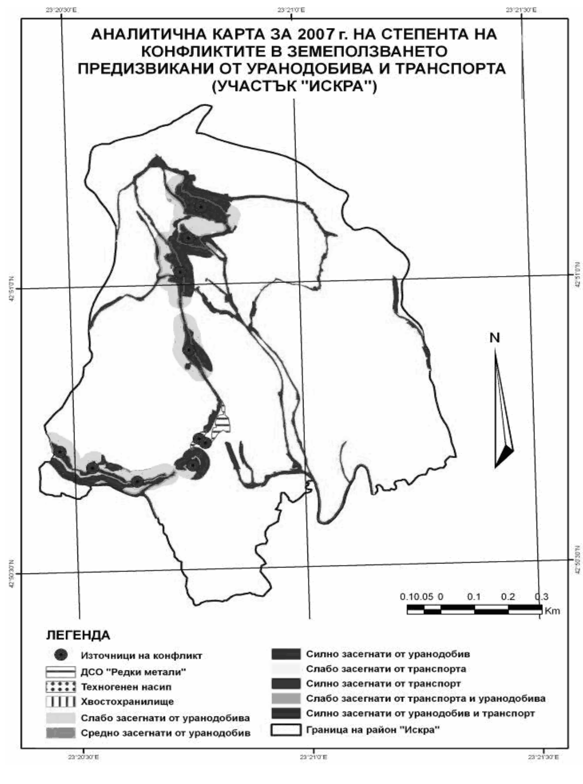

Fig. 4. *Analytical map of the rate of land use impact at the Iskra site caused by uranium mining and transport for the year 2007*

created. The analysis of the map reveals small-size land use changes compared to 1982, but for the terrains subject to reclamation by planting coniferous vegetation and demolition of the *Redki Metali* SEG's premises which make an exception. The geotechnical uranium mining method has resulted in mechanical disturbance of the soil, caused by drilling and explosion activities, the construction of the sorption plant, the laying of the drilling pipelines and the other technological equipment.

In the middle course of the Teyna River, the outflow has been changed by two barring dykes and the site's tailings pond, where three reservoirs have been formed. The deposit's area and the built-up production solution drainage system have experienced material change. The volumes of the three reservoirs: „pure" lake, „acid" lake and collector amount accordingly to 7,500; 1,500; and 2,000 m^3, their waters featuring strong seasonal changes, drying including.

Notwithstanding the undertaken measures, the problem with surface-flowing and underground waters caused by the tailings pond remains unresolved. The forest coniferous vegetation near the uranium deposits is strongly affected by the chemical element associations constantly penetrating soil, water and air, as well as by the emanations of radioactive decay. In the recent years, forests have been subject to increasing unregulated cutting for household needs. The „phenomenon" of extensive stock-breeding has appeared again, especially in the vicinity of quarry operations.

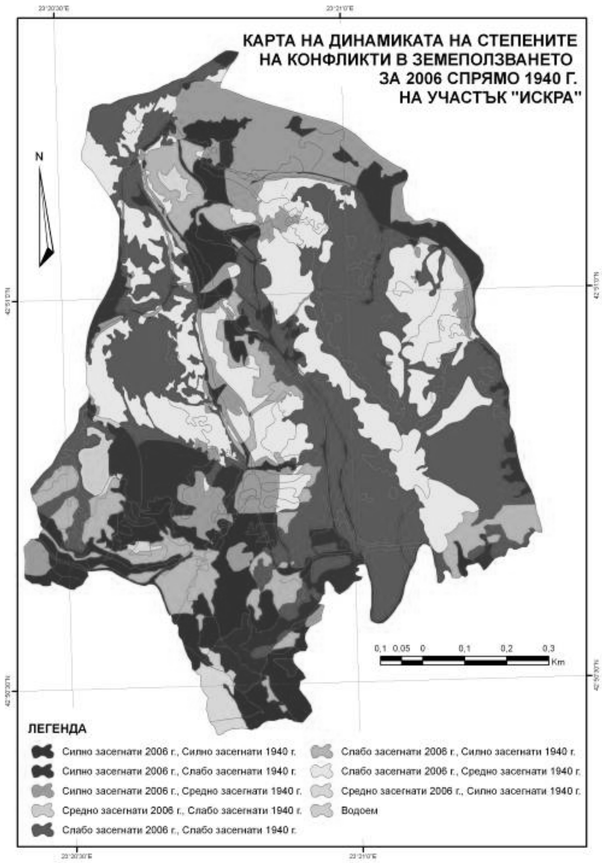

Fig. 5. *Map of land use impact dynamics of the Iskra site for the year of 2007 compared to 1940*

To clarify the region's current state, analytic map of land use impact rate caused by uranium mining and transport for the year of 2007 was created, using materials from the terrain studies and measurements performed by [1, 2, 3].

