



Original article

EDN: UKAGXU

DOI: 10.21285/2686-9993-2026-49-1-6



## Spatiotemporal distribution of elements in technogenic soils of Kovykta gas condensate field

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**Abstract.** The purpose of the conducted study was to identify the spatial and temporal distribution of heavy metals and arsenic in a gas condensate field for the period from 2019 to 2025. The annual increase in manganese, arsenic, and nickel concentrations exceeding the estimated permissible concentrations allowed for a clear assessment of the relationship between the intensity of development in the gas production zone and the level of negative impacts from the release of these elements into the soil. In accordance with the objectives, a critical analysis of all production units on the industrial site was conducted to assess the potential for pollutants to enter the soil. The coefficients of element accumulation were obtained relative to the global clarks according to Vinogradov. Thus, arsenic, manganese, and nickel showed an increased accumulation coefficient of  $K_k \geq 1.5$ . Geoecological processes associated with technogenesis in the area of the gas condensate field are accompanied by the formation of soil contamination halos, which was determined using geoinformation system technologies. Geochemical parameters of soils, as indicators of their conditions, reflect high functionality under the adverse impacts of gas production and provide a realistic assessment of the geoecological situation at the field. It is shown that the spatial distribution of manganese and nickel elements is primarily related to technological processes, regular production works and welding. The excessed contents of arsenic may be due to the inherited geological and geochemical features of the Baikal natural territory with the elevated content of this metalloid in the soil imported for the Kovykta gas condensate field development. Thus, the integration of geoinformation system technologies and geochemical survey results is an effective tool for the comprehensive geoecological assessment of the territory in the technogenic zone and serves as a basis for the development of effective, modern, object-oriented monitoring in the gas condensate field zone.

**Keywords:** gas condensate field, industrial site, gas well cluster, soil, geochemical parameters, heavy metals, geoinformation system

**For citation:** Pyzhianov D.I., Sarapulova G.I. Spatiotemporal distribution of elements in technogenic soils of Kovykta gas condensate field. *Earth sciences and subsoil use*. 2026;49(1):72-83. <https://doi.org/10.21285/2686-9993-2026-49-1-6>.

Научная статья

УДК 622.3+504.5+912.43

## Пространственно-временное распределение элементов в техногенных почвах Ковыктинского газоконденсатного месторождения

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**Резюме.** Цель проведенного исследования заключалась в выявлении характера пространственно-временного распределения тяжелых металлов и мышьяка на территории газоконденсатного месторождения за период 2019–2025 гг. Динамика повышения содержаний по годам для марганца, мышьяка, никеля с превышением ориентировочно допустимых концентраций позволила наглядно оценить зависимость между интенсивностью освоения территории в зоне добычи газа и уровнем негативного воздействия в виде поступления этих элементов в почву. В соответствии с задачами проведен критический анализ всех промзвлов на площадке с позиции потенциального поступления загрязняющих веществ в почвенный слой, получены коэффициенты накопления элементов относительно мировых кларков по Виноградову. Так, обнаружен повышенный коэффициент накопления мышьяка, марганца, никеля ( $K_k \geq 1,5$ ). Геоэкологические процессы техногенеза в районе газоконденсатного месторождения сопровождаются формированием ореолов загрязнения почв, что определено посредством геoinформационных систем технологий. Геохимические показатели почв как индикаторы их состояния отражают высокую функциональность в условиях негативного воздействия при добыче газа и реально оценивают геоэкологическую обстановку на месторождении. Показано, что пространственное распределение марганца, никеля преимущественно связано с технологическими процессами, регулярными производственными работами и сваркой. Превышение же содержаний мышьяка может



быть обусловлено наследованием геолого-геохимической особенности Прибайкальской природной территории с повышенным содержанием этого металлоида в составе привозного грунта для планировки территории Ковыктинского газоконденсатного месторождения. Таким образом, интеграция геоинформационных систем технологий с результатами геохимических исследований является эффективным инструментом комплексной геоэкологической оценки территории в зоне техногенеза и служит основой для создания эффективного современного объектно-ориентированного мониторинга в зоне газоконденсатного месторождения.

**Ключевые слова:** газоконденсатное месторождение, промплощадка, куст газовых скважин, почва, геохимические параметры, тяжелые металлы, геоинформационная система

**Для цитирования:** Пыжьбянов Д.И., Сарапулова Г.И. Пространственно-временное распределение элементов в техногенных почвах Ковыктинского газоконденсатного месторождения // Науки о Земле и недропользование. 2026. Т. 49. № 1. С. 72–83. <https://doi.org/10.21285/2686-9993-2026-49-1-6>.

## Introduction

The geoeological state of gas condensate field territories is influenced by increasingly intensive production and is associated with the problem of taiga landscape disturbance and the risks of soil contamination by drilling products, gas treatment, and transportation [1, 2]. This process involves mechanical soil destruction, adverse physical and chemical impacts with the fragmentary or complete annihilation of humus, and topsoil compaction. Chemical impact on the soil cover occurs both as a result of atmospheric deposition from industrial units and due to leaks and losses of process fluids from operating installations. This also occurs due to violations of equipment operating regulations and accidents. In gas production areas, there is a threat of persistent and sometimes irreversible transformation of natural ecosystems, leading to the formation of a mining industrial natural-technogenic system with a dominant technogenic component. Moreover, the boundaries of such an impact significantly exceed the territory of the immediate field development area [3].

