IMPACT OF THE TENGIZ OIL FIELD ON THE STATE OF LAND COVER

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Abstract: The study of the transformation of natural complexes in areas with a developed infrastructure for oil subsurface use is a prerequisite condition for solving the environmental problems of oil-producing regions. Located in the territory of the Atyrau Region in Western Kazakhstan, the Tengiz oil field is one of the largest oil fields in the world. The field has been under intensive development for more than 40 years and is characterised by a large volume of anthropogenic load, which contributes to a significant transformation of the landscape complex. The purpose of this study is to investigate the dynamics of landscape changes in the territory of the Tengiz field and to assess its ecological condition. Based on the materials from many years of research, the features of the Tengiz field and the main technogenic sources affecting the landscape complex were identified. Several quantitative indicators characterising the anthropogenic load were calculated based on satellite images. On the basis of Landsat – 5 TM, 7 ETM+ and 8 OLI and Sentinel-2A (S2A) data, the vegetation index of land cover was calculated using normalised difference vegetation index (NDVI), demonstrating the dynamics of landscape changes in the period from 1990 to 2020. The obtained results show that the areas of some landscape components continue to deteriorate. For example, the area of open soil in 2020 decreased due to the withdrawal of these areas for industrial facilities, which increased by 2.2 times by 2020 due to intensive field development. This study demonstrates the importance of monitoring and studying desert landscape complexes under active anthropogenic impact to ensure the sustainable development of territories.

Keywords: Tengiz oil field, technogenic impact, landscape complex, ecological condition

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Introduction

Kazakhstan has become one of the world's leading oil producers and exporters over the years of independent development, with the richest reserves in the Caspian region, and is one of the major oil-producing countries in the world, ranking 12th in explored oil reserves and 17th in oil production (1.7% of world production), as well as 28th in gas production (Oil and Gas Industry of the Republic of Kazakhstan 2019) (Fig. 1).

Kazakhstan is the second-largest oil producer among the Commonwealth of Independent States (CIS) after Russia. Confirmed hydrocarbon reserves of the republic include more than 250 oil, gas, oil-gas, and oil-gas-condensate fields (Abdullin, Votsalevsky 2001). Most (80%) of the fields are located in Western Kazakhstan, particularly in the Atyrau region, which is part of the Caspian oil

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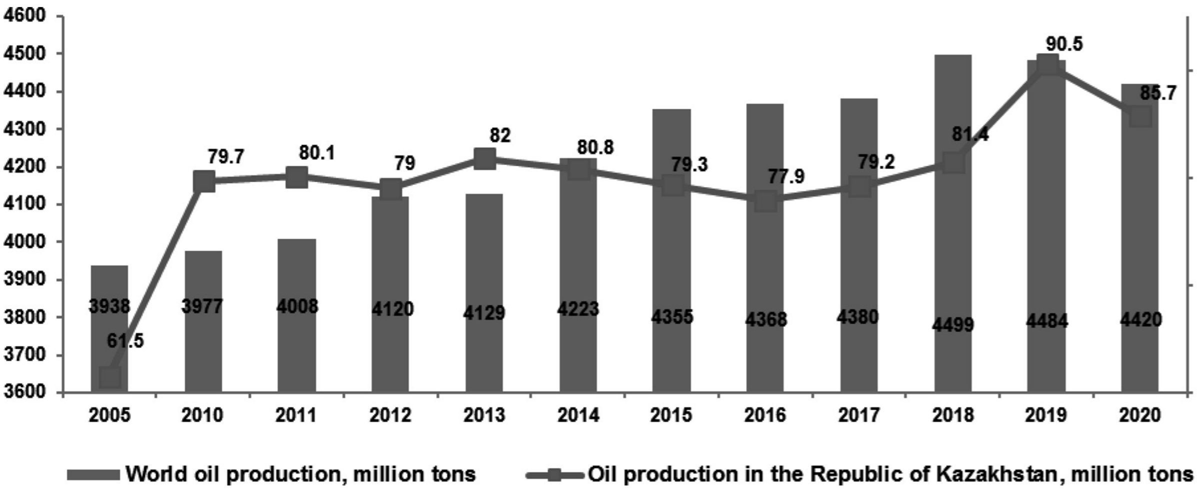

