

ECOGEOGRAPHY

DETECTION OF VEGETATION COVER CHANGES AND SOIL OIL POLLUTION IN AREAS AFFECTED BY LONG-TERM ANTHROPOGENIC IMPACT FROM OILFIELD ACTIVITIES

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Abstract

This article demonstrates the advantages of using remote sensing methods for environmental monitoring of areas subject to long-term anthropogenic impact, particularly in areas affected by the oil and gas industry. The study focused on the areas of Balakhany, most frequently affected by oil pollution. This article has both theoretical and practical significance. It describes methods for applying technologies that allow for the clear identification of pollution boundaries and changes in vegetation cover. The article also presents the results of processing and interpreting multi-temporal satellite images using a method for calculating vegetation indices, specifically the Soil-Adjusted Vegetation Index (SAVI), using the example of an oil field on the Absheron Peninsula. The obtained results confirm the effectiveness of using satellite data to identify the spatiotemporal dynamics of environmental change. The use of the SAVI index made it possible to determine the degree of vegetation degradation and localize zones of intense oil pollution. The analysis demonstrates the potential of remote sensing methods as an important tool for monitoring environmental conditions, assessing the impact of anthropogenic loads, and developing recommendations for the reclamation of contaminated lands.

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1. Introduction

Monitoring soil oil pollution remains one of the most pressing environmental challenges for the oil fields of the Absheron Peninsula, a unique geographic region located in eastern Azerbaijan bordering the Caspian Sea. Absheron is characterized by a high population density and intensive industrial development, which increases the anthropogenic impact on the environment. Given limited natural resources and dense urbanization, it is crucial to promptly assess the extent of soil and vegetation pollution to minimize risks to public health and the region's ecosystems. [4].

Balakhany deserves special attention - one of the oldest oil fields in the world, which played a key role in the development of Azerbaijan's oil industry. Historically, this field became the center of intensive production, leading to significant changes in the soil and vegetation. Currently, despite the decline in industrial activity, the Balakhany area continues to experience the effects of

long-term anthropogenic impact. Residual oil pollution, leaks from old wells, and landscape degradation require comprehensive monitoring using modern geoinformation and remote sensing methods. The use of high-resolution satellite data allows us to identify the scale of pollution, assess the recovery dynamics of natural ecosystems, and identify priority areas for reclamation. [2, 3, 6, 8, 10].

Thus, Balakhany serves not only as a site of historical and industrial significance, but also as an important research platform for developing innovative methods for environmental monitoring and assessing the condition of degraded areas in the Absheron region. Just 9 km northeast of Baku, the capital of Azerbaijan, lies the urban-type settlement of Balakhani, on the territory of the oil field of the same name. It is one of the oldest settlements in the Baku metropolitan area, possessing rich historical, cultural, and industrial significance. Balakhani occupied a strategic position on

the ancient trade route connecting Rus' with Persia, forming part of the Great Silk Road that ran from China to Lisbon. The settlement is mentioned in works of Russian literature, including a poem by Sergei Yesenin, emphasizing its cultural significance. The first Azerbaijani film was also shot here in 1898, making Balakhani an important center in the early history of Azerbaijani cinema. Furthermore, the family of Nobel Prize-winning physicist Lev Davidovich Landau, whose father served as chief engineer for the Rothschild company, lived in this settlement. An engineer - the father of the renowned explorer Richard Sorge - worked at the oil fields owned by the Nobel brothers, further highlighting the international significance and engineering potential of this region in the early 20th century.

Today, Balakhany represents a unique blend of historical heritage and industrial landscape. Despite decades of oil production, the village retains its historical and cultural identity and is becoming the subject of comprehensive environmental and socioeconomic research aimed at the restoration and sustainable development of areas with high levels of anthropogenic transformation.

Naturally, the long-term exploitation of oil fields has had a significant impact on the ecological status of the area, leading to soil and vegetation degradation, water pollution, and the accumulation of industrial waste. According to the Ministry of Ecology and Natural Resources of Azerbaijan, the area of degraded land on the Absheron Peninsula associated with historical oil production exceeded 10,000 hectares, of which approximately 1,200 hectares were in the Balakhani field. During the period of active production, more than 1,500 oil wells were operating here, a significant portion of which were subsequently abandoned.

Over time, as the profitability of Balakhani oil production declined, industrial activity declined, and the area gradually turned into a peculiar industrial landscape, reminiscent of an "oil pump graveyard." However, in recent years, the situation has begun to change. As part of the state program to reclaim the Apsheron oil fields, launched in 2011, over 300 hectares of contaminated land within Balakhany were remediated, over 150,000 cubic meters of oil-containing waste were removed, and over 200 old wells were abandoned.