The spatiotemporal distribution of pollutant elements, including heavy metals in soils, is characterized, as a rule, by high heterogeneity, concentrating near pollution sources and accumulating over time due to the absence of biodegradation. Maximum concentrations are characteristic of the upper humus horizon; the contamination is cumulative in nature, and under prolonged technogenic impact, the concentrations of heavy metals in the soil increase.

In this regard, forecasting the scale of the negative impact of gas production areas on soils is a relevant and necessary long-term task for identifying the most vulnerable natural components of the

territory under the influence of intensifying mining industrial technogenesis [4, 5].

Despite a number of studies on the geoeological state of territories in the gas production zone, the problem of establishing object-oriented ecological and geochemical monitoring within field territories, as well as the prospects of technogenic impact on soils, remains relevant [6–8].

It should be taken into account that at a high level of contamination exceeding the soil's capacity to bind toxicants, the accumulation of pollutants in the soil profile and their subsequent migration may occur [9–12]. Global research and soil condition monitoring record a dangerous global trend of increasing heavy metal concentrations, which is most acutely observed in the zone of subsurface development and mineral extraction. As a result, hazardous endogenous processes form in these territories, local geochemical anomalies with elevated toxicant contents arise, and a global technogenically altered geochemical structure of the lithosphere is formed [13]; therefore, the development of new approaches for the geoeological assessment of dynamically changing natural systems under conditions of intensifying technogenesis is a pressing problem [14].

In this work the main emphasis is placed on studying the spatiotemporal dynamics of the geoeological state of the soil cover, which serves as a natural depository for all pollutants entering it during the operation of numerous production units involved in gas extraction. The most effective and illustrative method is the use of geoinformation system technologies (GIS technologies), which allow for a highly informative assessment of changes in the state of the territory, including soils, and forecasting the development of the situation under technogenesis conditions.



As part of our systematic research in the technogenesis zone on the topic “Theory and methods of geocological assessment of ecosystems, engineering protection, and forecasting the state of the technogenically altered natural environment”, the following goals and objectives of this work have been formulated.

The purpose of the study is to identify, using geochemical parameters of soils and GIS technologies, the spatiotemporal distribution dynamics of heavy metals – cobalt, manganese, copper, nickel, lead, cadmium, zinc (included in the main list of priority pollutants), as well as arsenic – in technogenically transformed soils on the territory of a gas condensate field.

Research objectives:

1) to identify potential sources of technogenic pollutant input into the soils at the industrial site of the field;

2) to obtain quantitative parameters of the geochemical state of technogenic soils in dynamics over the years for the period 2023–2026 and earlier (for comparison), considering the priority list of pollutants;

3) to obtain the GIS distribution (halo maps) of the controlled elements in the soils on the field territory, to identify geochemical anomalies and associations, as well as the directions of pollutant migration.

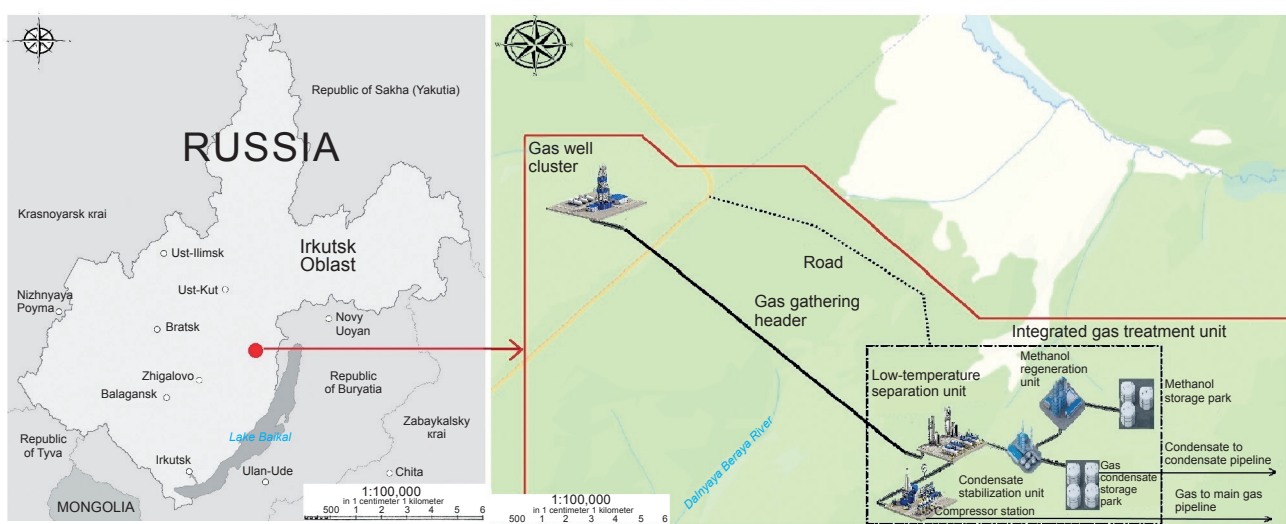
## Materials and research methods

**Object of the study.** The object of the study was technogenic soils on the territory of the Kovykta gas condensate field, located in the north of the Irkutsk region. Fig. 1 shows the location area of the gas condensate field and the industrial installations at the industrial site, where soil sampling for research was conducted over a period of three years.

