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An approach to integrated assessment of mining-disturbed land

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Abstract

Large-scale mineral mining, including critical minerals of oil, gas and coal, conditions withdrawal of vast land from the agricultural sector. The relevance of this problem is connected with prevention and elimination of disamenity of the subsoil use. It is necessary to determine a strategy of mining-disturbed land reclamation. The authors propose an integrated assessment of mining-disturbed land, which allows a comprehensive analysis of current condition of these man-made sites. The proposed procedure can serve as a framework for the development of recommendations on reclamation trend selection. It enables simultaneous sequential or parallel application of parameters and criteria from a compiled list. In the aggregate, these parameters and criteria describe features of man-made objects and their condition by quantitative and qualitative indicators determined during field study, field survey, lab-scale testing and office analysis. As a case study of the Novosibirsk Region, the necessity is demonstrated and a matrix is constructed for the mining-disturbed land assessment by the level and nature of the environmental impact, with the determination of boundaries and sizes of damage areas. The basis for ranking man-made objects was classification, typification and clustering of attributes which govern peculiarities of the external impacts on the environment (rocks, soil, artificial ground, surface water, groundwater, etc.). These attributes are characterized by parameters and quantitative indicators measured on various scales, which identify admissible and hyperadmissible environmental load. The proposed approach allows the integrated analysis of mining-disturbed land areas with a view to their further ranking by the environmental load, and for developing an expert system of the optimized selection of new application ranges for such land.

Keywords

mining-disturbed land; assessment; reclamation; environment; damage degree; criteria; matrix; MAC; radioactivity; pollutants; Novosibirsk Region

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Introduction

Rapidly growing consumption of mineral resources in the world governs the increased contamination caused by the mining sector of economy to all components of the environment. Mineral mining operations are unexceptionally connected with transformation of adjacent areas [1-3] and with formation of various disturbed land groups, which are classified for reclamation purposes according

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to GOST R 59060-2020. Subsoil use has a great effect on the environment, and mining-disturbed land reclamation and restoration is therefore a critical and relevant challenge aimed at minimizing ecological damage and retuning such land to economic circulation.

Selection of rational technologies of land reclamation should rest upon the integrated analysis of factors and research findings on all components of nature – air, soil, vegetation, fauna, water, terrain, groundwater, rocks, historical archeological and recreational resources, type of disturbed land, climatic conditions, social and economic needs, etc. Modern approaches and advanced technologies can enhance efficiency of reclamation activities and ensure sustainable development of land exposed to harmful effect of the mineral mining industry.

According to GOST R 59070-2020, disturbed land is the land, which is impossible to use because of its degradation. Such land that lost its wholesomeness as a result of economic or other activity, or due to natural or induced contingencies, as per the Federal Law on Subsoil and Russian Government Resolution N 781 as of May 25, 2025, need restoration (reclamation) in conformity with a designated purpose and permitted utilization. Resolution N 800 of the Russian Government as of June 10, 2018 reads that an integral part of mineral mining activities is reclamation [4-6] to be developed and implemented by parties which induced land degradation. During mine planning and design at a new mineral deposit, on the ground of the Federal Law on Environmental Audit, the State Ecological Expertise is carried out to estimate impact on components of the environment as mining operations can actuate natural processes – erosion by water, flooding, overwetting, swamp formation, degradation etc. Alongside with that, subsoil use results in soil pollution, which can change the physicochemical properties of soil and lead to degradation of vegetation cover [7-10].

The top-priority trend of eco-friendly urban development policy aimed at ecological improvement of urban areas and at industrial environment reorganization is decision-making with regard to ecological, social and economic factors. The Russian Federation introduces the system of the state subsoil monitoring, which, as per Resolution N 2029 of the Russian Government as of November 29, 2023, includes monitoring of soil polluted as a result of the subsoil use. One of the trends here can be an integrated approach to mining-disturbed land assessment with the development of measures aimed at partial or total land return to economic circulation.

Mineral extraction by open-pit and underground mining methods involves removal, displacement and storage of overburden and barren rocks, with formation of a new terrain, water drainage from surface and underground mines, with creation of artificial structures for water storage, treatment, recycling or discharge to natural hydrosystems, and deformation of ground surface due to displacement of rock masses [1, 11]. The key types of impact exerted by solid mineral mining on components of the environment include [12, 13]:

• Withdrawal of land of different purpose at low level of land reclamation. On the average, in open-pit mining, extraction of 1 t of coal requires removal of 3.6 m^3 of overburden rocks, and maintenance of open-pit mine productivity of 1 t/year requires withdrawal of 1-1.5 m^2/year of land. According to the Federal Service for Supervision of Natural Resources, by early 2023, the area of mining-disturbed land was 1100 thousand hectares at the annual increment by 85-101 thousand hectares.

• High dust production at open pit mines, dumps, storage facilities and tailings dams, with the annual expansion of land meant for storage of waste. Mine dumps inside Russia accumulate more than 12 Bt of overburden and host rocks.

• Impact of mining on geological environment. Mechanical effect in the form of displacement of rocks and intersection of underground aquifers; physical acoustic, electromagnetic and radioactive

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effects; intensification of geodynamic processes in the form of regular periodic earthquakes; stress and strain redistribution with landsliding, karsting etc.; man-made terrain formation; subsoil depletion.

• Formation of mining and processing waste – overburden and host rock dumps and piles, warehouses and storages of low-grade and noncommercial mineral materials, siftings, tailings of flotation and gravity or wet and dry magnetic separation, coal combustion residual and ferrous and non-ferrous slag.

• Violation of hydrological and hydrogeological regimes due to unwatering or flooding of economic activity areas, pollution of groundwater and strata.

• Alteration of natural landscape, with downwarping, fracturing and formation of sinkholes on ground surface. For instance, during mining of the Baykaim seam in the Krasnoyarskaya Mine, SUEK-Kuzbass JSC, at a depth of 250 m, sinkholes 7 m wide, to 3.5 m deep and a few hundred meters long appeared on ground surface. Ore extraction at the Tashtagol deposit in Gornaya Shoria led to creation of a sinkhole with a diameter more than 200 m and with a depth more than 50 m above the caving zone in the mined-out space [14-16].

In addition to open-pit and underground mining, not lesser impact is exerted by man-made deposits which are expedient to rank by the degree of their impact on adjacent land using scoring and rating with clustering [17]. Complimentary to the disturbed land estimates, it is possible to use indicators of safety and allowable level of impact on ecological subsystems, which represents a possible approach to studying hazards based on dimensionless environmental indicators [18, 19]. In this case, it is required to have both actual and retrospective data on a land area, and to analyze the past with the ecological audit of land sites withdrawn from commercial use and to assess potential risks associated with the adverse effect on the environment [20-22].

When handling issues connected with contamination of components of the environment, and in calculation of cadastral value of land meant for allocation of industrial facilities, including mines, it is proposed to take into account an integral index of man-made load on the natural environment [23]. The interaction between subsoil use and natural environment was comprehensively analyzed in three areas [24, 25], in particular, the forms and degree of mining-induced load on the main components of the environment were displayed, and the response of some biological communities to mining impact was investigated.