The implementation of these measures significantly improved the environmental performance of the area: the oil product content in the soil decreased from an average of 15-18% to 2-3%, and

the biological activity of the soil layer almost doubled. As a result, Balakhany is becoming a model for the successful transition from man-made degradation to ecological restoration and sustainable use of territories.

2. Study Area and Initial Data

Oil extraction on the Absheron Peninsula has been carried out for many decades, and the activities of oilfields have had a negative impact on the environment, soils, and vegetation. This negative effect is largely due to the presence of toxic compounds in production waste. Therefore, it is essential to promptly detect oil spills and conduct regular monitoring of oilfield operations, including through the use of aerospace monitoring methods.

Although the impact of oilfields on the ecological situation has been relatively well studied the purpose of this work is to explore new approaches to applying remote sensing and geoinformation technologies for monitoring the environmental impact of the oil industry [1, 2, 6, 7, 8, 10].

The object of study in this article is the Balakhany oilfield, located on the Absheron Peninsula (Fig. 1). The subject of the research is the assessment of the impact of oil contamination and oilfield waste on the soil and vegetation cover of the study area.

The Balakhany oil field has been operating since 1880 (Fig. 2), and is currently a territory with a modern oil production industry (Fig. 3).

In 1871, the first industrial well was drilled in Balakhany to a depth of 64 meters. It initially produced 700 poods of oil per day, later increasing to 2000 poods per day. This marked the beginning of the development of the oil industry in Azerbaijan.

The development of the oil industry is a key driver of economic growth in the Republic of Azerbaijan, accounting for up to 90% of export earnings and a significant share of the gross domestic product. However, this process also has a negative side: increased anthropogenic impact on the environment, particularly in areas of intensive oil production. The most vulnerable areas in this regard are the Absheron Peninsula, where over 60% of the country's historical oil wells are concentrated, approximately 35% of which are mothballed or out of operation.

The long-term exploitation of oil fields has led to the accumulation of significant volumes of hydrocarbon waste, degradation of soil and vegetation, and contamination of surface and groundwater with oil products.

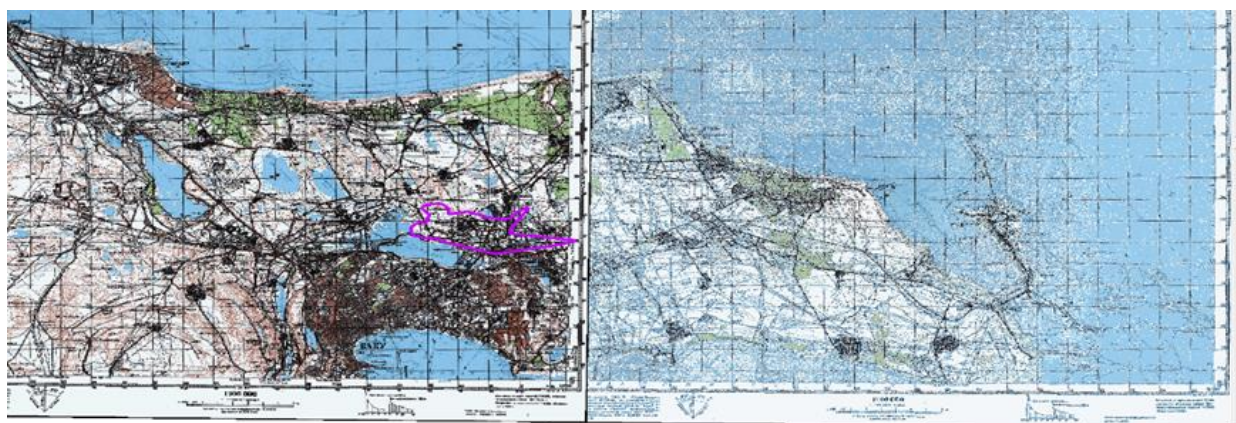


Figure 1. Topographic map at a scale of 1:100,000 and the outline of the Balakhany oil field (highlighted with a lilac outline)



Figure 2. Balakhany is one of the oldest oil-bearing regions on the Absheron Peninsula in 1880-1912