Fig. 1. Oil production in the world.
Source: own research, data taken from the official site of the Committee on Statistics of the Republic of Kazakhstan and the official site of the Ministry of Energy of the Republic of Kazakhstan.

and gas province (Portnov et al. 2015; Mahmood, Orazalin 2017) and borders the same oil-bearing regions as the Mangystau, West Kazakhstan and Aktobe regions.

A specific ecological situation is forming on landscapes of oil and gas subsoil use. A special type of ecological system is forming, natural complexes of which are exposed to diverse and intensive technogenic loads. Landscapes acquire a new set of properties and modes, affecting the ability to perform ecological functions effectively. Therefore, natural landscapes of the oil and gas production regions refer to the territories which need systematic monitoring of the ecological state.

Nowadays, satellite monitoring is increasingly used along with the traditional ground-based methods of observing the state of landscapes (Bloomfield, Doolin 2017; Mjachina et al. 2018). The advantages of remote monitoring of land cover based on satellite images are the scale of research and the possibility of obtaining a variety of operational or archival information about the state of natural components. As indicated previously in the literature (Yelsakov, Shchanov 2004; Bondur 2011), the use of satellite imagery data on territories with homogeneous vegetation cover and a low degree of stability allows recognition of disturbed areas with high accuracy. In addition, it is often difficult to control the state of landscapes in large areas subjected to constant intensive anthropogenic loads by ground-based methods due to financial and organisational reasons (Kozin 1984; Nikitina, Olzoev 2014). The satellite images provide an opportunity to use indicators determining the value of anthropogenic load in the oil-bearing areas of the desert zone of the Atyrau region, in particular, in the territory of the Tengiz oil field, which was selected as a key site.

The study of the transformation of natural complexes in areas with a developed infrastructure of oil subsurface use is a required condition in solving the environmental problems of oil-producing regions, since:

– the areas ratio of the natural landscapes with the areas of natural–technogenic complexes determines the possibility of further sustainable development of the territory;
– there might be an insufficiency regarding the information about the state of land cover, and about their changes, which may be a cause of environmental risk.

The purpose of this work is to study the dynamics of landscape changes in the territory of the Tengiz oil field and assessment of its environmental condition based on the earth’s remote sensing data. Results may contribute to the development of recommendations to optimise subsoil use in the study area, preventing possible negative consequences and ensuring the environmental safety of the region.

Materials and methods

The object of the study is the Tengiz oil field, located 155 km southeast of the regional centre of Atyrau, on the territory of the Zhylyoi District (46°09'10"N, 52°23'00"E). The Zhylyoi District is considered to be