The analysis of reference sources on the discussed topic reveals that they mostly aim to determine and substantiate of a single criterion or parameter of the disturbed land condition. An integrated approach to considering a land area from different angles of aspect is almost never used. For instance, in some regions, comparative assessment of mining-induced eco-risks is carried out, and ecological-and-economic damage is calculated for urban land [25, 26], where disturbed land is assessed by the degree of stress or environmental load with its ranking into favorable, relatively favorable, satisfactory, trouble and critical. There are risks of generation and accumulation of large volume of industrial waste required to be recycled. In this case, in land reclamation design, with a view to developing an ecological planning technology, it is necessary to use an indicator of ecological load [26], or to carry out land ranking or zoning by various indicators, with the synthesized analysis of multi-spectral images, and with the identification of levels and degree of the environmental impact of mining [27, 28]. The criteria were only the damage area and atmospheric emission of pollutants, but information on the condition of water and soil, and on radioactivity was neglected [29, 30].

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Considering the aforesaid, and in view of the expedient improvement of the mining-disturbed land assessment reliability and the objective necessity of handling the problem of alternative utilization of such land, the goal was set to develop an integrated approach to the analysis of components of the environment using a compiled list of criteria. For achieving the goal, some local problems were formulated and solved, namely, a case study of the mining-disturbed land analysis in a certain region; identification of reclamation objects and their distinctive features for the condition survey of these objects; definition of estimation criteria for such objects based on their distinctive features and with regard to the attributes of their division, typification and clustering; compilation of a matrix with the list of man-made objects, their parameters and laboratory and field study data on components of the environment.

Research methods

The research used the selected analytical reports of the Federal Services for Statistics (Rosstat), State Registration, Cadastre and Cartography (Rosreestr) and Supervision of Natural Resources (Rosprirodnadzor), State Register of Mineral Reserves and high-resolution satellite images. An additional informative framework was the registered database (Certificate RU2023624553) on disturbed land in solid mineral mining and use in the Novosibirsk Region, including the retrospective data of remote sensing. For achieving the preset goal and problem solving, advanced methods of research were used, including the system, comparative, structural and factor analysis, the subject and sampling research, disturbed land description, landscape synthesis and analysis, geoinformation cartography, etc.

Some researchers analyzed the geoecological evaluation techniques for mining-disturbed land [31-33] and proposed a method of geospatial data acquisition and interpretation for estimating condition of mining sites (Patent N RU 2806406 C1). For the overall estimate of such land and decision-making on its safe recycling, there is either no complete, qualitative and reliable information, or it is impossible to obtain it. Monitoring in combination with field and laboratory studies is either deficient or totally absent, especially at mined-out and abandoned deposits. As per Resolution N 800 of the Russian Government as of July 10, 2018, and according to construction regulations SP 446.1325800.2019 and SP 47.13330.2016 for site investigations for the construction purposes, disturbed land reclamation should be based on the results of surveying. The survey should be sufficient for justification of the scope of land reclamation and conservation, with regard to the recorded physical, chemical and biological data on the condition of soil, and the geological engineering survey results. However, the mentioned documents omit the fact that mineral mining using various methods and geotechnologies generates a new man-made geomedium, with spatially variable geometry, structure and texture, in rock mass which also has its peculiar mechanical, technical, and physicochemical properties.

Alongside with key pollutants, with the preset maximum allowable concentrations to affect the environment as per GOST R 54003-2010, it should be taken into account that dumps may contain low-grade and non-commercial minerals together with mining and processing waste. All these materials undergo changes while being stored for different time, lose their original processing properties, and experience intense natural biological and chemical effects. As a result of such transformations, dust, gases and chemical elements with nonuniform grain composition and properties form; they contaminate air, soil, surface water and groundwater over vast areas, at various intensity and levels of hazard. Even after deactivation and closure of mines, adverse impact on the environment can last for a long time.

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When estimating mining-disturbed land, it is advisable to have data on the content of hazardous and extra hazardous elements in minerals and in host rocks for making a program of field studies and laboratory testing, and for engineering investigations aimed at detecting such elements at newly formed man-made objects. Additional research is also required to prove or disprove the fact of detection of sites with the increased concentrations of chemical elements and compounds, including higher than the enforceable standards, on mining sites and in adjacent areas.

Review of technical literature, regulatory documents and practical experience of mining shows the expediency of integrating approaches and principles of the analysis of mining-disturbed land condition and prospects for the further use. It is required to fully consider the main features of study objects in terms of their identification (material, size, shape, morphology, composition, structure, functions, properties), differentiation (groups, classes, purpose, formation) and clustering (similarity, differences, possibility and conditions of clustering, relevancy criteria).

The proposed approach to the analysis of condition of disturbed land allows using such principles as:

• division, which can be general for all types of effects, and enabling more accurate grouping for the further assessment by the level and character of impact on components of the environment, zoning by the factor of admissible and hyperadmissible environmental load, and mapping with delineation of damage areas and with specification of their sizes;

• typification and clustering which define features of the man-made impact on the natural environment representing rocks, soil, artificial ground, surface water and groundwater, and atmospheric air, which are characterized by parameters and indicators measured on various scales.

The ground for the division of disturbed land sites are assumed to be attributes which enable identification of objects by admissible and hyperadmissible environmental load. For instance, the attribute for typification and clustering can be the type of a man-made impact which leads to the land damage, and the variants of this impact in the form of the quantitative estimates of the disturbed land area which changes in time and space. The consequences of the man-made impact on components of the environment are assessed as the maximum allowable concentrations (MAC) of the test substances from the field studies and laboratory experiments. It should be taken into account that the presence of suspended particulate matter PM 2.5 and PM 10 in the environment, and the radioactivity in the course of mineral mining is also an adverse factor possessing hazardous potential.

The approach proposed by the present authors to the integrated research of mining-disturbed land includes the land analysis by the criteria related to the factors of technology and ecology, which are divided into controllable and uncontrollable (Fig.1). Using the collected and interpreted data, and based on the systematization of parameters and values obtained from the laboratory testing and field studies, disturbed land sites are estimated and recommendations are made on selecting the ranges of their further utilization.

The technology factors are the criteria, which point at the type of an anthropogenic effect and at the category of land at the study objects, presence of special status areas, population density, level of the induced damage, as well as the natural and climatic peculiarities. The ecology factors are the content of hazardous and particularly hazardous elements and radionuclides, radioactivity and index of anthropogenic load on water bodies.

