UDC 621.398
DOI 10.56525/PBGF7059

SNUDY OF THE TIME DYNAMICS OF THE NDVI INDEX IN THE TERRITORY NEAR AKTAU CITY

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Annotation. The purpose of this study is to analyze the temporal dynamics of the normalized relative vegetation index (NDVI) in the territory adjacent to the city of Aktau, while simultaneously assessing its potential as an indicator of the accumulation of heavy metals in the soil cover. The main focus is on assessing the impact of anthropogenic activities on the marine area and the coastal zone of the Caspian Sea, which is an ecologically significant and vulnerable natural system. Aktau city, located on the coast of the Caspian Sea, is considered as a representative facility for conducting comprehensive geoecological research. As part of field and laboratory work, the content of humus, heavy metals, and other physico-chemical parameters of the soil was determined. Laboratory analyses of the humus composition and chemical characteristics of the soil layer revealed that the increased content of heavy metals in the upper soil horizon clearly correlates with the levels of anthropogenic stress, which indicates a significant impact of anthropogenic factors on the environment.
Keywords: Monitoring, heavy metals, vegetation index NDVI, remote sensing of the Earth, Mangystau region.

Introduction

The Caspian Sea is the world's largest enclosed body of water, located on the border of Europe and Asia [1]. In recent decades, the region has faced increasing environmental problems caused by the active development of the oil and gas industry, including the development of offshore fields and the transportation of hydrocarbons. Significant pollution of the water area and coastal zone by petroleum products and other man—made compounds, as well as erosion processes, lowering of water levels and transformation of coastal ecosystems are caused, among other things, by the construction of hydraulic structures - dams, canals and other infrastructure facilities. These processes indicate the intensification of anthropogenic impact on a unique natural system and emphasize the need for comprehensive geoecological studies aimed at assessing the current state of the environment and predicting the consequences of further impacts [2].

The purpose of this study is to assess the impact of heavy metal pollution, in particular copper, on the state of ecosystems in the coastal zone near the village of Shapagatova village (Mangystau region) using methods of geoinformation analysis and remote sensing data.

The soil cover is the main medium of accumulation of heavy metals coming from the atmosphere and hydrosphere. The largest amount of these pollutants accumulates in the humus horizon, where they enter into stable chemical bonds with various soil components — aluminosilicates, non-silicate minerals, and organic matter. Characteristics such as humus content, acid-base balance, redox potential, sorption capacity and the level of biological activity of the soil play a key role in the retention and migration of heavy metals. These parameters determine the degree of metal fixation in the upper soil horizon, reducing their mobility and potential toxicity to biota. Nevertheless, mobile forms of heavy metals that retain the ability to migrate vertically pose a serious environmental threat [3]. The research results indicate that the concentrations of heavy metals in the upper layers of the soil are a reliable indicator of the degree of anthropogenic impact on the environment [4].

Materials and methods

The purpose of this work is to conduct a comprehensive geoecological study, including an analysis of the temporal dynamics of the normalized relative vegetation index (NDVI) in Aktau city, in order to assess its applicability as an indirect indicator of the accumulation of heavy metals in the soil cover. Additionally, the impact of anthropogenic activity on the marine water area and the coastal zone of the Caspian Sea, one of the most vulnerable natural objects in the region, is being investigated.

Field studies were conducted in a narrow coastal zone of the Caspian Sea near the village of S. Shapagatova (Mangystau region, Republic of Kazakhstan) using a route method. As part of the expedition work, four research sites were allocated: RS-1, RS-2, RS-3 and the RS-4 control site. Soil sampling was carried out in 2019 and 2021.

Five-point samples were taken at each of the four sites, totaling 20 samples. Samples were taken from a depth of 5-20 cm in accordance with GOST 17.4.4.02-84. All samples were taken within one day to minimize the influence of weather and time factors. The soil samples were dried to an air-dry state at room temperature, sifted through a sieve with a hole diameter of 1 mm and combined into composite samples for further analysis.[5]

A complex of laboratory analyses was carried out, including the determination of the following soil characteristics: humus content, color of soil material, granulometric composition, total nitrogen content, content of mobile forms of potassium and phosphorus, mobile compounds characteristic of carbonate soils, as well as other physico-chemical parameters. The method of atomic absorption spectrometry using the MGA-915M installation in an accredited laboratory of Accu Test LLP was used to determine the content of heavy metals. The mobile forms of the following metals were determined: lead (Pb), nickel (Ni), chromium (Cr), mercury (Hg), vanadium (V), copper (Cu), iron (Fe), zinc (Zn). The data obtained were compared with the established maximum permissible concentrations (MPC) according to regulatory documents [6].