**Subject of the study.** The subject of the study was the soil in the zone of influence of industrial facilities (units) at the industrial site of the Kovykta gas condensate field and its geochemical parameters, which serve as indicators of the ecological state.

**Research methods.** To achieve the set objectives, the following methods were applied in the work: a systems approach, comparative and geocological analysis, mathematical and GIS modeling. Sample preparation was carried out in accordance with State Standard 17.4.4.02-2017<sup>1</sup>. The elemental chemical composition of soils (total contents) was determined using standard geochemistry methods: atomic absorption spectroscopy (on certified equipment) and X-ray fluorescence analysis using a portable SciAps X-200-30453 series instrument.

Soil pH values were obtained potentiometrically according to State Standard 26212-91<sup>2</sup>. Organic



**Fig. 1. Location of the Kovykta gas condensate field and industrial installations at the industrial site**  
**Рис. 1. Расположение Ковыктинского газоконденсатного месторождения и промышленные установки на промплощадке**

<sup>1</sup> State Standard 17.4.4.02-2017. *Nature protection. Soils. Methods for sampling and preparation of soil for chemical, bacteriological, helminthological analysis.* Moscow: Standartinform; 2018, 20 p.

<sup>2</sup> State Standard 26212-91. *Soils. Determination of hydrolytic acidity by Kappen method modified by CINAO.* Moscow: Izdatelstvo Standartov; 1992, 7 p.



carbon content was determined photometrically according to State Standard 26213-2021 (clause 6.1)<sup>3</sup>, and total nitrogen content was determined by the photometric method according to State Standard R 58596-2019 (clause 7.2)<sup>4</sup>. Statistical data processing was performed in Statistica 10; schematic maps were built in Surfer 23.1.162 using GIS techniques<sup>5</sup> [15–17].

## Results and discussion

To support economic activities during the operation period of the Kovykta field, more than 7,500 km<sup>2</sup> of land have been utilized, which, under intensive gas production and adverse impacts on soils, inevitably leads to soil degradation. However, the production area continues to expand. Loamy soils on the field territory have formed as technozems, which are distributed across the entire industrial site. Soil materials for site development and grading were imported from nearby quarries and borrow pits within the Irkutsk region, particularly from the Zhigalovo and Kazachinsko-Lensky districts. Mudstones and clay rocks were imported from local quarries of the Yarakinsky field and nearby locations.

In accordance with the objectives, a critical analysis of production units at the industrial site was conducted from the perspective of the potential release of pollutants into the soil layer.

**Gas wells.** Gas wells are a critically important initial technological facility that determines the operational capacity and overall efficiency of the field. During well operation, drill cuttings, petroleum products and condensate, methanol (as a hydrate formation inhibitor), and brine rich in heavy metals and salts enter the soil. Drilling fluids used during drilling may also contain reagents such as polymers and rheological modifiers [18, 19].

**The gas gathering header.** The gas gathering header is a pipeline system for collecting gas and condensate. Pollutants from leaks may include gas condensate and hydrocarbons, methanol, and

brine containing large amounts of heavy metals and salts that seep into the ground due to metal corrosion or damage [20].

**Low-temperature separation unit.** This technology involves separating liquid from gas and separating condensate and water-methanol solution by cooling it to -40°C using a turboexpander, heat exchanger, ejector, and throttle. Leaks result in the release of light hydrocarbons, methane, refrigerants, and methanol into the soil.

**Compressor station.** At the station, gas is compressed by screw, piston, or centrifugal compressors to maintain pressure in the network and transport gas through the main gas pipeline. Substances contaminating the soil as a result of leaks include: lubricants, oils, gases, and condensates.

**Condensate stabilization unit.** This unit carries out the process of heating and rectifying unstable condensate to remove light hydrocarbon fractions. Leakage waste includes: raw condensate, propane-butane fraction, and wastewater penetrating into the ground.

**Methanol regeneration unit.** This unit recovers methanol from the rich mixture through heating and rectification for reuse in preventing hydrate formation. Leaks contain methanol and water impurities with salts.

**Methanol storage park.** The methanol storage park is a tank farm with cylindrical vessels on foundations. Leaks cause methanol to seep into the soil, leading to toxic contamination of the territory.

**Gas condensate storage park.** The gas condensate storage park is a tank complex for light hydrocarbons. The main waste entering the soil due to corrosion or overflows includes: raw condensate and gasoline fractions.