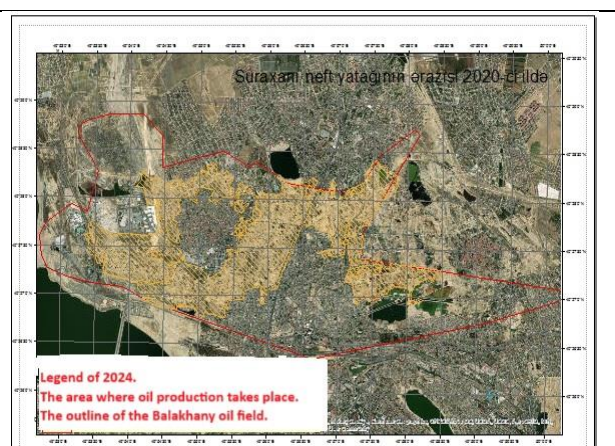


Figure 3. View of the Balakhany oil field from a satellite image in 2024

According to the State Agency for Alternative and Renewable Energy Sources, more than 15,000 hectares of land on the Absheron Peninsula are subject to oil pollution of varying degrees of intensity. In this regard, the search for new, more effective approaches to environmental monitoring is particularly relevant. This article uses a comprehensive method based on the integration of Earth remote sensing (ERS) and geographic information technologies (GIS) to detect and assess oil-contaminated soils. Analysis of multi-temporal satellite data (Sentinel-2, Landsat-8, WorldView-2) allows for the identification of spatiotemporal changes in land cover structure, the degree of soil degradation, and the distribution of oil spills [2, 7].

The use of vegetation indices such as the Soil-Adjusted Vegetation Index (SAVI) and Normalized Difference Vegetation Index (NDVI) ensures highly accurate interpretation of vegetation cover and allows for quantitative assessment of the level of soil contamination. [2, 3, 5]. Thus, the combination of satellite observations and geographic information analysis tools creates an effective ba-

sis for operational environmental monitoring, forecasting, and management of oil-contaminated areas in Azerbaijan.

The advantage of space-based technologies lies in the fact that Earth observation has been conducted for many decades, and multi-temporal images of the same areas are preserved in the archives of leading space agencies. Researchers use these datasets, apply various digital processing methods, and extract information about the ecological condition of the study area.

3. Methodology

The methodological framework of this research integrates remote sensing and geoinformation technologies to evaluate the spatiotemporal dynamics of vegetation and soil oil contamination within the Balakhany oil field. The methodological approach combines several sequential stages, including data acquisition, preprocessing, index-based analysis, classification, and validation. Each stage was designed to ensure a high degree of spatial accuracy and reliability in the interpretation of environmental conditions.

At the first stage, multi-temporal satellite datasets (Landsat-8 OLI/TIRS and Sentinel-2 MSI) were collected for the years 2014, 2019, and 2024. These datasets were selected due to their optimal spatial (10–30 m) and spectral resolution, which enables the detection of subtle changes in vegetation and surface reflectance characteristics. The WorldView-2 imagery (spatial resolution 0.5 m) was additionally used for detailed mapping and validation of micro-scale oil contamination patterns. Landsat-8 and Sentinel-2 satellite data were downloaded from the USGS EarthExplorer and Copernicus Open Access Hub platforms.

At the second stage, radiometric and atmospheric corrections were applied using the *Dark Object Subtraction (DOS)* method and *FLAASH* (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) module in ENVI 5.6. This ensured the elimination of atmospheric scattering and absorption effects, enabling reliable spectral comparison between multi-temporal datasets. Additionally, *geometric correction* was carried out using topographic maps (scale 1:100,000) and ground control points obtained during field campaigns, with a final RMS error of less than 0.5 pixels.

The third stage involved the calculation of vegetation indices — primarily the Soil-Adjusted Vegetation Index (SAVI) and the Normalized Difference Vegetation Index (NDVI) — to assess the degree of soil degradation and vegetation density. The parameter $L = 0.5$ was adopted for SAVI calculations in accordance with Huete (1988), allowing for an effective correction of soil background reflectance in sparsely vegetated oilfield landscapes. The indices were computed using ArcGIS 10.4.1 Raster Calculator and subsequently classified into five density categories corresponding to vegetation coverage levels (bare soil, sparse, moderate, dense, and very dense) [5, 7].

In the fourth stage, GIS-based spatial analysis was conducted. The results of the index-based classification were overlaid with vector layers representing oilfield infrastructure, residential areas, and reclamation zones. This allowed for the identification of spatial relationships between oil production intensity and vegetation degradation. Temporal overlays of SAVI maps from 2014, 2019, and 2024 enabled the assessment of landscape restoration trends and the delineation of pollution hotspots.

Finally, field validation was performed using GPS-referenced sampling sites and visual surveys

to verify satellite-derived interpretations. Soil samples were analyzed for hydrocarbon concentrations to correlate the spectral response with actual contamination levels. This integrative methodology ensured a scientifically sound and reproducible approach to environmental monitoring, combining remote sensing data with in-situ verification for comprehensive analysis of oilfield-affected territories.