Characteristics of research sites

RS-1 is located near the village of Akshukyr, at a distance of 303.65 m from the coastline of the Caspian Sea.

RS-2 is located along the Aktau — Fort Shevchenko highway, at a distance of 1,635.1 m from -1, near an open warehouse of mineral fertilizers and building materials.

RS-3 is located in the area of private residential development in the village of Shapagatov, at a distance of 2135 m from RS-2.

RS-4 (control site) is located at a distance of 9578 m from RS-3 and is used to assess the background state of the environment, minimally affected by anthropogenic impact.

The location of the soil sampling points is shown in Figure 1. The map was compiled in a GIS environment using the QGIS software.

Figure 1 – Soil sampling points

Methods of geoinformation technology

The Sentinel Hub platform was used via the EO Browser web interface to obtain and pre-analyze remote sensing data. The satellite images were selected based on a cloud cover criterion of no more than 30%, which ensured high-quality visualization of the Earth's surface. Multispectral images obtained from the Sentinel-2 spacecraft with a spatial resolution of up to 10 meters were used as the source [7].

Satellite data processing, calculation of the NDVI vegetation index, and visualization of the results (including mapping the location of soil sampling points in Aktau) were performed in the QGIS 3.32 software environment.

Vegetation status was analyzed using the normalized relative vegetation index (NDVI), widely used in ecological, geographical, and agroecological research. NDVI was calculated using the standard formula:

$$\text{NDVI} = NIR - RED/NIR + RED, \quad (1)$$

where NIR is the reflectivity in the near infrared range,
RED is the reflectivity in the red range of the spectrum.

This index makes it possible to quantify the level of vegetation productivity and can be used as an indirect indicator of the ecological state of the territory, including when monitoring man-made impacts [8].

The results of the calculation of the normalized relative vegetation index (NDVI) are presented as numerical values ranging from -1 to +1. These values reflect the degree of vegetation development in the study area. High NDVI values (close to +1) indicate the presence of dense, physiologically active vegetation, while low values (close to -1) indicate the absence of green vegetation and the presence of water surfaces, artificial objects or an exposed substrate. Values approaching zero correspond to areas with sparse vegetation or open soils and soils.

The NDVI calculation was performed on the basis of Sentinel-2 satellite data, using reflectivity values in the near—infrared range (channel 8 - NIR) and the red spectral range (channel 4 — RED).

Based on the calculated values, an NDVI spatial map was constructed, visualizing the degree of vegetation development in the studied area [8].

To assess the condition of the vegetation cover and its potential connection with soil contamination with heavy metals, a coastal area was selected within the city limits of Aktau, including a soil sampling zone. The total area of the analyzed territory was 462.52 km^2.

Research results and their discussion

In the study area near the village of Akshukyr, along the direction to Aktau airport, brown desert soils typical of arid conditions prevail. In the subsurface horizons, at depth, the presence of a saline layer is recorded, which indicates a transition to saline and saline soil types.

The results of a soil analysis conducted in 2019 [9] showed that the humus content in the upper horizon varies from 1.18 to 2.62%, while in deeper layers the humus concentration decreases to 0.42–0.97%. The level of soil nutrient availability remains relatively low.

The content of mobile phosphorus in the surface horizons ranges from 515.17 to 2004 mg/kg, and the content of carbonates is in the range of 1.77–3.11%. The total nitrogen content varies from 0.26 to 0.39%.

The granulometric composition affects the cation exchange capacity, which varies in the range from 9.62 to 32.15 mg-eq/100 g. The composition of the soil-absorbing complex (SAC) is dominated by exchangeable magnesium, which makes up 40-80% of the total amount of absorbed cations, which is typical for soils exposed to salinity and carbonate exposure.