Each criterion has certain ranges, which help decide on the choice of the further use of disturbed land. For instance, such criteria as the content of hazardous and particularly hazardous elements in

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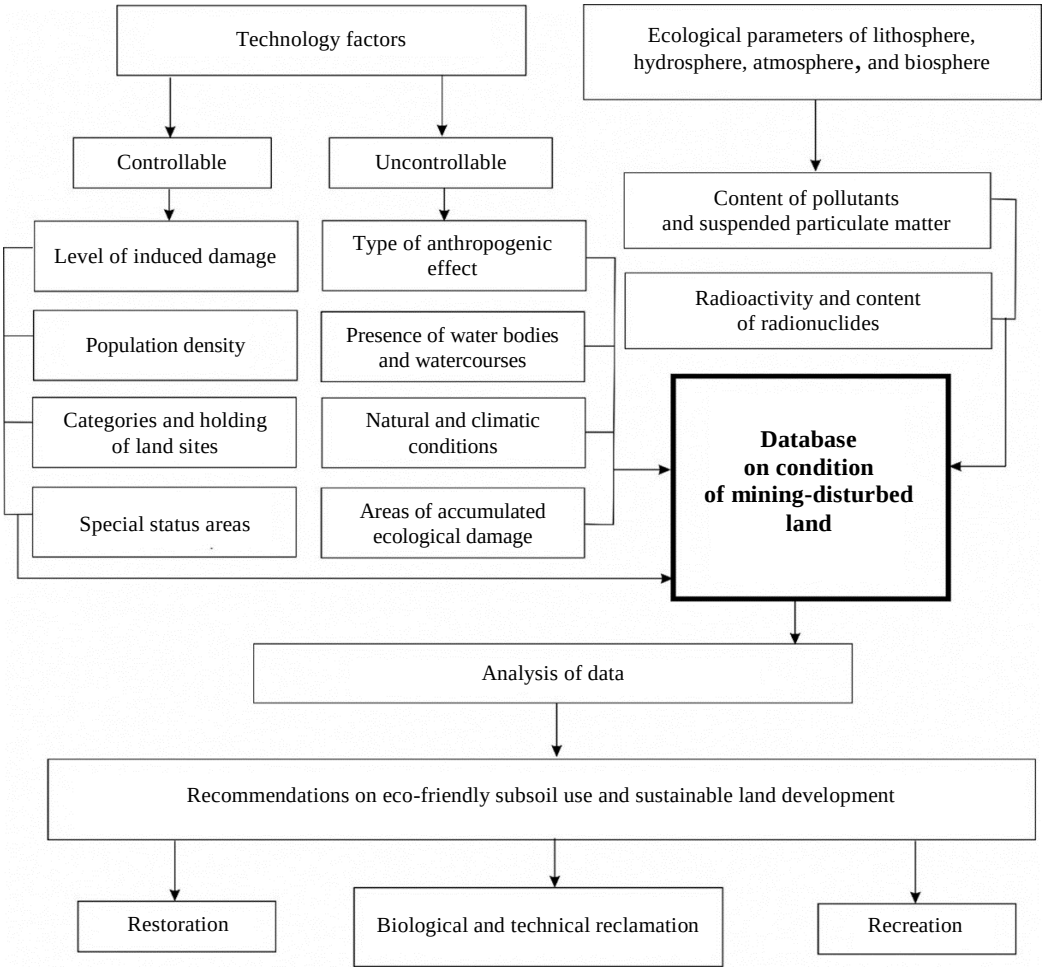


Fig.1. An approach to integrated assessment of mining-disturbed land

the environment, the water content of radionuclides (Rn) or the radioactivity of rocks (U, Ra, Th, K) have numerical values and are correlated with MAC values. The other criteria allow assessing damage of an object in terms of quantitative indicators of such land areas or population density. Moreover, additional criteria are introduced to describe areas with the by-gone ecological damage or with a special status; they both provide retrospective data on a mining region and reveal its natural and climatic characteristics. Such information can make it possible to adjust the rehabilitation trends of mining-disturbed land toward reclamation, restoration, and recreation.

Let us discuss some earlier-proposed criteria and parameters integrated in our case study for the assessment of mining-disturbed land and its environmental impact in one of the region of our country.

1. Type of anthropogenic alteration of soil, vegetation and original land topography, when various man-made damage is induced by direct or indirect anthropogenic influence, including mining and construction, placement of industrial infrastructure for integrated works, withdrawal of land for stock-piling overburden, ash of heat and power stations, processing tailings, domestic waste, etc.

2. Degree of land site damage. There are different assessment procedures with certain advantages and disadvantages. The present authors build their procedure upon Kamyshev's approach (1999), with spotlight on typification and contour delineation of disturbed landscape. For a specific area, a classification was developed for the types of the locality, as well as simple and complex holdings,

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their landscape characteristics were determined, and five categories of damage were introduced and correlated with the values of the damage degree[1].

In this work, the degree of induced land damage is determined as a ratio of an area of an anthropogenic object to the total area of the object location,

$$K_{\text{d}} = \frac{S_i}{S_{\text{tot}}}.$$

The anthropogenic objects are open pits, overburden dumps, dirt piles, and disposal areas of ash from heat and power stations, and domestic waste. Inclusion of the total area of the object location as a normalizer unifies the estimate for the objects of different scale and ensure a correct comparative analysis within a test area.

Since mining objects can be located on different-type landscape, Table 1 offers a classification of the mining-induced damage (MID) for the test area without differentiated ranking of the landscape units (facies, holdings, types of localities). The distribution of the man-made objects by their damage degree used a topological principle, when a damage category was defined by the type of an object (open pit, quarry, dump) with regard to its size. In view of the lack of detailed data on the depth of the objects and on the toxicity of rocks, the main quantitative index was selected to be the area of an object as the handiest and most representative parameter for the preliminary assessment.

Based on the analysis of actual data on 106 objects of the mining sector in the Novosibirsk Region (open pits, quarries, dumps), the damage categorization was performed. It is found empirically that the highest percent of objects comes in the category of weak damage (63 %), medium-disturbed objects total 12 %, and the highly disturbed and extremely disturbed objects make up 7.5 % equally (Table 1).

Table 1

Degree of mining-induced damage in the Novosibirsk Region

Category of damage	Objects	Condition of land at the assessment	Degree of damage, 10^{-3}
Conditionally undisturbed and slightly disturbed land	Flooded and self-overgrown mined-out spaces (open pits, waste rock and ash dumps, dirt piles, etc.) – 10 objects	No mining or other activities for a long time	$K_{\text{d}} = 0$
Weakly disturbed land	Very small open pits (quarries) – 67 objects	Mining or other activities in process	$0.5 \le K_{\text{d}} \le 5$
Moderately disturbed land	Small open pits (quarries) – 13 objects		$5 \le K_{\text{d}} \le 10$
Highly disturbed land	Medium-size open pits (quarries) – 8 objects		$10 \le K_{\text{d}} \le 30$
Extremely disturbed land	Large open pits (quarries) nearby residential areas – 8 objects		$K_{\text{d}} \ge 30$

Note. The limits of K_{d} are determined empirically from sampling of 106 objects in the Novosibirsk Region, and can be revised in expansion of the database.

3. Data on content of pollutants in the environment (soil, air, hydrosphere). The ecological evaluation of test areas should take into account:

[1] Kamyshev A.P. Methods and Technologies of Monitoring Natural-and-Technical System in the Northern West Siberia. Moscow: VNIPIGAZDOBYCHA, 1999, p. 230.