On the map shown in Fig. 4., the territories directly affected by uranium mining and transport are outlined. The rating method uses 3-stage scale for the disturbance rate of impact sources and the pertaining territories. The main subject of anthropogenic impact in uranium mining is soil cover. Its integrity is disturbed (in some cases, the soil horizon is completely destroyed), and during chemical extraction of uranium, the soil profile is subject to the influence of mining solutions: sulphur-acid or sodium-alkaline ones. Geotechnological uranium mining on the territory of *Kourilo* has activated the processes of generating acid drainage waters. These waters are characterized by low pH and high concentrations of heavy metals, uranium, iron, and manganese, which exceed manifold the adopted Maximal Allowed Concentrations. The ecological studies carried during the period 2000–2002 [1, 2, 3] reveal that the main soil pollution source on the territory are drainage waters originating from the *Brezi Vruh* quarry and the site's spoil heaps. It has been established that the soils most polluted by geotechnological uranium mining are those located 0–3 m off the Teyna River. As a result of this, actually, these soils feature no vegetation cenosis. This results in drastic reduction of the supplied biomass for decomposition which, in its turn, leads to twofold reduction of the humus content in each horizon of the soil profile.

The conducted comparative analysis of land use impacts' spatial and time dynamics at the *Iskra* site for the year 2007 compared to 1940 reveals the following changes (Table 2).

- The weak-affected territories which were found to be unchanged by the conducted monitoring constitute 32.5% of the territory. These are mostly areas occupied by forests, meadows and pastures located in the eastern and western part of the territory.
- There are no medium-affected territories in 1940 which have remained unchanged until 2007.
- The strong-affected territories which were found to be unchanged by the conducted monitoring constitute 11.86% of the territory. These are mostly strongly eroded areas located in the eastern and western part of the territory.

➢ Strong-affected territories with unchanged impact rate but a different impact source, which in 1940 were steep deforested slopes, and in 2007 were territories occupied by uranium mining quarry, technogenic embankments and bare soil formed as a result of uranium mining. The impact source has switched over from forest cutting to uranium mining.

➢ The weak-affected areas have increased by 29.68%, 9.12% of the strong-affected areas have been transformed into weak-affected ones as a result of the carried out reclamation and afforestation initiatives. Weak-medium – 20.56%. Scarce forest (1940) – thick forest (2007).

Table 2. *Matrix of land use impact rate dynamics of the Iskra site for the year 2007 compared to 1940 (in %)*

AREA (%)		1940				Temp	
		Strong-affected	Medium-affected	Weak-affected	Σ		
2007	Strong-affected	11.86%	11.16%	12.67%	35.69%	13.34%	↑
	Medium-affected	1.37%	-	0.83%	2.20%	29.52%	↓
	Weak-affected	9.12%	20.56%	32.45%	62.13%	16.18%	↑
	Σ	22.35%	31.72%	45.95%	100.0%		

Conclusions

The conducted monitoring of the *Iskra* site revealed that there are no areas that have remained unaffected by human activity. The mining activities carried out at the *Iskra* site have changed the landscape, destroying soil cover at some places. The ecological equilibrium is considerably disturbed, resulting in social-economic losses. There are significant changes in land use impact rate, whereas the weak-affected territories have increased by nearly 16%, while the medium-affected have decreased by about 30% as a result of the carried out reclamation and relieved anthropogenic loading of the territory. Against the background of this restoration, enhanced technogenic loading and increase of the strong-affected areas by 13% is observed as a result of uranium mining and forest cutting in the reclaimed territories.

The composed geodatabase for the *Iskra* site containing spatial and attributive data from the performed monitoring is to be supplied with new aerial, satellite, and ground-based data. Alongside with supplying the geodatabase with such information, real and accurate assessment of the conducted reclamation initiatives' efficiency will be made to enable taking proper decisions and improving reclamation strategy.

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