In the soils of the studied field territory, exceedances of total forms were identified for manganese – up to 1,700 mg/kg (maximum permissible concentration (MPC) – 1500 mg/kg), arsenic – up to 11–14.4 mg/kg (estimated permissible concentration (EPC) – 2 mg/kg), and

<sup>3</sup> State Standard 26213-2021. *Soils. Methods for determination of organic matter*. Moscow: Russian Institute of Standardization; 2021, 11 p.

<sup>4</sup> State Standard R 58596-2019 (clause 7.2). *Soils. Methods for determination of total nitrogen*. Moscow: Standartinform; 2019, 11 p.

<sup>5</sup> Getting to know ArcView GIS: the geographic information system (GIS) for everyone by Environmental Systems Research Institute (Redlands, Calif.). Available from: [https://archive.org/details/isbn\\_9781879102460/page/n9/mode/2up](https://archive.org/details/isbn_9781879102460/page/n9/mode/2up) [Accessed: 15th November 2025].



nickel – up to 85 mg/kg (EPC – 40 mg/kg). The EPC of arsenic in soil is regulated by Hygiene standards 2.1.7.020-94<sup>6</sup> and depends on the physicochemical properties of the soil, including the granulometric composition; specifically, for loams, the EPC of arsenic is 10 mg/kg. The current regulation of arsenic content does not take into account its speciation in soils. However, when addressing the degree of soil contamination by arsenic, the form in which arsenic accumulates in a given object is of significance. The toxicity of arsenic depends on its oxidation state: trivalent arsenic is 2–3 times more toxic than pentavalent arsenic, which is less mobile and more strongly adsorbed. Determination of the chemical forms of arsenic in soil waters has shown that in aerobic soils it is contained mainly in the form of  $\text{As}_3\text{O}_4^{3-}$  anions, and in anaerobic soils – as  $\text{AsO}_3^{3-}$ . Arsenic oxides are water-soluble, whereas haloarsenates, conversely, are hydrophobic. However, naturally, these nuances are not taken into account when assessing the level of soil contamination and are not monitored as part of environmental control.

The value of the key parameter of soil condition, the pH of the aqueous extract, ranges from 4.2 to 5.5, which characterizes acidification of the surface soil layer in the industrial site zone. This may lead to an increase in the mobility of heavy metals entering from the subsurface during drilling as associated elements and to their immobilization in the soil.

Over the period from 2019 to 2025, a comparative temporal analysis of heavy metal and arsenic contents in soils was conducted at the GIS points of regular sampling (geoecological monitoring – spring–autumn) across all the specified technological areas (units).

A preliminary background assessment of chemical element contents was carried out outside the industrial site at a distance of 10 km from it. In addition, the geochemical background for soils was calculated using the clarke method (according to A.E. Fersman). The values of total element content in soil are most commonly used in geochemistry and technogeochemistry. Based on the total con-

tent values, the contrast and capacity of geochemical barriers are assessed, and the formation of anomalous geochemical modules is determined. The use of the clarke allows for evaluating the intensity of a natural or technogenic anomaly, both positive (when exceeding the clarke) and negative (when below the clarke level).

In our case, compared to the clarks of world soils, the following elements in the studied soils are at or above the accumulation level:

- arsenic, manganese, nickel (accumulation coefficient  $Kk \geq 1.5$ );
  - the near-clarke association includes copper and zinc (accumulation coefficient  $Kk = 0.8–1.5$ );
  - lead and cobalt are recorded with a content deficiency (accumulation coefficient  $Kk \leq 0.7$ ).
- Median values were used for the comparative geochemical characterization relative to the global clarks of world soils according to A.P. Vinogradov – arsenic – 5 mg/kg, nickel – 40 mg/kg, manganese – 850 mg/kg.

The temporal dynamics of increasing contents for three elements – manganese, arsenic, and nickel – from the beginning of the field operation were revealed by year. Histograms (box-and-whisker plots) were obtained, allowing for a clear assessment of the relationship between the intensity of territory development in the gas production zone and the level of adverse impact manifested as the release of these elements into the soil from industrial units (Fig. 2).

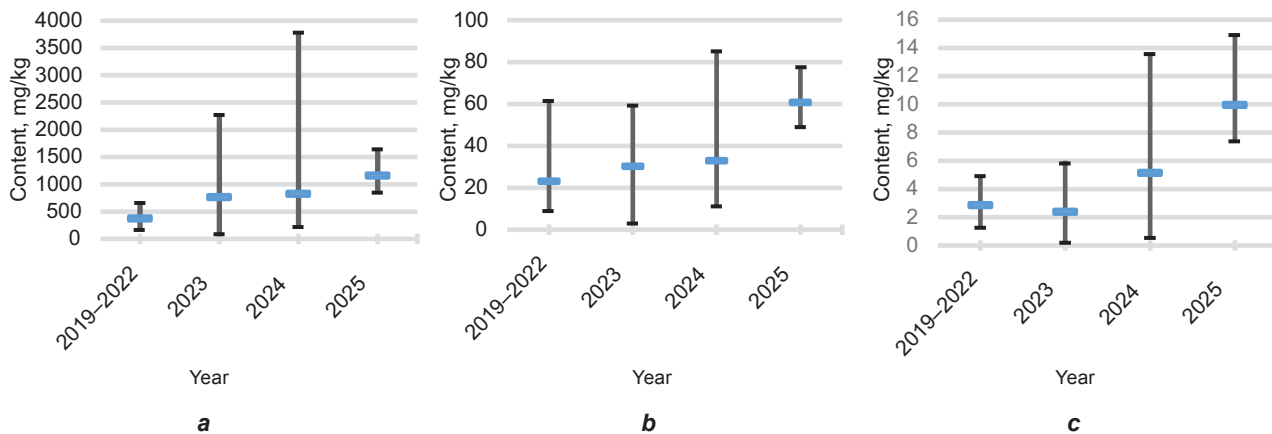
To elucidate the varying nature of the observed distribution of controlled elements in soils, an analysis of the pace and scale of industrial site development and infrastructure construction was conducted for the specified years.