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• the content of pollutants and their compounds in the hydrosphere. The 2024 State Report on the Condition and Protection of Environment in the Russian Federation[2] puts in this category: oil products, phenols, manganese, aluminum, zinc and copper, total iron, nitrite nitrogen and ammonium nitrogen, as well as chemical oxygen demand (COD). The level of pollution is estimated on a two-alternative scale – a single element exceeds MAC or neither element exceeds MAC;

• the content of pollutants in air; according to regulatory documents, these pollutants include elements from the class of extremely hazardous down to the class of weakly hazardous – suspended particulate matter (dust), sulfur dioxide, carbon oxide, nitrogen dioxide, nitrogen oxide, benzpyrene, hydrogen sulfide, phenol, soot, fluorine hydride, ammonia, formaldehyde and metals. Their contents exceeding MAC are used. The level of pollution is estimated as in the previous case;

• the content of pollutants in soils as per The Year Book on Soil Pollution in the Russian Federation with Industrial Pollutants in 2022[3]. We use the contents of industrial toxicants – a set of metals – as the overall pollution index,

$$Z_{\text{b}} = \sum_{i=1}^{n} K_{\text{b}i} - (n-1),$$

where n is the number of metals; $K_{\text{b}i}$ is the metal concentration factor equal to the ratio of mass fraction of an i-th metal to its background mass fraction in soil in the test area.

Our study used the scale of soil contamination hazard by the overall pollution index – tolerable pollution ($Z_{\text{b}} < 16$), moderate hazard (Z_{b} 16-32), hazard (Z_{b} 32-128), extreme hazard ($Z_{\text{b}} > 128$).

4. Radiological safety of water for the use as recreational water, determined by the content of radionuclides in water with regard to the overall volumetric activity of radionuclides, and total alpha or beta activities.

Determination of specific activity of radionuclides (H, C, I, Pb, Ra and Th) in water is obligatory as per SanPiN 1.2.3685-21. The content of Rn in drink water is 60 Bq/kg. Today there are no available data on the total alpha and beta activity in drink water at the test objects, therefore, we only estimate the content of ^{222}Rn in drain water.

Ranking by the criterion of the content of radionuclides in water used two levels (excess, no excess) for the overall volumetric activity of radionuclides ^{222}Rn (> 1.0 Bq/m^3 and ≤ 1.0 Bq/m^3), total alpha activity (> 0.2 Bq/kg and ≤ 0.2 Bq/kg) and total beta activity (> 1.0 Bq/kg and ≤ 1.0 Bq/kg).

5. Natural radioactivity of rocks, which defines radioactivity of soil cover and depends on the content of uranium (radium), thorium and potassium [34]. Maximal radioactivity is typical of soil cover on acid magmatic rocks and clay, and is lower than radioactivity of sedimentary rocks. The effective specific activity of natural radionuclides is found from the formula

$$A_{\text{ef}} = A_{\text{Ra}} + 1.3A_{\text{Th}} + 0.09A_{\text{K}},$$

where A_{Ra} and A_{Th} are the specific activities of ^{226}Ra and ^{232}Th which are in radioactive equilibrium with the other members of the uranium and thorium rows, Bq/kg; A_{K} is the specific activity of ^{40}K, Bq/kg.

According to SanPiN 2.6.1.2523-09 of Radiation Safety Standard (NRB-99/2009), for the use of mining-disturbed land as recreational zone, A_{ef} should never exceed 370 Bq/kg.

[2] The 2024 State Report on the Condition and Protection of Environment in the Russian Federation. Moscow: Minprirody Rossii; VNII Ekologiya, 2025, p. 721.

[3] The Year Book on Soil Pollution in the Russian Federation with Industrial Pollutants in 2022. Obninsk: Taifun, 2023, p. 139.

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6. Population density is assessed as low, average and high – to 10 people/km^2 is the low level, 10-100 people/km^2 is the average level and over 100 people/km^2 is the high level. This criterion is required for the feasibility study of choice of a reclamation trend for mining-disturbed land.

7. Historical data on land and holding for selecting and justifying the reclamation trend for mining-disturbed land. According the National standard for the Environmental Protection in Russia, disturbed land should preferably be reclaimed for the use as agricultural land.

8. Volume and rate of discharge of runoff and drainage water in watercourses in the period of mining operations; conditions and places of change of river and stream channels which can influence quality of surface water and groundwater, and migration of pollutants in them. The quality evaluation of natural water, according to GOST 57075-2016, can use a reference index of anthropogenic load (AL^r) and (or) the specific combinatorial water pollution index. They evaluate water quality loss and water ecosystem degradation, which characterize typical adverse effects and are calculated by basic analytical markers. It is proposed to rank quality degradation and change of condition of water ecosystems under anthropogenic load by AL^r which offers an ecological characteristic of a water body between the low and high quality (Table 2) as per Order N 552 of the Russian Ministry of Agriculture as of December 13, 2016, GOST R 58556-2019, GOST R 57075-2016, and GOST 17.1.3.07-82. For them, we assumed the estimation levels dependent on the ecosystem criticality and AL^r for certain quality classes of water bodies (Table 2).

Table 2

Quality of water ecosystems

Estimation index	Water quality class				
	Crystal clear	Clean	Moderately polluted	Polluted	Filthy
AL^r	$AL^r \le 4.2$	$4.2 < AL^r < 10.8$	$10.8 < AL^r \le 24.0$	$24.0 < AL^r < 70$	$70 < AL^r < 135$
Criticality of ecosystem	Reversible changes		Vulnerability threshold	Reversible and irreversible changes	

Calculation of AL^r, by GOST R 58556-2019, needs basic analytical markers by basic types of impact: dry residue (overall mineralization), pH (acidification or alkalization), decrease of transparency (inert suspended matter or anthropogenic suspended matter), reduction of dissolved oxygen content (COD, BOD_5), euthrophication (total phosphorus, including phosphate phosphorus, total nitrogen, including ammonia nitrogen, nitrate nitrogen and nitrite nitrogen), biogenic infeed of water bodies (total iron), and secondary pollution from bottom sediments (total manganese),

$$AL^r = \sum_{i=1}^{n} AL_i,$$

where AL_i is the anthropogenic load of an *i*-th type of impact, conv.m^3/m^3; *n* is the number of the types of impact.

9. Areas with the historically accumulated ecological damage (harm), which, by Resolution N 2239 of the Russian Government as of December 21, 2023, include the areas contaminated with chemical substances as a result of by-gone economic or other activity, storages of industrial and domestic waste, outcast industrial areas and buildings, outcast and flooded objects in water zones. The modern audit of such land in mining areas and urban agglomerations allows accumulated waste management, disturbed land reclamation and rehabilitation, improvement of ecological conditions of living, as well as reduction of ecological hazards and risks.

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10. Sanitary protection zones (SPZ) which should never include mining-disturbed land as per SanPiN 2.1.4.1110-02. Particular attention should be given to special status areas, such as water intake facilities and adjacent area, and natural areas of preferential protection. Their protection from contamination assumes creation of SPZ.