The reaction of the soil medium varies from neutral to slightly alkaline, with the pH values of the aqueous extract in the range of 6.85–7.41.

The physico-chemical characteristics of the studied soils are presented in Table 1, based on monitoring data from 2019 [10].

Table 1 – Physico-chemical properties of the soil of research sites in 2019

Physico-chemical characteristics of the soil	Research sites (monitoring of soil conditions)			
	RS-1	RS-2	RS-3	RS-4 (background)
Humus, %	1,18	1,39	1,47	2,62
Total nitrogen, %	0,26	0,34	0,39	0,27
Phosphorus (gross), mg/kg	1660,3	472,5	515,17	2004
Carbonates, %	3,11	1,77	1,82	2,75
Exchange capacity, mg-eq/100 g	9,62	22,85	24,15	32,15
Exchangeable calcium, mg-eq/100 g	1,5	4	5	1,3
Exchangeable magnesium, mg-eq/100 g	7,11	17	18,45	11,7
Exchangeable sodium, mg-eq/100 g	0,61	0,93	0,97	16,13
The sum of the salts	0,57	1,06	1,3	0,2
pH	7,39	7,1	7,41	6,85

According to the data presented in Table 2, the content of organic matter in the upper soil horizon of the study area in 2021 ranged from 1.19 to 2.63%. The level of nutrient availability remains low: the concentration of mobile phosphorus ranges from 473.4 to 2003.8 micrograms/kg, the content of carbonates is from 1.78 to 3.13%, and the total nitrogen content is from 0.24 to 0.41%.

The dependence of the cation exchange capacity on the granulometric composition is noted: with a heavier soil texture, the ability to exchange increases. The value of the cation exchange capacity (CEC) varies in the range from 9.65 to 32.19 mg-eq/100 g. The structure of the soil-absorbing complex (SAC) is steadily dominated by exchangeable magnesium, accounting for 40-80% of the total exchange capacity.

The reaction of the soil medium is characterized as neutral or slightly alkaline, with pH values of the aqueous suspension in the range of 6.87—7.63.

A comprehensive analysis allows us to characterize the soils of the studied territory as poorly enriched with organic matter, with an alkaline reaction, signs of salinization and reduced resistance to anthropogenic impact, which is confirmed by data from previous studies [11].

The analysis of the physico-chemical properties of the soil environment in the study area indicates a low content of organic matter, an alkaline reaction of the soil solution, a tendency to salinization, as well as a low resistance of soils to anthropogenic impact. These characteristics reduce the buffering and self-cleaning properties of soils, increasing their vulnerability to the accumulation of pollutants.

Table 2 – Physico-chemical properties of soils of the studied sites in 2021

Physico-chemical characteristics of the soil	Research sites (monitoring of soil conditions)			
	RS-1	RS-2	RS-3	RS-4 (background)
Humus, %	1,19	1,41	1,48	2,63
Total nitrogen, %	0,24	0,36	0,41	0,28
Phosphorus (gross), mg/kg	1662	473,4	516,15	2003,8
Carbonates, %	3,13	1,78	1,84	2,77
Exchange capacity, mg-eq/100 g	9,65	22,89	24,89	32,19
Exchangeable calcium, mg-eq/100 g	1,7	4,2	5,2	1,4
Exchangeable magnesium, mg-eq/100 g	7,12	17,2	18,5	11,8
Exchangeable sodium, mg-eq/100 g	0,63	0,95	0,98	16,29
The sum of the salts	0,59	1,07	1,33	0,24
pH	7,42	7,52	7,63	6,87

Taking into account the potential environmental hazard of heavy metals, monitoring of their concentrations in the soil cover should be based on the regulatory values of maximum permissible concentrations (MPC). The results obtained can serve as a basis for long-term monitoring of the state of the environment, as well as for the development of programs to reduce the anthropogenic load, including measures to rehabilitate disturbed areas and control pollution sources [12].