All industrial facilities (the integrated gas treatment unit, well clusters, warehouses, terminals, etc.) occupy approximately 7 km<sup>2</sup>.

The years 2019–2022 are characterized by the commencement of works; this represents the pilot operation stage of the facility, involving the installation and preparation of the main industrial facilities. Operation of gas wells had not yet begun.

2023 was marked by intensive welding works and the installation of all equipment.

<sup>6</sup> Hygienic Standards 2.1.7.020-94. *Tentative allowable concentrations (TAC) of heavy metals and arsenic in soils with different physical and chemical properties (gross contents, mg/kg)*. Addendum no. 1 to the list of MAC and TAC no. 6229-91-91.



**Fig. 2. Dynamics of manganese (a), nickel (b), arsenic (c) contents in the soils of the industrial site relative to average values**  
**Рис. 2. Динамика содержаний марганца (a), никеля (b), мышьяка (c) в почвах промплощадки относительно средних значений**

2024 represents the period of maximum production capacity and the scaling-up of production capabilities.

2025 is the stage of technological process stabilization and reaching the design parameters.

It has been shown that the soils are characterized by an acidic and slightly acidic environment, low organic carbon content, and low nitrogen enrichment ( $pH = 4-5$  units), organic carbon ( $C_{org} = 10\%$ ), and total nitrogen ( $N_{tot} = 0.6\%$ ). Soil acidification and the lack of the necessary amount of organic matter and nitrogen in the soil may determine the mobility of certain heavy metals and arsenic, which also contributes to the migration of these elements.

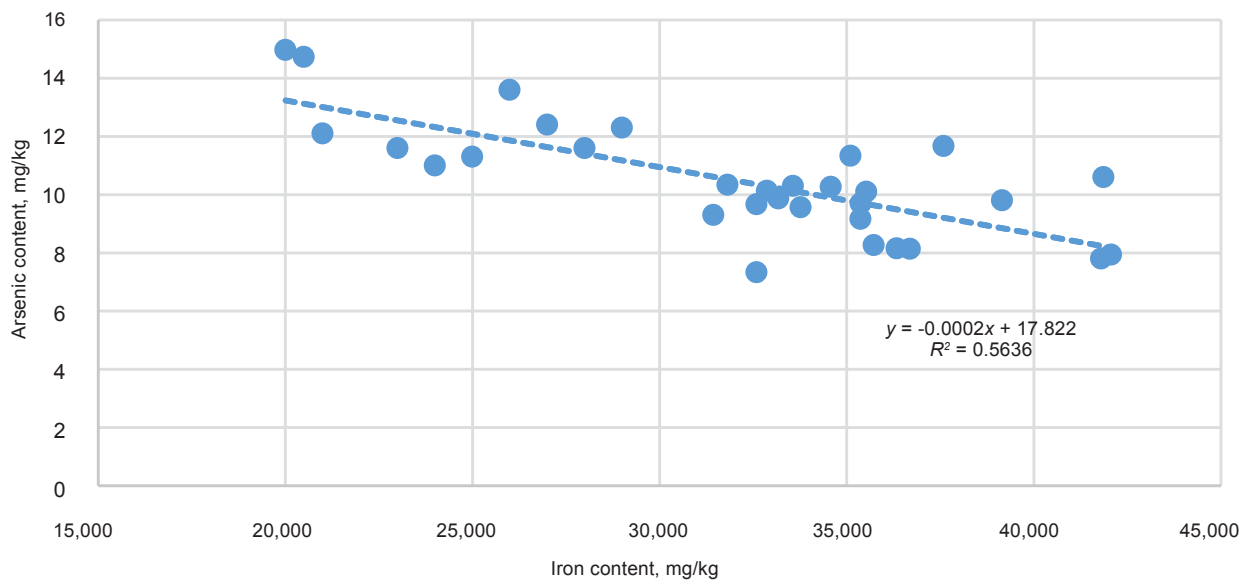
Continuous welding operations, especially on pipelines laid across the entire territory of the industrial site, cause an active input of manganese into the soils. Concurrently, a high content of total iron in the technogenic soils was also identified. This has resulted in the accumulation of manganese in the soil layer at the geochemical barrier represented by iron oxides and their concretions. Moreover, regardless of the concentration of manganese entering the soil, the geochemical barrier in the form of iron oxides in the soil effectively fulfills its accumulative role.