4. Analysis and discussion.

This study employs geoinformation technologies, methods for processing multi-temporal multispectral satellite imagery, and digital cartography. At the initial stage of aerospace monitoring, a digital database of ground infrastructure is created based on archival cartographic materials, which serves as a baseline for analyzing the dynamics of oilfield infrastructure. The stage of developing the digital database was based on topographic maps from 1980 (Figs. 4, 5, 6, 7).

As can be seen from the data processed from different periods (Figs. 4, 5, 6, 7), it can be concluded that the area where oil production is taking place is shrinking, while the area of populated areas is expanding. Populated areas expanded due to the freeing up of land for oil production.

Analysis of images obtained by calculating vegetation indices. The influence of reduced oilfield activity on the soil and vegetation cover of the territory can be demonstrated through the calculation of vegetation indices SAVI and NDVI:

$$NDVI = (NIR - RED) / (NIR + RED),$$

$$SAVI = (NIR - RED) / (NIR + RED + L) \times (1 + L)$$

In this study, satellite imagery from Landsat 8 was used. For Landsat 8, the SAVI index is calculated as follows:

$$SAVI = ((Band\ 5 - Band\ 4) / (Band\ 5 + Band\ 4 + 0.5)) * (1.5),$$

where NIR refers to pixel values in the near-infrared wavelength range of the electromagnetic spectrum, and RED corresponds to pixel values in the red wavelength range.

The coefficient L in the SAVI formula is not a constant value; it ranges between -1 and $+1$ depending on the density of vegetation cover in the study area. For areas with dense vegetation, $L = 0$, in which case the SAVI and NDVI values are identical. In regions with sparse vegetation, $L = 1$. Most commonly, $L = 0.5$, as this value is suitable for analyzing the majority of vegetation types [4]. An evaluation of vegetation cover using SAVI is provided in Table 1.

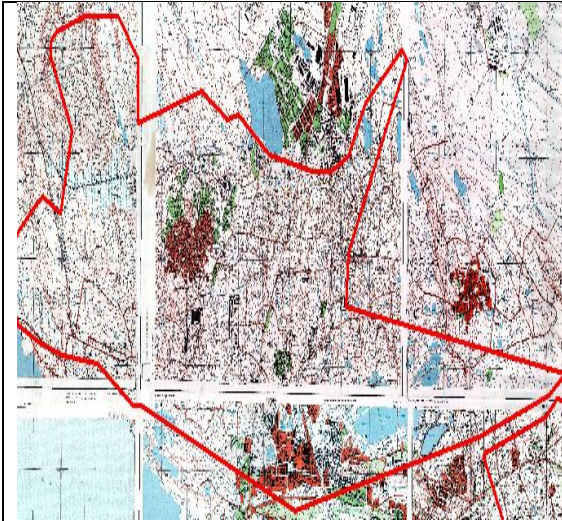


Fig. 4. Archival topographic map of the Balakhany oil territory.

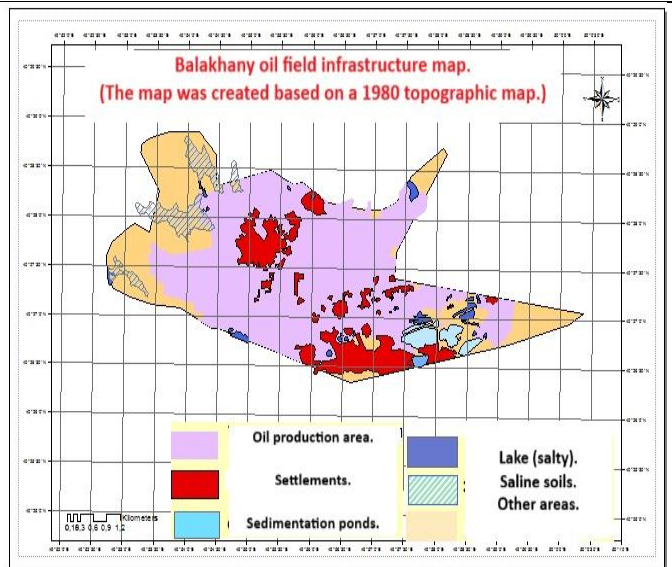


Fig. 5. Digital electronic map of oil field infrastructure obtained by digitizing a 1980 topographic map.