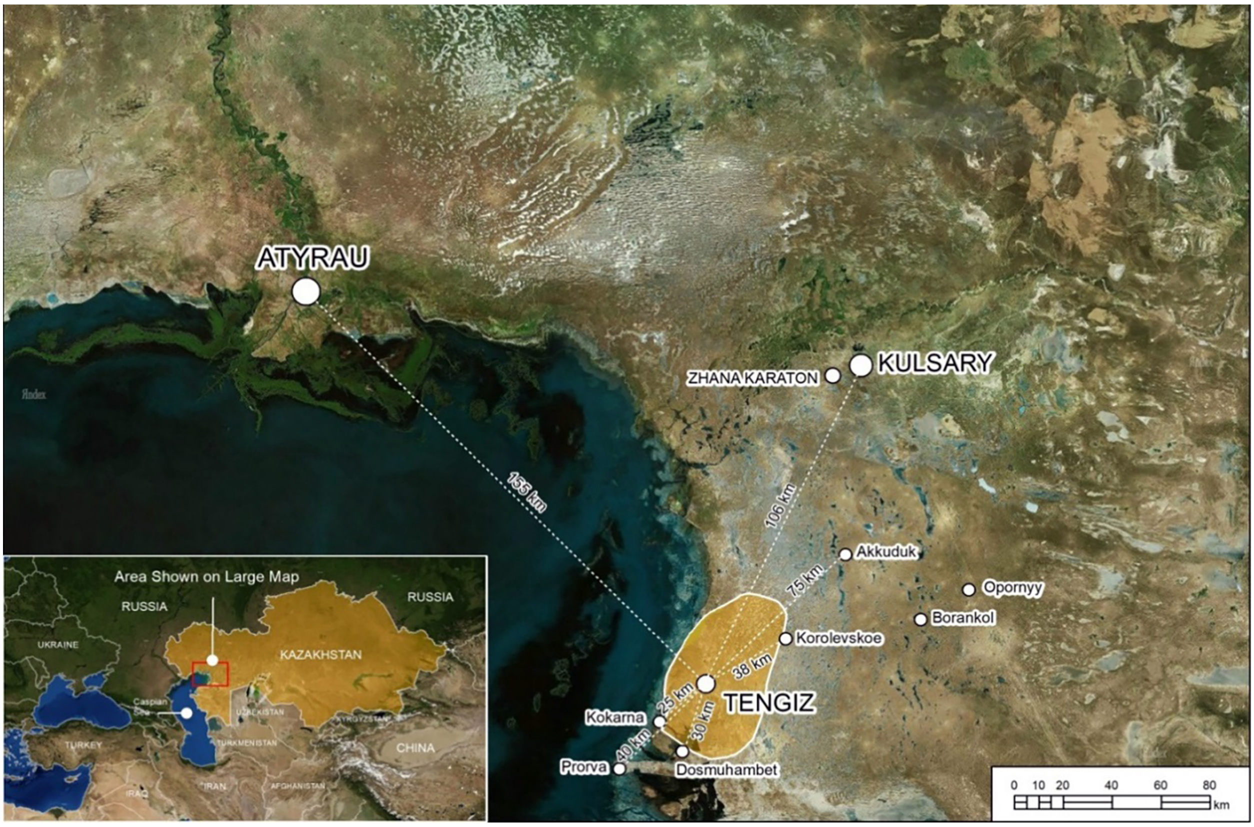

Fig. 2. An overview map of the study area (Tengiz oil field).
Source: own elaboration.

the region with the maximum oil-bearing capacity, as it contains 39 fields on its territory. The Tengiz field, having a total area of 565 km^2, was discovered in 1979, where the first oil production began in 1981. There are many large fields in the area of the Tengiz field: Korolevskoye, Prorva, Kokarna, Dosmukhamed, Tazhigali, Pustynnoye, etc.

The Karaton-Sarkamys villages, which are close to the field, were relocated to the northern part of the area because of harmful emissions (Fig. 2).

The selection of the Tengiz field as a key site was related to the following factors:

- Tengiz is the world's deepest supergiant oil field;
- the Tengiz oil field is characterised by a large volume of accumulated technogenic load, which contributes to a significant transformation of the landscape complex;
- the field is located in the desert zone on the surface of the sea plain, covered with loose sediments (more than 10 km thick), which are quickly exposed to both external and anthropogenic impacts. Many modern forms of relief emerge, including technogenic ones, which are developed on them.

Materials

Materials of the monitoring studies conducted by the authors within Western Kazakhstan which includes the Atyrau region were used to write this article (Koshim et al. 2014, 2016, 2017, 2018; Akhmedenov et al. 2015). The state of the landscape, in particular relief, soil and vegetation cover, and the ecological condition of the region were investigated. The field studies included route observations, analytical studies and population questionnaires. The obtained materials were then correlated with the geological–geomorphological and landscape studies conducted by the authors earlier. The results of the work were used in the preparation of thematic maps, presented in various publications and monographs. The study of this region is still being carried out, but for the last two years, due to the limitation of field studies because of Covid-19, the research has been conducted mainly with the help of remote sensing data. The publications addressing environmental problems of the region in connection with oil and gas development were used as additional information (Efendiyeva 2000; Chigarkina 2001; Nurushev et al. 2017; Bulatov et al. 2020) where some authors

Table 1. Summary of the datasets used: Satellite images and their sensors with resolutions.