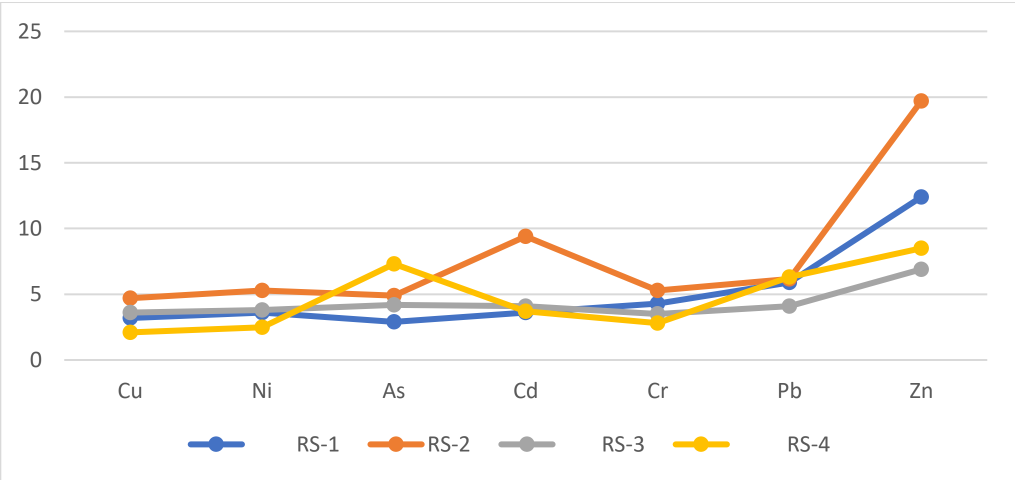


Figure 2 – The presence of heavy metals in the soil in 2019

At the RS-2 site, located near the highway and an open warehouse of road construction materials, an excess of nickel content to 1.32 of the maximum permissible concentration (MPC) was recorded. This excess is most likely due to the use of various storage tanks for paint and varnish materials at the facility, as well as the operation of heavy-fuel vehicles (including tractor equipment running on fuel oil). At the same time, the zinc concentration at this site remains within the regulatory limits.

The analysis of the arsenic content showed an excess of the maximum permissible concentration in all the studied sites, including the RS-4 control site, where the maximum value was noted. This fact may be due to the natural geochemical features of the Mangystau region, where the processes of arsenic accumulation and migration are of a natural rather than exclusively man-made nature.

The cadmium level on RS-2 also exceeds the regulatory threshold, reaching 1.88 MPC, which is probably due to the activity of diesel vehicles used in the storage and transportation of construction materials.

For chromium in all the studied areas, the values remain within the MPC, which indicates the absence of significant sources of supply of this element at the time of the research.

Excess lead content was also recorded at RS-2, which can be explained by exposure to exhaust fumes from vehicles, including specialized equipment (graders, tractors, etc.) operating near the site under study.

Thus, the RS-2 site, characterized by its proximity to transport infrastructure and man-made facilities (open warehouse, highway), demonstrates the highest degree of heavy metal pollution. At the same time, the RS-4 control site conditionally retains the environmental condition closest to the background, despite the excess concentration of arsenic caused by natural factors.