11. Natural climatic conditions of a region is a factor of no little significance when selecting an application range for mining-disturbed land. Accounting for this factor is required in determining conditions and sequence of reclamation activities as location of an object, for instance, in the Far North, or in arid regions, on a broken or flat terrain, needs an individual approach.

Discussion of results

As a case study of application of the listed criteria, we estimated the environmental impact of mining-disturbed land in the Novosibirsk Region. Solid mineral mining is carried out mainly in the east of the region, in coal fields, at placers and at deposits of nonmetallic minerals.

Review of the State Register of Mineral Reserves of Russia and periodicals shows a certain increase in production of coal and gold in the Novosibirsk Region in recent years [35-37]. Extraction of building materials has also grown by 20 % on the average (except for building stone – its production decreased by 10 %). Accordingly, we can say that the area of mining-disturbed land expands annually [38-40].

For the approval of the proposed procedure for the assessment of mining-disturbed land with the further ranking by the level of impact on components of the environment, a matrix was composed of man-made objects and their estimation criteria.

Using obtained data integrated into a database, in the study region, 106 mining-disturbed land sites are identified together with the storage sites of produced minerals and processing waste. For the assessment of the disturbed land in the Novosibirsk Region, clustering was used to group the man-made objects [28, 29].

By the type and nature of anthropogenic impact that induced damage, 87 objects were referred to mined-out spaces, 8 – to production pools, 3 – to domestic waste dumps and 6 – to ash dumps.

By the factor of the environmental load with the evaluation of MAC of hazardous and extremely hazardous elements (pollutants) from the laboratory testing, the following subgroups were sorted out:

• conditionally undisturbed sites of three objects, including flooded, abandoned or self-overgrown mined-out spaces of mineral mining, with the revealed exceedance of MAC in water;

• weakly disturbed (damage area less than 0.5 % of the total area was selected for the correlation) sites of 85 man-made objects, including three objects with the exceedance of MAC in soil and water; five objects – in water, and two objects – in air;

• moderately disturbed (damage area from 0.5 to 1.0 %) sites of 12 objects, including only one object with the exceeded value of MAC in air;

• highly disturbed (damage area from 1.0 to 3.0 %) sites of two objects without exceedance of MAC;

• extremely disturbed (damage area larger than 3.0 %) sites of two objects without any revealed exceedance of MAC.

In the Novosibirsk Region, according to Rosstat, population is more than 2.7 million people, and Novosibirsk, where more than 1.6 million people live, features high population density. Meanwhile, some localities of mineral mining have low density of population. By the criterion of population density, out of 106 man-made objects in the Novosibirsk Region, 87 objects with mined-out space were selected, including 65 objects with low population density to 10 people/km^2 (75 %), 17 – average population density to 100 people/km^2 (19 %) and 5 – high population density more than 100 people/km^2 (6 %). The group of production pools was also ranged by the population density

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criterion: low density – six objects, average density – two objects; solid domestic waste dumps: low density – two objects, average density – one object, high density – one object. Ash dumps: low density – two objects, average density – four objects. The data analysis shows that only six objects feature high population density, which allows a conclusion that the disturbed land sites with high population density occur mostly within the limits of the city.

Based on the data from The 2024 State Report on the Condition and Protection of Environment in the Russian Federation[4] for the Novosibirsk Region and on the published materials, we analyzed components of the environment as follows.

Atmospheric air. From 2019 to 2022 in the region of Novosibirsk, mid-annual concentration of dust somewhat grew, with MAC exceeded by 80-90 % sometimes. The atmospheric air monitoring of the contents of carbon and sulfur dioxide, ozone dust particles, with concentrations higher than MAC showed that the exceedance was recorded at 3 out of 14 observation points. In the area of the town of Iskitim, within the same time span, mid-annual dust concentration increased by 2.5 times and reached 3.7 MAC in 2022. This fact is also proved by satellite images, which show the distance of coal dust migration from the producing Kolyvan field of anthracite, Gorlovo coal basin, to Iskitim (Fig.2).

Soil. Between 2019 and 2022, on three sites in the Iskitim district with the developed mineral production, exceedance of MAC was revealed for strontium by 10 times and for barium and lead by 3 times. The ecological condition of soil at Novosibirsk is moderately hazardous in terms of tin and cadmium contents. The periodic soil monitoring at ash dumps of heat power stations N 2-5 shows no exceedance of MAC for benzpyrene, zinc, copper and lead.

Water. The surface water objects in the Novosibirsk Region, belonging to the national water resources, represent watercourses (rivers, streams, and drain channels) – more than 7 thousand, and water bodies (a water reservoir, lakes, ponds, swamps) – more than 6 thousand. Small watercourses less than 10 km long are 94.2 % of the total number of watercourses in the region. The current condition of the most water objects and coastal areas disagrees with the effective environmental

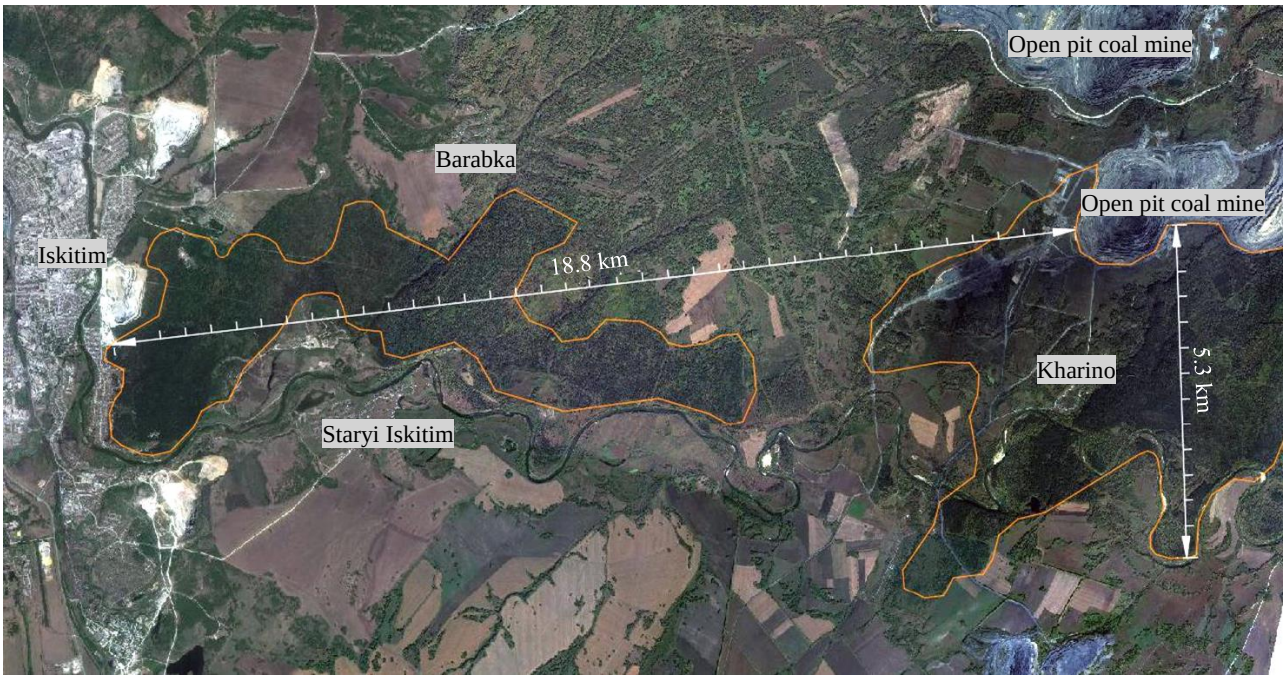


Fig.2. Migration of coal dust from operating open pit coal mine

[4] The 2024 State Report on the Condition and Protection of Environment in the Russian Federation. Moscow: Minprirody Rossii; VNII Ekologiya, 2025, p. 721.