Satellite images and sensors		Resolution (m)
LT05_L1TP_165028_19900807_20200915_02_T1	TM	30
LT05_L1TP_165028_20000802_20200906_02_T1	TM	30
LC08_L1TP_165028_20200809_20200918_02_T1	OLI-TIRS	30
S2A_MSIL2A_20200808T072621_N0214_R049_T39TXM_20200808T100005	S2A	10

S2A – Sentinel-2A.
Source: Satellite Images Sensor.

noted even the initial stage of ecological disaster in the region (Diarov 2003). The issues of natural environment monitoring (air, water and soil) related to oil production in the Atyrau region were considered (Kenzhegaliev et al. 2003; Zhanburshin 2005), and the studies of Izteleuova (2002), Holstein et al. (2018) and Issanova et al. (2020) concerning oil pollution issues of various components of the natural environment, such as soil, vegetative cover and formation of technogenesis, were also analysed. Literature dealing with the application of satellite images in the study of oil-bearing areas was used (Jafari 2010; Kenzhegaliyev, Bekmukhanov 2010; Kenchinbaev 2011; Gossen, Velichkina 2012; Kaczyńska et al. 2015; Khajehpour et al. 2017), and the principle of mapping oilfield sites was considered as well (Smejkalová et al. 2017; Sabirova et al. 2019; Myachina, Chibilev 2020). Also, cartographic material (The National Atlas of the Republic of Kazakhstan 2010) and topographic maps of M:200,000 scales were used to clarify the boundaries of some geographical objects, as well as landscape complexes in the area of the field.

Space images—from Landsat 5 TM, 7 ETM+ and 8 OLI-TIRS and Sentinel-2A (S2A) and with a spatial resolution of 30 m and 10 m—were also used as material to assess the dynamics of the landscape complex for the period 1990–2020 (Table 1).

Methods

A set of complementary methods was used to characterise the landscapes of the deposit area: information search on the study topic, analytical review of the collected materials and publications. Since the site of the field is part of the same landscape area with surrounding territories (marine plain, composed of loose sediments of clays, loams, sands, with poor saltwort vegetation on salt marshes) the coastal, western part, the southeastern part of the field, as well as the area of the shift camp of the Tengiz field were surveyed by a route method. Vegetation cover, ground, soils and the presence of relief-forming processes were described. The characteristics of the study object were determined from other fields by the comparative geographical method, and the quantitative indicators of the objects were calculated from the satellite images. Based on the remote sensing data and the method of automated photo interpretation, the vegetation index was determined using the normalised difference vegetation index (NDVI) of the land cover.

Discussion results

Subsoil use is considered as a cumulative type of human activity in a broad system of economic activities associated with the development of mineral resources, which have a complex impact on the natural components and their transformation.

The Tengiz oil field is located on the Caspian lowland, on the surface of the accumulative valley, with −20 m elevations. Relative elevations of small relief elements are 0.5–1 m (Koshim 2020) (Fig. 3). The valley has a slight slope to the west, towards the sea, where there is a flat sandy valley—the former bottom of the Caspian Sea. The Caspian Karakum sands border the field to the east.

The desert landscape complex of the field is represented by a marine valley, composed of loose sediments of clay, loam and sand, with poor saltwort vegetation. A characteristic feature of the climate of the study area is sharp, continentally cold winters (up to −30°C) and dry summers (+45°C). The annual precipitation is 100–200 mm.

The vegetation period is very short; it begins in the middle of May and ends by the end of August. This happens because of the impact of the arid climatic conditions (Kulikova et al. 2017). The temperature regime, the amount of winter and spring-summer precipitation, and the intensity of snowmelt are the most significant factors that shape the natural state of natural complexes (Khoroshev 2006).