A similar stable accumulation relationship is observed in the case of nickel distribution in soils. However, in the case of arsenic distribution in technogenic soil, the nature of the process, the binding of arsenic by iron, changes substantially (Fig. 3).

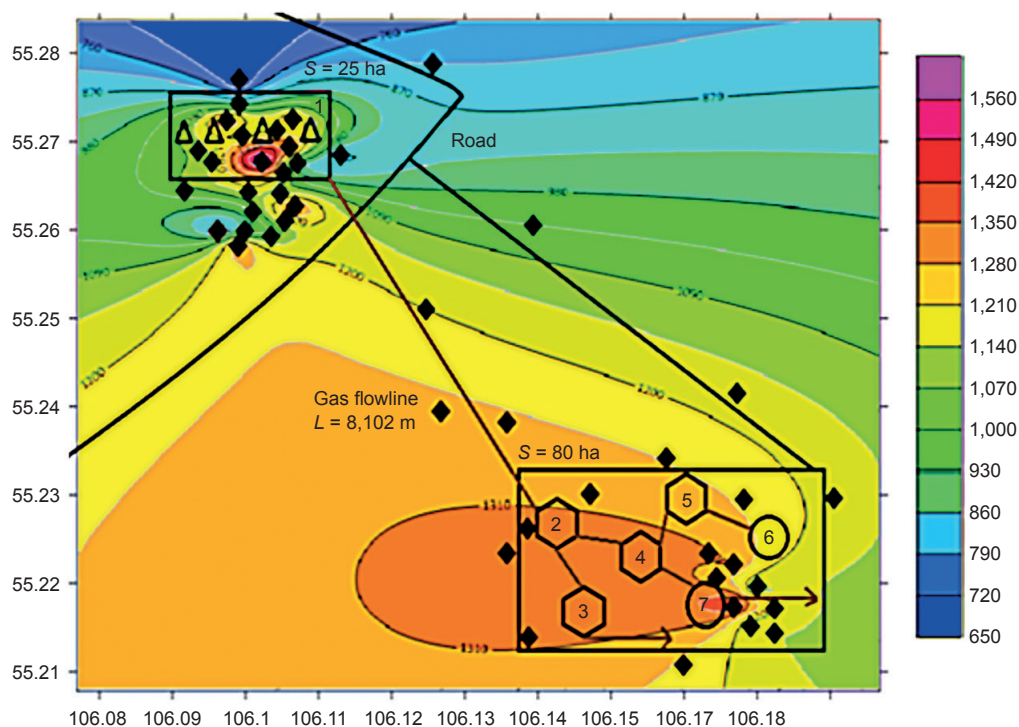
A negative correlation (a noticeable, moderate, statistically significant relationship) was found between the content of iron and arsenic, with a coefficient of determination  $R^2 = 0.5636$ . This means that, unlike manganese and nickel, arsenic is weakly sorbed onto the solid ferruginous phase. The reason for the observed effect may be the high sensitivity of this metalloid to the pH environment: it is maximally bound in a high oxidation state V in an alkaline environment compared to an acidic one. Since the observed pH of the soil environment at the industrial site is acidic ( $pH = 4-5$ ), arsenic is not immobilized on iron hydroxides. It is also evident that, under these conditions, the total forms transition into more mobile ones; therefore, a decrease in the effectiveness of the ferruginous barrier for binding total arsenic is observed.

For the visualization of geochemical data, GIS distributions of the dominant pollutant elements in the soil layer were obtained for the entire observation period. A GIS based on the spatial referencing of geochemical data to the territory represents a multifunctional tool for the comprehensive assessment of its condition and for forecasting the resilience of territories to adverse environmental impacts. Using the year 2025 as an example, visualized results of the geochemical analysis of soils and the direction of element migration are presented (Fig. 4-6).

The conducted temporal and spatial GIS analyses confirmed the results of the technological analysis of production units at the industrial site



**Fig. 3. Dependence of arsenic content on iron content**  
**Рис. 3. Зависимость содержания мышьяка от содержания железа**