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and zoning standards. The change in the natural water regime and the wrong situation of water objects in the Novosibirsk Region is induced by the anthropogenic loading (discharge of runoff water and pollutants, arrangement of man-made objects in water protection zones and in coastal protective belts, etc.); natural factors (cyclic fluctuations of water level due to climate change, water bloom due to algal nuisance, insufficient oxygen); man-made causes of impairment of outflow at water intakes and water regime worsening (river flow adjustment, damming of lakes and watercourses, construction and open pit mining on riverbeds). The quality of surface watercourses within the limits of the Novosibirsk and large regional settlements, except for the Ob River, puts them in the class of dirty and filthy water. The main pollutants are oil products, phenols, COD, manganese, aluminum, zinc, copper, total iron, nitrite nitrogen and ammonia nitrogen[5].

The chemical analysis of drainage water at operating, mined-out and flooded quarries of broken stone, coal, marble, and sand shows that water at granite quarries and open pit coal mines have neutral pH, and at sand and marble quarries – alkaline pH [37, 38]. At open pit coal mines, water is more mineralized, with total mineralization to 1171 mg/dm^3, which conforms with slightly salted water, while the rest of drainage water is ultra-sweet and sweet. By the calculated geochemical ratios, water at sand and marble quarries accumulate mostly sodium, calcium and magnesium, and at granite quarries and open pit coal mines – silicon. Increased sodium in solution is connected with anthropogenic pollution. Drainage water at the Borok and Skala quarries of granite contain dissolved oxygen 1.3-1.5 times lower than MAC set for fishery water bodies (MAC$_{fish}$), while concentration of sulfates is 1.2-2 times higher. The maximal concentration of sulfates in drainage water (2-5 times higher than MAC$_{fish}$) is recorded at the Urgun, Gorlovo and Kolyvan open pit coal mines. The highest concentrations of radionuclides are found in water of granite-bearing rock mass, where the contents of uranium and thorium reach 1.40 mg/dm^3 and $2.16 \cdot 10^{-3}$ mg/dm^3, respectively, which is logical as this type of rock accumulates incoherent elements [34]. So, discharge of drainage water from solid mineral mining to watercourses in the east of the Novosibirsk Region has unsubstantial impact on the natural water quality.

During open pit mining, it is often required to divert surface watercourses beyond the boundary of a mining lease, with creation of an artificial channel. This leads to total transformation of a watercourse ecosystem, which is only recoverable in a long time. An illustration of such transformation is the Urgunchik stream, a second-order tribute of the Berd River. As a result of the stream diversion beyond the mining lease boundary of the Urgun site of the Gorlovo open pit coal mine, Siberian Anthracite JSC, the natural flow of the stream was re-directed by damming to a man-made channel. The stream takes a discharge of treated runoff (mine) water. Natural water conforms to the requirements of MAC$_{fish}$ and sanitary standards in terms of almost all indicators. At the same time, all indicators of vegetation, both on the stream bed and in the water protection zone, are reflective of the ecosystem crisis. Thus, the cause of this situation is the diversion of the Urgunchik stream channel. Currently, the ecosystem of the new channel is at the stage of formation, which explains low plant diversity and predominance of species-indicators of unhealthy situation at the new watercourse.

The adverse effect mitigation is possible through disturbed land reclamation [1, 11], including both surface mines and dumps. On the site of the Malyi Elbash River (Kolyvan field of anthracite, Gorlovo coal basin), after implemented reclamation of overburden dumps, the condition of vegetation cover on the riverbed and in the water protection zone is satisfactory. High species diversity and projective cover of water and coastal bet vegetation is observed. By the saprobity index, water in this area feature throphic and saprobic indicators of water of satisfactory purity.

[5] The 2024 State Report on the Condition and Protection of Environment in the Russian Federation. Moscow: Minprirody Rossii; VNII Ekologiya, 2025, p. 721.

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Since the Novosibirsk Region lies in the zone of the increased regional radioactivity background, the content of radionuclides in water and the radioactivity of rocks was analyzed. Allowable content of natural radionuclides in mineral raw materials and mineral products (natural and artificial stone, ceramics, ceramic granite, etc.), as well as their radiation safety is set by SanPiN 2.6.1.2523-09. During 2022-2024 at Trofimuk Institute of Petroleum Geology and Geophysics, SB RAS, more than 200 rock samples from water intake wells at operating open pit mines (core and slurry) and from natural outcrops of country rocks representing the Ob and Barlak granitoids (P_3-T_1, T_{1-2}) were investigated [34]. The Ob rock studies show that this type of rocks features low concentrations of uranium (1-3 g/t) and thorium (1-16 g/t). Some samples of leucogranite (probably, from dykes) from the Gorsky site contain up to 8 g/t of uranium and 25 g/t of thorium. High contents of uranium and thorium are found in the Barlak granite-leucogranite meso-abyssal system, which are on the average 21 and 36 g/t, respectively, which puts these types of rocks in Class III by the value of A_{ef}.

The radioactivity study of water-bearing rocks sampled in the coal section of surface mines in the Gorlovo coal basin in the Novosibirsk Region (Fig.3) and at some other objects shows that the contents of uranium and thorium are 9.6 and 17.7 g/t, respectively, in magmatic rocks and 2.5 and 4.6 g/t, respectively, in sedimentary rocks. The highest contents of uranium (to 65.1 g/t) and thorium (to 108.8 g/t) are found in the intrusive complexes of the Kolyvan granitoid massive. This fact is confirmed by the high value of A_{ef}, which is 1216-1377. The most of the studied objects present no danger to population, which puts these rocks in Class I of radiation safety of construction materials. Radioactivity of drainage water is directly correlated with distribution of radioactive elements in