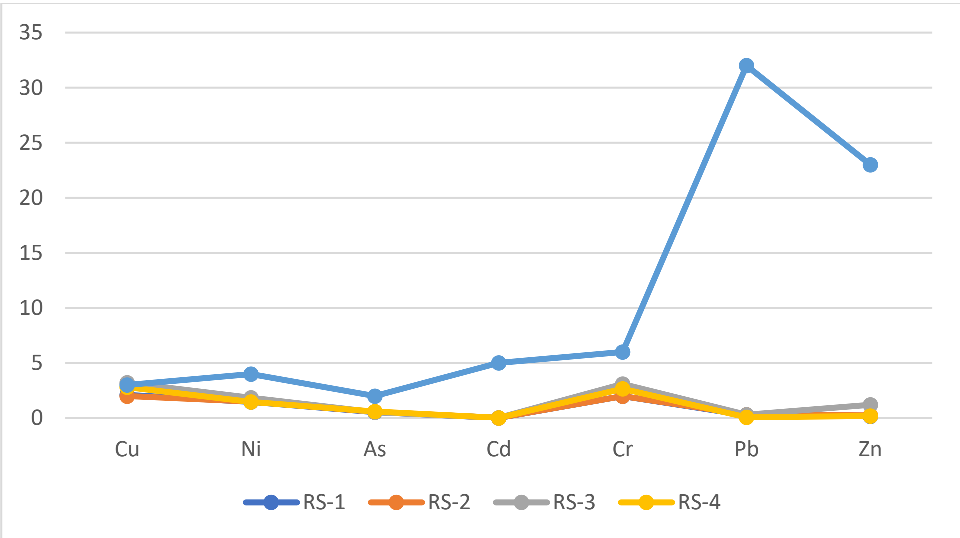


Figure 3 – The content of heavy metals in the soil in 2021

A comparison of data on the content of heavy metals in soils for 2019 and 2021 showed a downward trend in the concentration of copper in most of the studied sites. In particular, an excess of 0.2 MPC copper content was recorded at RS-3, which may be due to the residual impact of economic activity, despite the overall reduction in anthropogenic load caused by restrictions during the COVID-19 pandemic.

The highest concentrations of copper, nickel, zinc, arsenic, cadmium, chromium and lead were also recorded at this site compared to other studied sites. This is probably due to the presence of private residential development, as well as activity in the field of small-scale construction and industrial activities, accompanied by emissions of harmful substances.

A significant decrease in copper and chromium concentrations was noted at RS-2 — approximately 2.5 times compared to 2019. This trend is apparently related to the temporary cessation of the storage of building materials near the site during the restrictions imposed in connection with the pandemic. A similar decrease was recorded for cadmium, arsenic and nickel, which indicates a temporary reduction in the anthropogenic impact on the soil cover. In order to spatially assess the state of vegetation, an analysis of remote sensing data obtained using the Sentinel-2 satellite was carried out. A total of 11 multispectral images were processed, including 5 images for 2019 and 6 images for the spring period of 2021. The images were selected based on the criteria of minimum cloud cover and maximum phase activity of vegetation (spring growing season), which allowed for a reliable assessment of the ecological condition of the territories.

The calculation of the normalized relative vegetation index (NDVI) showed the dynamics of decreasing vegetation productivity in a number of areas. A comparative analysis of the NDVI over the years revealed changes in the state of vegetation, which can serve as an indirect indicator of changes in the ecological state of the soil cover. Given that vegetation reacts sensitively to concentrations of pollutants in the soil, NDVI indicators can be used to monitor ecosystem degradation and restoration processes.

According to the analysis, a significant part of the studied territory corresponds to the categories of degradation, environmental risk and crisis status according to NDVI values. Thus, the quality of vegetation cover can be considered as an integral bioindicator of the ecological state of soils, including the accumulation of chemicals, in particular heavy metals.

Figure 5 shows the scale of NDVI values with the corresponding color coding used for interpreting satellite images.

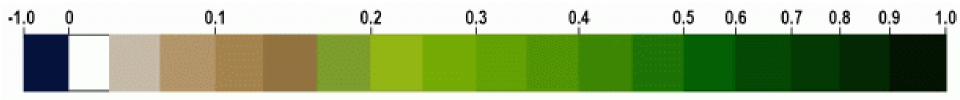


Figure 4 – NDVI discrete scale

The analysis of remote sensing data, based on the processing of 11 satellite images, demonstrated significant changes in the state of vegetation cover in the study area over the period 2019-2021.

In 2019, the values of the normalized relative vegetation index (NDVI) ranged from 0.5 to 0.6, which indicates a high productivity of vegetation and a relatively favorable condition of the soil cover. At the same time, in 2021, there is a decrease in NDVI values to the range of 0.3–0.4, which reflects the deterioration of vegetation and the possible intensification of soil degradation processes.