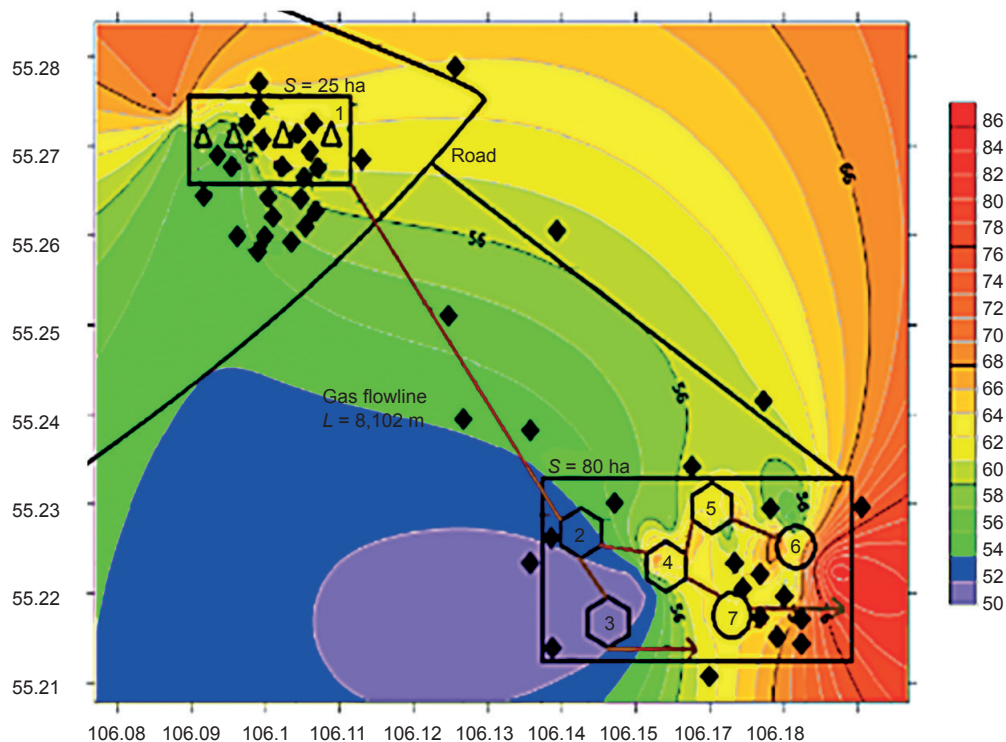


**Fig. 4. Geoinformation system distribution of manganese in soils at the Kovykta gas condensate field site, mg/kg:**

- 1 – gas well cluster; 2 – low-temperature separation unit;  
3 – central booster compressor well;  
4 – condensate stabilization unit; 5 – methanol recovery unit;  
6 – methanol storage facility; 7 – stable condensate storage facility

**Рис. 4. Геоинформационное системное распределение марганца в почвах на территории промплощадки Ковыктинского газоконденсатного месторождения, мг/кг:**

- 1 – куст газовых скважин; 2 – установка низкотемпературной сепарации;  
3 – центральная дожимная компрессорная скважина;  
4 – установка стабилизации конденсата; 5 – установка регенерации метанола;  
6 – парк хранения метанола; 7 – парк хранения стабильного конденсата

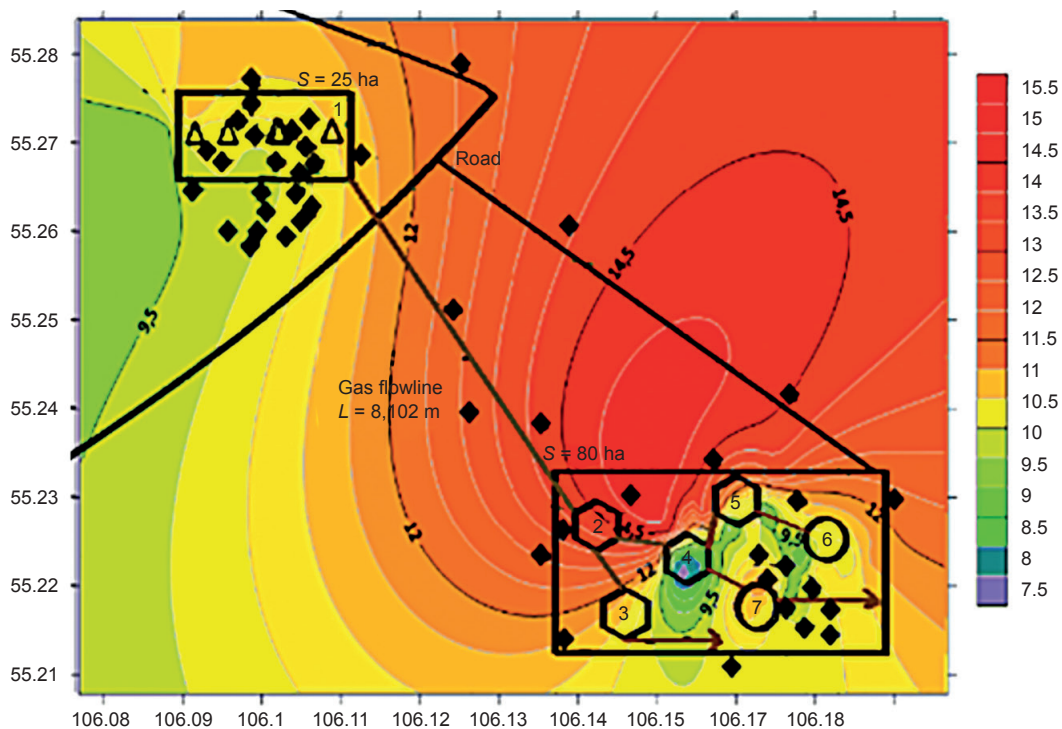


**Fig. 5. Geoinformation system distribution of nickel in soils at the Kovykta gas condensate field site, mg/kg:**

For a description of the symbols, see Fig. 4

**Рис. 5. Геоинформационное системное распределение никеля в почвах на территории промплощадки Ковыктинского газоконденсатного месторождения, мг/кг:**