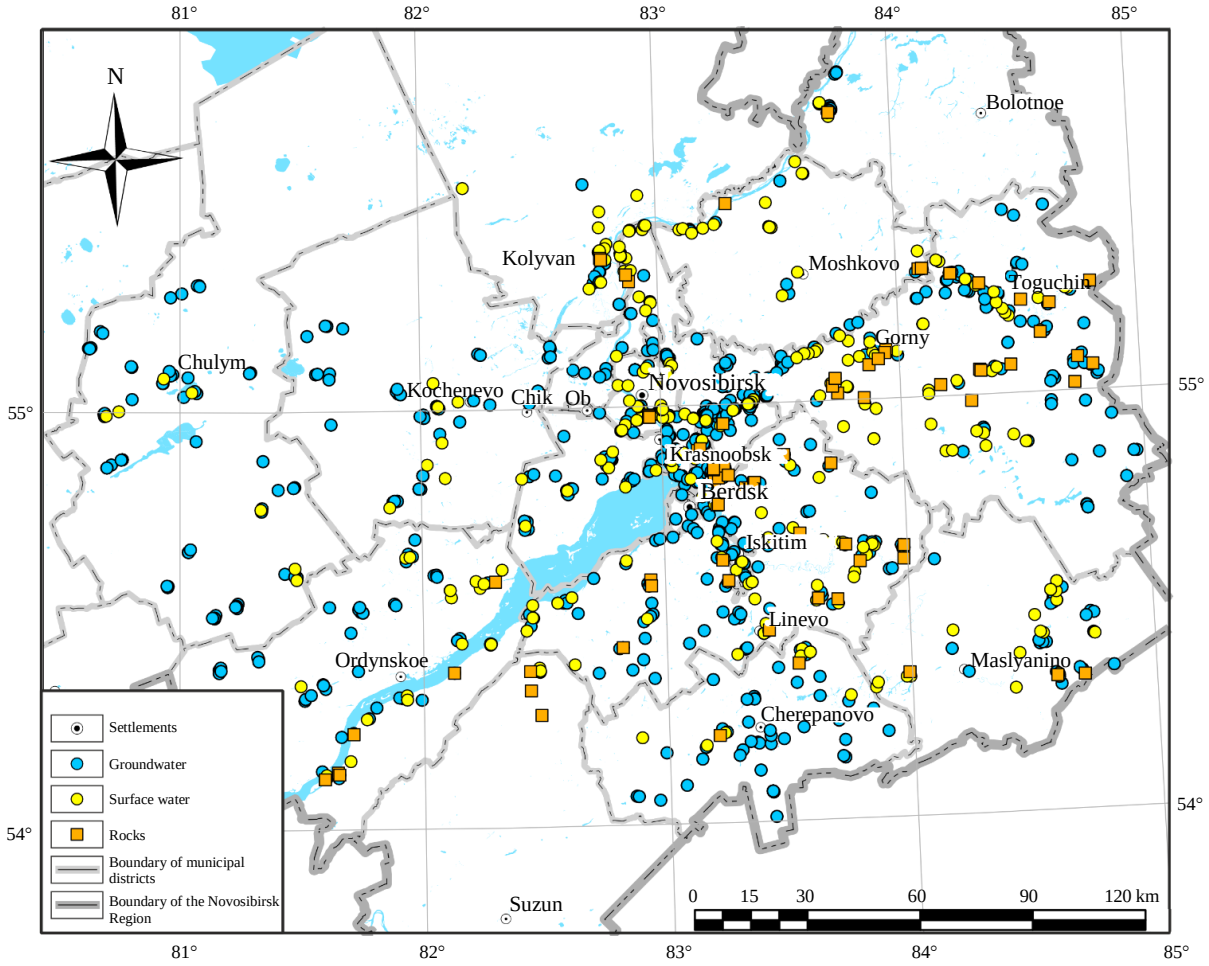


Fig.3. Layout of sampling points for radioactivity of natural water and rocks

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host rock mass [34]. The feature of the Novosibirsk Region is the granite plates with the high content of natural uranium, which decomposes, and emits ^{222}Rn due to the presence of scattered radioactive minerals. In connection with this, an important criterion of mining-disturbed land assessment in the Novosibirsk Region is the content of radionuclides in water [34].

Based on the collected data and using the proposed criteria, a matrix of mining-disturbed land areas was created for their further ranking by the level of their impact. The matrix includes the objects, their environmental impact, and the adjacent area condition. The matrix allows a comprehensive analysis of mining-disturbed land and is a tool of the strategic analysis aimed at social and economic development planning in the test region.

As the assessment objects in the matrix, we study surface mining operations producing solid minerals in different districts of the Novosibirsk Region. For instance, the Borok and Kirovsky quarries are situated in the Oktyabrsky and Novosibirsky districts of Novosibirsk, and the Gorlovo open pit and a gold placer at the Kinterep River – in the Iskitim and Maslyanino districts, respectively (Fig.4). The objects, which are within the limits of the city, exert a high impact both on people and on components of the environment. The main impacts of solid mineral mining are withdrawal of different rank land, harmful emission during drilling, mining and haulage of rocks, noise, violation of ecosystems of rivers and water bodies, alteration of landscape, dust formation, etc.

The analysis revealed additional and very specific adversities for the environment. For instance, the main mineral extracted at the Borok quarry (Fig.4, *a*) is hornstone which is used to produce broken stone. In this context, the main environmental impact is connected with harmful emission during crushing, and with impact on water resources, namely, the change of the hydrological regime as the quarry is situated in the old channel of the Inya River. At the Kinterep River (Fig.4, *c*), hydraulic mining of placer gold is carried out, and the main impact is the change of landscape on both banks