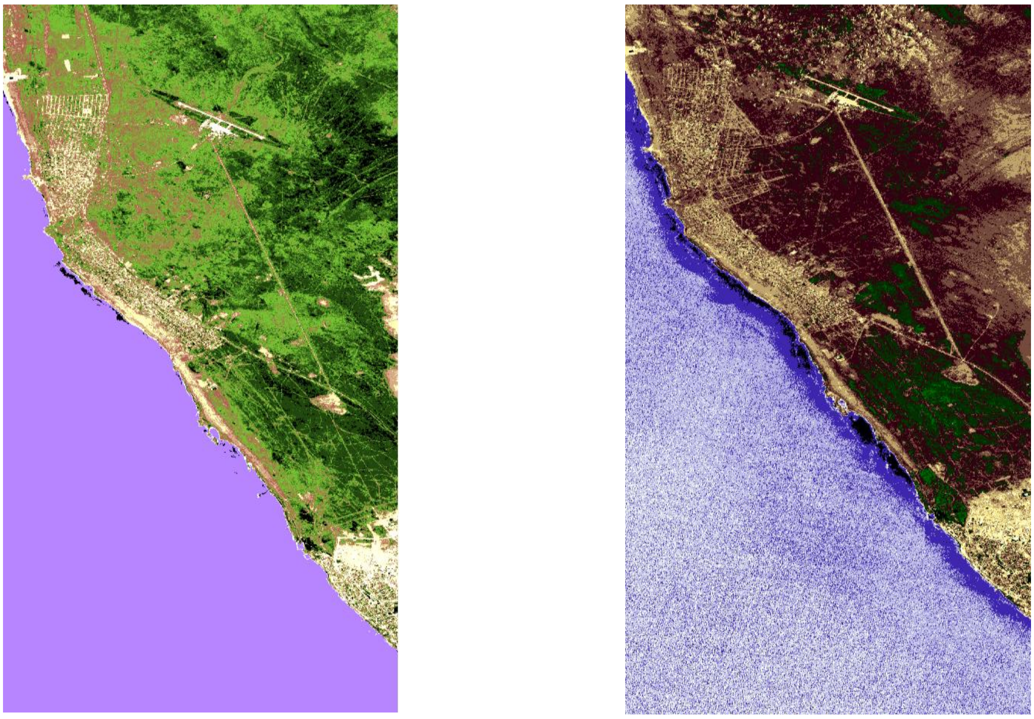
Figure 3a shows a satellite image from April 26, 2019, demonstrating a higher density and quality of vegetation cover in the study area. On the contrary, Figure 3b (dated April 15, 2021) clearly shows a decrease in the area and density of green vegetation, which correlates with a decrease in NDVI values.

The decrease in the NDVI index in 2021 indicates unfavorable changes in ecological and geochemical conditions that contribute to the deterioration of soil conditions and a decrease in their bioproductivity. These processes can have cumulative effects and long-term consequences, especially in the context of ongoing anthropogenic impact.

The primary data on the normalized vegetation index (NDVI) obtained for the study area indicated a high density and biological activity of vegetation cover. In particular, in the RS-1, RS-2, and RS-3 sites, during the initial observation period, the NDVI values ranged from 0.5–0.7, which corresponds to a healthy vegetation cover with active photosynthetic activity.

However, during repeated monitoring conducted in 2021, a sharp decrease in NDVI values was recorded, up to zero or negative values at all research sites. Values close to 0 reflect the absence of active vegetation, the presence of heavily degraded cover, or its complete disappearance.

Such a significant decrease may be due to a number of adverse factors, including: accumulation of heavy metals in the soil and disturbance of its chemical balance; hydroclimatic anomalies such as drought; phytopathological processes (plant diseases); intense anthropogenic impact, including man-made pollution, mechanical destruction of the soil and infrastructural construction.



a) 26.04.2019 b) 15.04.2021

Figure 5 – Satellite image with the NDVI index

A sharp drop in NDVI values to critical levels is an ecologically alarming indicator indicating a disruption in the functioning of plant communities and possible ecosystem degradation. In this regard, additional diagnostics of the causes of the processes and the development of measures for the restoration of vegetation cover are necessary, including measures for the rehabilitation of contaminated soils, control of sources of anthropogenic impact and restoration of the natural environment.

Conclusion

The results of a comprehensive analysis conducted in 2019 and 2021 indicate the presence of significant soil contamination with heavy metals within the studied territories, with particular attention being paid to copper, which demonstrates the highest concentrations among the studied elements.

The suspected sources of increased copper content are industrial emissions, including the activities of metallurgical and chemical enterprises, the production of electronics, as well as wastewater and the use of medicinal agrochemicals in agriculture. Elevated copper levels in the soil environment can have a toxic effect on plants, disrupting physiological processes.: causing chlorosis, inhibition of root system growth, disruption of photosynthesis, as well as a decrease in total biomass and vegetation productivity.