Описание условных обозначений см. на рис. 4



**Fig. 6. Geoinformation system distribution of arsenic in soils at the Kovykta gas condensate field site, mg/kg:**

For a description of the symbols, see Fig. 4

**Рис. 6. Геоинформационное системное распределение мышьяка в почвах на территории промплощадки Ковыктинского газоконденсатного месторождения, мг/кг:**

Описание условных обозначений см. на рис. 4



from the perspective of soil contamination: in one case, this represents a natural input of an element, and in the other, a technogenic origin of elevated heavy metal concentrations in the soil layer. Thus, manganese predominantly accumulates in soils in the pipeline zone and where welding is regularly performed: up to 700 m of pipes are welded per day, reaching up to 5,000 m per week. During welding, a welding aerosol is formed in the arc discharge zone, containing manganese and nickel oxides from electrode coatings. The presence of sodium fluorides in the electrodes also contributes to the generation of large amounts of manganese that settles onto the soils.

The GIS distribution of nickel may also be associated with ongoing metal repair operations, pipe welding, and the abrasion of machine parts due to heavy vehicle traffic. At peak operations, 100–300 vehicles pass through the field daily, including 50–100 trucks and 20–50 units of special machinery, which is equivalent to 3,000–9,000 vehicles per month.

The areal exceedance of arsenic content in soils identified through GIS is linked to the imported soil material from the Yarakinsky field used for the grading and infrastructure development of the gas production site. This is consistent with data on the exceedance of the EPC for arsenic in the soils of this region, which is attributable to the natural geological and geochemical background of the Irkutsk region in the Baikal area. Furthermore, the development of drilling pads and the laying of geophysical seismic survey profiles continuously disturb the soil cover, bringing arsenic from the lower horizons to the surface. The exceedances of arsenic content are also related to the underlying rocks of the production area. The imported soil used for backfilling and grading of the industrial sites of the Kovykta gas condensate field is rich in arsenic.

It should also be emphasized that the accumulation of the indicated elements in the soil may be influenced by the sorption activity of mobile ions (cations) of calcium, magnesium, potassium, and sodium in the soil absorption complex, which enter the territory of the industrial site in the form of brine (a highly concentrated salt solution) from

well drilling. This may additionally lead to the immobilization of certain elements at the chemical barrier due to the formation of compounds with low migration rates, such as hydroxo complexes involving heavy metals.

### Conclusion

The nature of the spatiotemporal distribution of heavy metals and arsenic on the territory of the gas condensate field for the period 2019–2025 has been identified. The temporal dynamics of the increase in the contents of manganese, arsenic, and nickel from the beginning of the field's operation by year allows for a clear assessment of the relationship between the intensity of territory development in the gas production zone and the level of adverse impact manifested as the release of these elements into the soil. Geochemical indicators reflect their high functionality under the conditions of adverse impacts during gas production and provide a realistic assessment of the geoecological situation at the field. The coefficients of element accumulation relative to the global clarks according to A.P. Vinogradov were obtained: an elevated accumulation coefficient was found for arsenic, manganese, and nickel ( $K_k \geq 1.5$ ). Illustrative GIS distributions of the controlled elements – the dominant pollutants (manganese, nickel, arsenic) – revealed their dispersion halos and migration directions. It has been shown that the spatial distribution of manganese and nickel is related to technological processes, regular production operations, and welding.

Cases of arsenic content exceeding the regulatory standard may be attributed to the inheritance of the geological and geochemical features of the Baikal natural territory, with an elevated content of this metalloid in the composition of the imported soil used for grading the gas condensate field territory.

Thus, the integration of GIS technologies with the results of geochemical surveys is an effective tool for the comprehensive assessment of the territory in the technogenesis zone and serves as a basis for the development of effective, modern, object-oriented monitoring in the gas condensate field zone.



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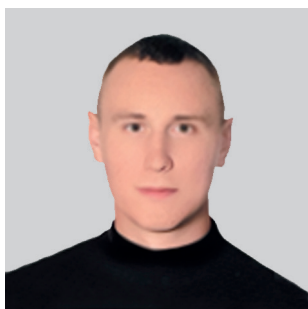
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**Conflict of interests / Конфликт интересов**

The authors declare no conflict of interests.

Авторы заявляют об отсутствии конфликта интересов.

*The final manuscript has been read and approved by the authors.*

*Авторы прочитали и одобрили окончательный вариант рукописи.*

**Information about the article / Информация о статье**

The article was submitted 13.02.2026; approved after reviewing 25.02.2026; accepted for publication 05.03.2026

Статья поступила в редакцию 13.02.2026; одобрена после рецензирования 25.02.2026; принята к публикации 05.03.2026.