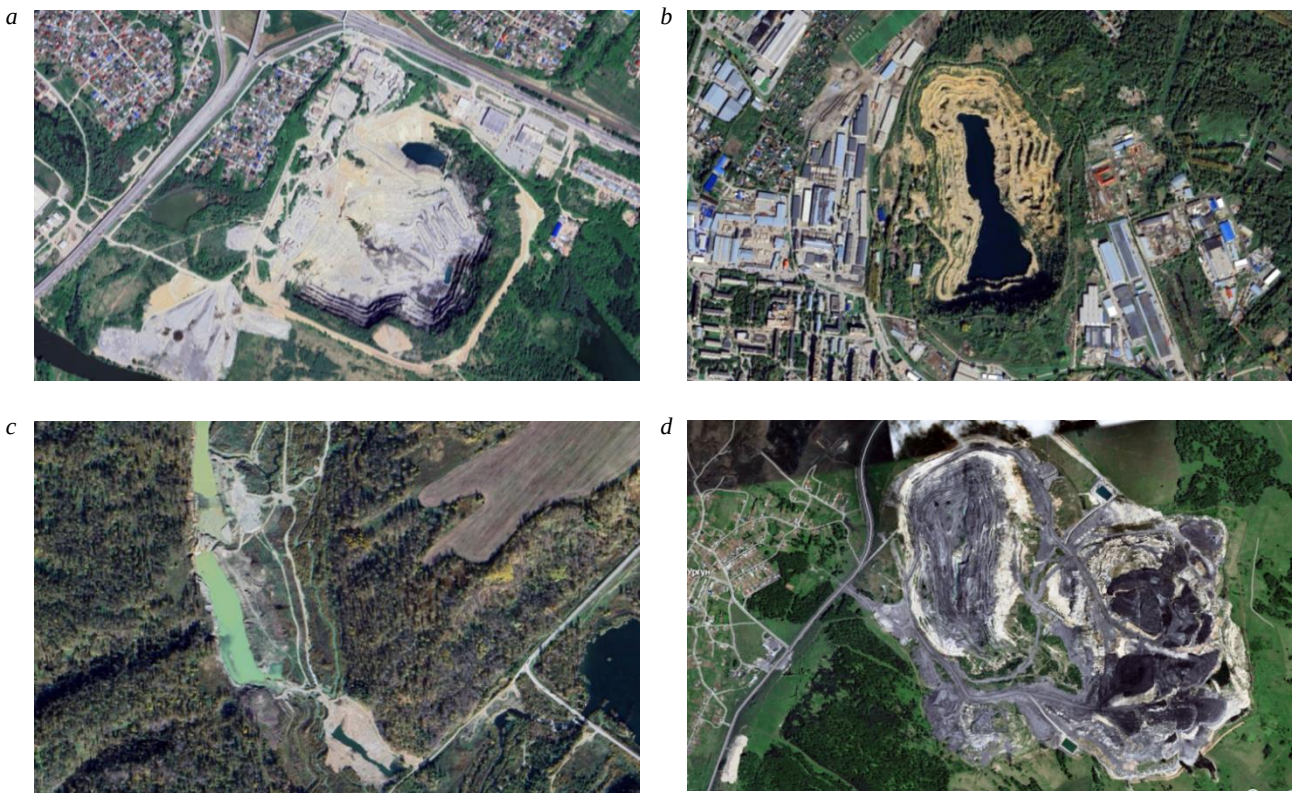


Fig.4. Mining-disturbed land objects:
a – Borok quarry; *b* – Kirovsky quarry; *c* – Kinterep River; *d* – Gorlovo open pit

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of the river. At the test open pit coal mine (Fig.4, *d*), the main adversity is coal dust which can migrate for very long distances (see Fig.2).

The implemented analysis of impact generated by each of the test objects revealed their significant difference both in type of the impact and in its intensity. For the descriptive characteristic and comparative appraisal with the further ranking, the objects are compiled in the matrix of mining-disturbed land assessment (Table 3).

Table 3

Matrix of mining-disturbed land assessment for the listed objects in the Novosibirsk Region[6] [34]

Assessment criteria	Mining-disturbed land by remote sensing data				Kirovsky quarry (sand)	Gorlovo open pit mine (coal)	Kinterep River (gold)	Borok quarry (construction stone)
Mining-induced damage (quality assessment)	MID < 0.5 %		Conditionally disturbed					
	0.5 % < MID < 1 %		Weakly disturbed		■		■	■
	1 % < MID < 3 %		Moderately disturbed					
	3 % < MID < 10 %		Highly disturbed			■		
	10 % < MID		Extremely disturbed					
Content of hazardous and extremely hazardous elements (with determination of MAC exceedance area)	Laboratory testing of MAC for hazardous and extremely hazardous elements	Total index of soil pollution with a set of metals	Z_b < 16	Permissible				
			16 < Z_b < 32	Moderately hazardous				■
			32 < Z_b < 128	Hazardous	■			
			Z_b > 128	Extremely hazardous				
		Content of pollutants in water	Exceedance of MAC for fluorides		■			
			No exceedance of MAC for fluorides			■	■	
		Content of pollutants in air	MAC exceeded					
			MAC unexceeded					
Content of radionuclides in water (Rn)	Total volumetric activity of radionuclides		Higher than 1.0 Bq/m^3					
			Not higher than 1.0 Bq/m^3					
	Total alpha activity		Higher than 0.2 Bq/kg					
			Not higher than 0.2 Bq/kg					
	Total beta activity		Higher than 1.0 Bq/kg					
			Not higher than 1.0 Bq/kg					
Radioactivity of rocks (U, Ra, Th, K)	Index of effective specific activity of natural radionuclides		Higher than 370 Bq/kg					
			Not higher than 370 Bq/kg		■			
Population density	To 10 people/km^2			Low				
	10-100 people/km^2			Average	■	■	■	
	Over 1000 people/km^2			High				■
Integrated index of anthropogenic load on watercourses and water bodies located nearby industrial sites	AL^r ≤ 4.2 conv.m^3/m^3		Crystal clear	Low				
	4.2 ≤ AL^r ≤ 10.8 conv.m^3/m^3		Clean					
	10.8 ≤ AL^r ≤ 24 conv.m^3/m^3		Moderately polluted	Average				
	24 ≤ AL^r ≤ 70 conv.m^3/m^3		Polluted	High				
	70 ≤ AL^r ≤ 135 conv.m^3/m^3		Filthy					
Categories and holding of land resources	Agricultural land							
	Industrial land				■	■	■	■
	Natural area of preferential protection							
	Land of forest resources							
	Land of water resources							
Areas of accumulated ecological damage	Present							
	Absent				■	■	■	■
Special status areas	Present							
	Absent				■	■	■	■
Specific natural and climatic conditions	Present							
	Absent				■	■	■	■
Anthropogenic cause of disturbed land	Mineral mining				■	■	■	■
	Production pools							
	Ash dumps of heat power stations							
	Solid domestic waste dumps							

[6] The Year Book on Soil Pollution in the Russian Federation with Industrial Pollutants in 2022. Obninsk: Taifun, 2023, p. 139.

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The analysis of the matrix in Table 3 allows an intermediate conclusion on the nonuniform environmental impact of the mining objects in the Novosibirsk Region. The disturbed land assessment by the proposed criteria (environmental impact, land category, type of impact) confirms the necessity of differentiated reclamation approach. The research findings can serve as a framework for the strategic planning of the social and economic development in the region, with the identification of the top-priority trends of the land rehabilitation and ecological risk minimization.

Conclusion

The review of technical literature and regulatory documents revealed the necessity of integrated periodic monitoring of man-made objects, as well as their investigation on laboratory and full scales for determining their environmental safety. The regular monitoring of the natural environment components can enable evaluation of ecological damage because of disturbance and contamination of land, with the ultimate target at cost estimation of the prevention and elimination of the adverse after-effects, and at selection of trends for the further recovery of mining-disturbed land.

The existing procedure available for the evaluation of man-made impact on the environment omit specifics of a test region, and the required study is carried out before mining operations, which prevents from taking into account all possible ecological risks. For the well-timed acquisition of quantitative and qualitative data on the environmental impact of mining-disturbed land, it is required to increase the number of fixed points for the real-time continuous monitoring. Remote sensing data provide a visual evidence of migration distances for suspended particulate matter.

The new approach proposed by the authors rests upon a geoinformation database on disturbed land and a matrix of anthropogenic object assessment, including such criteria as the type of the anthropogenic impact, contents of hazardous and extremely hazardous element in components of the environment, radioactivity, population density, etc. The approach allowed an integrated assessment of mining-disturbed land sites in the Novosibirsk Region for their further ranking by the level of the environmental impact, and for selecting optimized ranges for the further land use.

The integrated assessment of mining-disturbed land is necessary for the development of an expert system based on the list of the proposed criteria, and can be expanded and joined together with indexes determined on various scales. Yet, the implementation of this system requires complete, high-quality and reliable information on objects of the mining industry.

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