At the early stages of the study, a possible correlation was assumed between the copper concentration and the values of the NDVI (Normalized Difference Vegetation Index), a spectral indicator sensitive to changes in the health and density of vegetation cover. It has been established that high levels of copper can lead to a decrease in NDVI, which confirms its potential as an indicator of anthropogenic degradation of soil and vegetation cover.

The dynamics of observations over the period 2019-2021 demonstrates a decrease in the number of sites exceeding the maximum permissible concentration of copper, which may be due to a number of factors: the transition to more environmentally friendly technologies, improved filtration and purification systems for emissions, stricter environmental regulations and standards, and a decrease in industrial activity amid the COVID-19 pandemic.

Thus, copper and other heavy metals pose a serious environmental threat, having cumulative and long-term effects on soil and plant systems. This highlights the need for regular monitoring of heavy metal content in soils, as well as the use of GIS and remote sensing methods, including NDVI, as tools for rapid environmental assessment.

To minimize environmental risks, it is necessary to develop and implement comprehensive man-made pollution management measures, including technological innovations, regulatory regulation and an ecosystem approach to environmental protection. The implementation of such strategies will contribute to the sustainable development of the regions and increase environmental safety.

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ИЗУЧЕНИЕ ВРЕМЕННОЙ ДИНАМИКИ ИНДЕКСА NDVI НА ТЕРРИТОРИИ ВБЛИЗИ ГОРОДА АКТАУ

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Аннотация. Целью данного исследования является анализ временной динамики нормализованного относительного растительного индекса (NDVI) на территории, прилегающей к городу Актау, с одновременной оценкой его потенциала как индикатора накопления тяжелых металлов в почвенном покрове. Основное внимание уделяется оценке воздействия антропогенной деятельности на морскую акваторию и прибрежную зону Каспийского моря, которое является экологически значимой и уязвимой природной системой. Город Актау, расположенный на побережье Каспийского моря, рассматривается как репрезентативный объект для проведения комплексных геоэкологических исследований. В рамках полевых и лабораторных работ было определено содержание гумуса, тяжелых металлов и других физико-химических параметров почвы. Лабораторные анализы состава гумуса и химических характеристик почвенного слоя показали, что повышенное содержание тяжелых металлов в верхнем горизонте почвы четко коррелирует с уровнем антропогенной нагрузки, что свидетельствует о значительном воздействии антропогенных факторов на окружающую среду.

Ключевые слова: мониторинг, тяжелые металлы, вегетационный индекс NDVI, дистанционное зондирование Земли, Мангистауская область.

АҚТАУ ҚАЛАСЫНЫҢ МАҢЫНДАҒЫ АУМАҚТА NDVI ИНДЕКСІНІҢ УАҚЫТША ДИНАМИКАСЫН ЗЕРТТЕУ

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Андатпа. Бұл зерттеудің мақсаты Ақтау қаласына іргелес аумақтағы нормаланған салыстырмалы өсімдік индексінің (NDVI) уақытша динамикасын талдау болып табылады, сонымен бірге оның әлеуетін топырақ жамылғысында ауыр металдардың жинақталу индикаторы ретінде бағалау болып табылады. Экологиялық маңызды және осал табиғи жүйе болып табылатын Каспий теңізінің теңіз акваториясы мен жағалау аймағына антропогендік қызметтің әсерін бағалауға басты назар аударылады. Каспий теңізінің жағалауында орналасқан Ақтау қаласы кешенді геоэкологиялық зерттеулер жүргізу үшін өкілдік объект ретінде қарастырылады. Далалық және зертханалық жұмыстар аясында гумустың, ауыр металдардың және топырақтың басқа физика-химиялық параметрлерінің құрамы анықталды. Гумустың құрамын және топырақ қабатының химиялық сипаттамаларын зертханалық талдау топырақтың жоғарғы горизонтындағы ауыр металдардың жоғарылауы антропогендік жүктеме деңгейімен нақты корреляцияланғанын көрсетті, бұл антропогендік факторлардың қоршаған ортаға айтарлықтай әсерін көрсетеді.

Түйін сөздер: мониторинг, ауыр металдар, NDVI вегетациялық индексі, жерді қашықтықтан зондтау, Маңғыстау облысы.