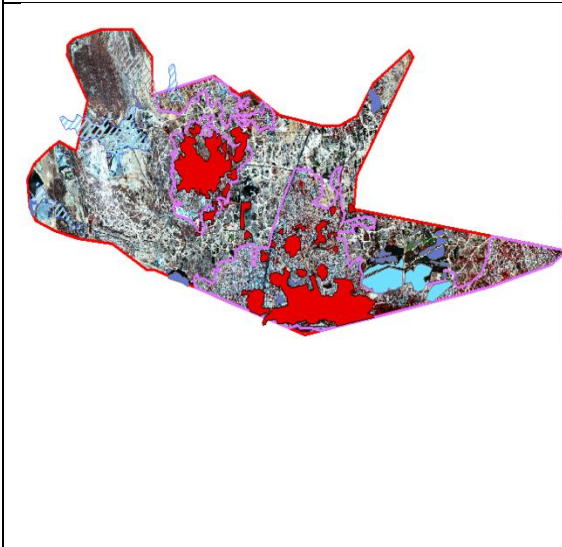


Fig. 6. The red outline on the image of 2024 is the area of populated areas according to archival data, the area of their increase in territory outlined by the lilac line.

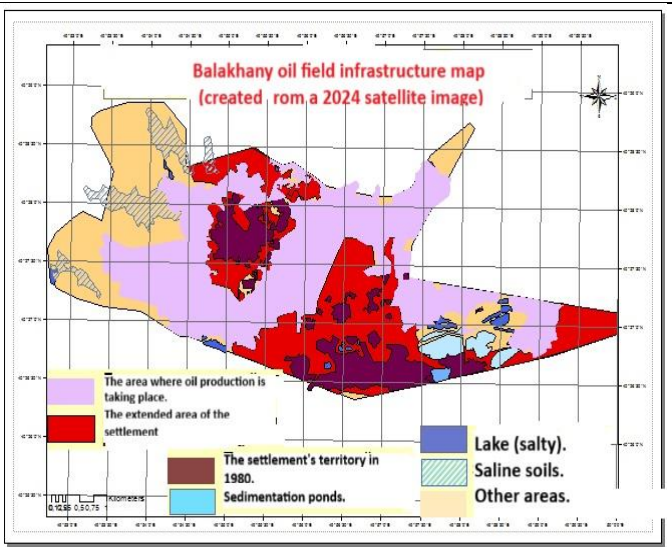


Fig. 7. Division of the oil field territory according to a 2024 space image into zones: working area, populated areas, settling ponds, salt lakes, etc.

The stage of developing the digital database was based on topographic maps from 1980 (Figs. 4, 5, 6, 7).

Table 1

Relationship between SAVI Values and Vegetation cover density

| SAVI values | Vegetation cover |
|-------------|--|
| < 0.1 | Wet soils and water surfaces |
| 0.1 – 0.3 | Soil covered with sparse or grassy vegetation |
| 0.3 – 0.5 | Vegetation of medium density, dense grass or shrub cover |
| > 0.5 | High-density vegetation cover |

To analyze the relationship between oil field activity and soil and vegetation cover in the oil field area, Landsat-8 satellite images for 2014, 2019, and 2024 were processed. All images were radiometrically and atmospherically corrected and

processed using ArcGIS 10.4.1. Figures 8, 9, and 10 present the results of calculating the Soil-Adjusted Vegetation Index (SAVI) for the indicated periods.

For the calculations, the parameter L was set to 0.5. This value was chosen in accordance with the recommendations of Huete (1988), who proposed using this coefficient in cases where the surface is characterized by a moderate density of vegetation cover. The parameter L serves as a correction factor, reducing the influence of soil reflectivity on the final index value.

The choice of $L = 0.5$ is optimal for areas where vegetation is unevenly distributed and contains both bare soil areas and patches of vegetation. This is especially relevant for oil production zones, where anthropogenic impacts and pollution create a mosaic landscape structure. Therefore, using $L = 0.5$ provides a more accurate assessment of vegetation status and allows for the correct interpretation of changes in heterogeneous soil conditions. [9].

Image interpretation using the 2014 SAVI index: Initial situation. The 2014 SAVI map shows that the vegetation in the Balakhany oil

field area is predominantly steppe grassland, generally sparse and weak.

The following observations are noted:

According to the index, dark green (-0.41–0.05) indicates aquatic and moist soils.

The oil field area, marked in light green (-0.05–0.11), is an oil production area without vegetation cover.

Areas with bare soil, partially covered by sparse steppe grassland vegetation, and subject to anthropogenic impact are marked in yellow.

Areas with low vegetation cover, primarily near populated areas, are marked in orange (0.17–0.27). (Red (0.26–0.73): Areas with high vegetation are present only on the southwestern outskirts and within populated areas.

Based on the SAVI vegetation index, the oil field area has low-growing, stunted grassland vegetation. A predominance of open or unused areas is also observed, along with oil production areas.

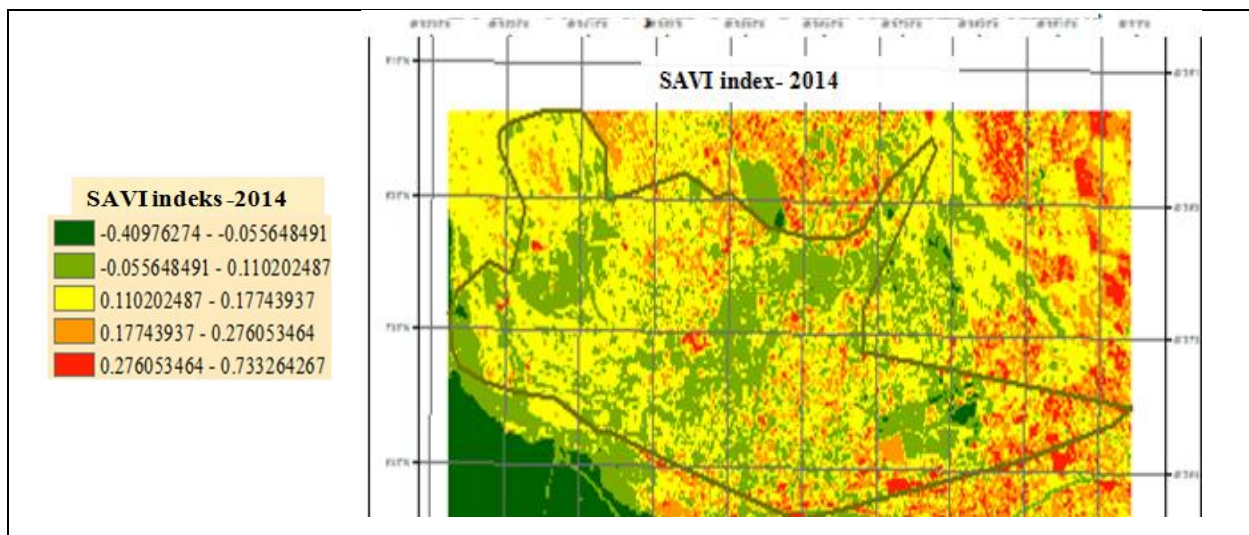


Fig. 8. Image of the oil field according to the SAVI index in 2014

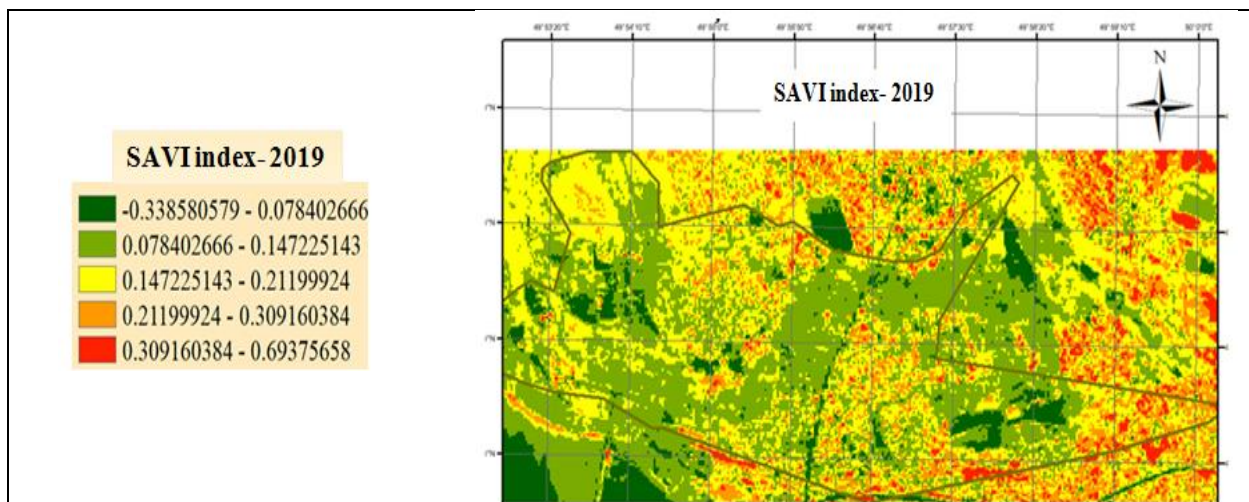


Fig. 9. SAVI Image of the Oilfield in 2019

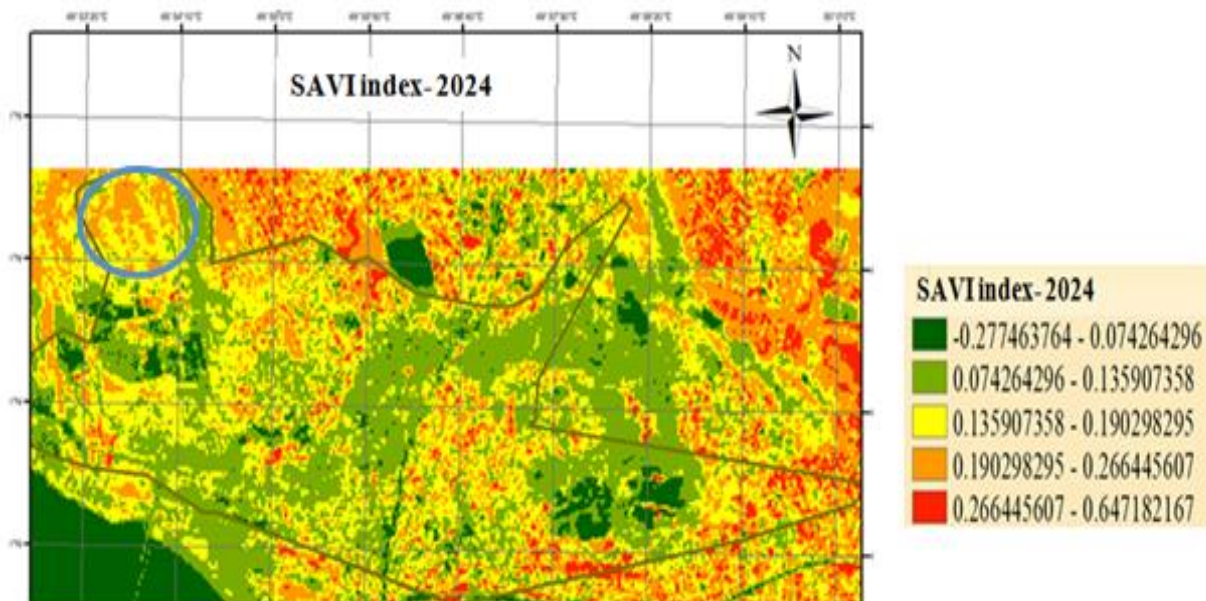


Fig. 10. Image of the oil field according to the SAVI index in 2024

Interpretation of SAVI Image for 2019: Improvement Phase. Compared to the 2014 map, the 2019 image reveals oil extraction zones with more clearly defined boundaries. Areas shaded in green (0.078–0.14) correspond to oil production sites and soils contaminated by oil extraction waste.

The zone of weak vegetation cover (yellow, 0.14–0.21) decreased relative to 2014, giving way to areas with medium-density vegetation (0.211–0.31). Areas of medium to high vegetation density (0.31–0.69) were primarily observed within settlements.

Negative and very low values (≤ -0.1) represent water bodies and moist surfaces.

Overall, the extent of active oil production areas contracted and became more spatially confined. The area where oil production takes place is gradually shrinking and being limited to specific boundaries. This reduction is due not only to a reduction in production volumes but also to the implementation of environmental rehabilitation programs. Strengthened measures for landscaping, reclamation of contaminated lands, and monitoring of ecosystem health are contributing to the gradual restoration of the natural landscape. As a result, improved soil quality, increased vegetation cover, and reduced levels of oil pollution are observed, demonstrating the effectiveness of modern approaches to the sustainable management of industrially transformed areas.

Interpretation of SAVI Image for 2024: Recovery and Stabilization. The SAVI index values for 2024 indicate that vegetation cover, compared

to previous years, continued to increase and stabilize.

- Negative and very low values (≤ -0.1): Water bodies, moist surfaces, saline lakes, and oil-field settling ponds.

- Green zones (0.07–0.14): Areas of soil cover associated with oil extraction and oil-contaminated land. Compared to 2014, these areas have decreased in size and are now partially covered with sparse steppe vegetation along roads and between oil wells. Thus, the share of bare or heavily degraded surfaces within the active oil production zone has diminished.

- Medium vegetation cover (0.15–0.26): Increased relative to previous years, not only within settlement areas but also in regions that previously lacked vegetation cover (outlined in blue in Fig. 10).

High vegetation cover (0.26–0.65): Still dominates within settlements, reflecting ongoing greening activities and the presence of private gardens.

5. Conclusion

This study demonstrates that the combined use of remote sensing (RS) and geoinformation technologies provides a robust and scalable framework for environmental monitoring in territories exposed to long-term anthropogenic pressure, with the oil-producing landscapes of the Absheron Peninsula and the Balakhany oil field serving as a representative case. Multi-temporal analysis of Landsat 8 imagery enabled an objective evaluation of soil–vegetation dynamics for 2014, 2019, and 2024, capturing both degradation patterns and

recovery trends through consistent spatial comparison.

A key contribution of the work is the use of SAVI as a quantitative indicator in sparsely vegetated, heterogeneous oilfield environments. The results indicate a clear increase in SAVI values from 0.12 to 0.28 over the ten-year period, which reflects an improvement in vegetation conditions and a partial restoration of degraded soils. In parallel, the spatial extent of active oil production contracted markedly - from approximately 1,200 ha (2014) to 700 ha (2024) - suggesting that the landscape has become more spatially confined, likely due to both production decline and rehabilitation initiatives.

Importantly, the observed positive dynamics are supported by reported on-the-ground interventions, including the cleanup of more than 150,000 m³ of oil-containing waste, the abandonment of about 200 inactive wells, and the restoration of more than 300 ha of soil and vegetation. The documented reduction in average soil oil-product concentrations from 15–18% to 2–3% further reinforces the interpretation that environmental management and reclamation measures have produced measurable improvements.

From a methodological perspective, the study establishes a reproducible monitoring workflow based on multi-temporal datasets (including Landsat-8, Sentinel-2, and high-resolution WorldView-2), standardized radiometric/atmospheric corrections (e.g., DOS and FLAASH), high-accuracy geometric alignment (RMS < 0.5 pixels), and index-based classification integrated with GIS overlays of infrastructure and land-use zones. The approach is strengthened through field validation using GPS-referenced observations and hydrocarbon analysis of soil samples, which increases confidence in satellite-derived interpretations and improves the reliability of hotspot delineation.

Overall, the findings confirm that RS+GIS monitoring can simultaneously delineate contaminated and industrially disturbed zones, track restoration trajectories over time, and support evidence-based planning of reclamation priorities and follow-up field inspections. The results indicate that continued implementation of environmental programs and rational land management can contribute to the gradual recovery of bioproductivity and landscape sustainability across oil-impacted territories of Absheron.

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NEFT HASILATI FƏALİYYƏTI NƏTİCƏSİNDƏ UZUNMÜDDƏTLİ ANTROPO- GEN TƏSİRƏ MƏRUZ QALAN ƏRAZİLƏRDƏ BITKİ ÖRTÜYÜNDƏ DƏYİŞİKLİKLƏRİN VƏ TORPAQLARIN NEFTLƏ ÇİRKƏNMƏSİNİN AŞKARLANMASI

Cəfərova N.R., İsmatova X.R.

Xülasə: Bu məqalə uzunmüddətli antropogen təsirə məruz qalan ərazilərdə, xüsusilə neft-qaz sənayesinin təsir etdiyi sahələrdə ətraf mühitin monitorinqi üçün məsafədən zondlama metodlarından istifadənin üstünlüklərini nümayiş etdirir. Tədqiqat neftlə çirklənmədən ən çox zərər çəkən Balaxanı ərazilərinə yönəldilmişdir. Məqalə həm nəzəri, həm də praktiki əhəmiyyət daşıyır və çirklənmə sərhədlərini, eləcə də bitki örtüyündə baş verən dəyişmələri dəqiq müəyyən etməyə imkan verən texnologiyaların tətbiq üsullarını təsvir edir. Məqalədə,

həmçinin Abşeron yarımadasındakı neft yatağı nümunəsində Torpağa Tənzimlənən Bitki Örtüyü İndeksinin (SAVI) hesablanması əsasında çoxzamanlı peyk təsvirlərinin işlənməsi və interpretasiyası nəticələri təqdim olunur. Alınmış nəticələr ətraf mühit dəyişikliklərinin fəza-zaman dinamikasını müəyyən etmək üçün peyk məlumatlarından istifadənin səmərəliliyini təsdiqləyir. SAVI indeksinin tətbiqi bitki örtüyünün deqradasiya dərəcəsini qiymətləndirməyə və intensiv neft çirklən-

məsi zonalarını lokallaşdırmağa imkan vermişdir. Təhlil məsafədən zondlama metodlarının ətraf mühitin vəziyyətinin monitorinqi, antropogen yüklənmənin təsirinin qiymətləndirilməsi və çirklənmiş torpaqların rekultivasiyası üzrə tövsiyələrin hazırlanması üçün mühüm alət olduğunu göstərir.

Açar sözlər: neft, monitorinq, bitki örtüyü, SAVI, torpaq.