Fig. 3. Tengiz oil field. Gas processing plant-2.
Source: photo taken by the authors.

All technological preparation and development processes of the Tengiz oil complex cause disturbance and pollution of natural components. Therefore, the size of its impact on the natural environment allows us to consider it as a single oil-industrial complex, which would have its own features. The features of the field include:

1. Corrosive qualities of hydrocarbon raw materials;
2. Deep location of the oil reservoir, on Palaeozoic carbonate rocks;
3. High content of chemical impurities in oil;
4. Profitability of the operation, i.e. large volume of extraction of raw materials;
5. The use of powerful drilling and construction equipment, as well as a variety of heavy vehicles with a high environmental impact;
6. Creation of transport systems (railway and highway roads) of great length for oil export, expanding the impact on natural components;
7. Reduced reliability of maintenance of field equipment and vehicles in harsh environmental conditions.

It is known that oil and oil products are considered one of the main pollutants that harm the natural environment in the area. Oil wastes pollute and disrupt the landscape complex during production, industrial and mainline transport, storage and utilisation. They cause profound changes in all elements of the landscape.

Oil production at the Tengiz field has been going on for more than 40 years. The area where the main oil development is carried out encompasses 250 km^2. The number of wells drilled in the area is about 300, the average density of each of which is 1.2 pcs × km^{-2}. Some places have up to five wells located in one area due to the huge oil reserves (amounting to 0.750–1.125 billion tons) and the deep location of the oil layer (having a depth of more than 4,000 m). The oil reservoir is 19 km (12 miles) long and 21 km (13 miles) wide, and the oil reservoir is one mile high. The whole area of the oil reservoir is 399 km^2 (Table 2).

Technogenic risk factors that destroy the landscape complex of the area are as follows (calculated from Google Earth Pro satellite images):

– high infrastructure density (administrative and technological facilities) (Fig. 4);

Table 2. Characteristics of the Tengiz oil field.

Parameter	Details
Initial parameters	
Coordinates	46°09'10"N, 52°23'00"E
Location within Atyrau region	Zhylyoi district
Opened (year)	1979
Oil-saturation factor	0.82
Gas oil ratio	487 me × me^{-1}
Formation pressure	84.24 MPa
Temperature	105°C
Oil-related parameters	
Oil density	789 kg × m^{-3}
Constituent elements (%)	
Sulphur	0.7
Paraffinic	3.69
Low-resin	1.14
Oil reserves	1.8 trillion m^3
Extractable volume of oil	750 million–1125 billion tons
Estimated volume of oil	3,133 billion tons
Associated petroleum gas reserves	1.8 trillion m^3
Field-related parameters	
Total field size	565 km^2
Depth of oil layer	4,000–5,700 m
Oil reservoir length	19 km (12 ml)
Oil reservoir width	21 km (13 ml)
Oil reservoir area	399 km^2
Oil layer height	1,200–1,500 m
Number of wells	255
Average density of wells	1.2 pcs × km^{-2}
Number of gas processing plants	3
Oil development partners	– JSC NC "KazMunayGas" (20%), – Chevron Overseas (50%), – ExxonMobil (25%), – Lukoil (5%)

Source: own elaboration.

Fig. 4. The infrastructure of the Tengiz oil field.
Source: Map data ©2022 Google Earth, CNES Airbus/Tengiz, Kazakhstan.

– gas processing plants (two are currently operating, the construction of the third plant is nearly completed);
– number of wells drilled – 255 (data for 2019);
– pipeline network – 150 km;
– railway network for oil transport – 38 km;
– paved highway road – 19 km;
– dirt road connecting field facilities, gas processing plants and wells.

The most common problem of the site is the violation and destruction of the soil and vegetation cover over a large field due to the construction of technological facilities, industrial infrastructure, laying wells, building roads to industrial facilities and transferring heavy lifting equipment. There is a complete change in the area and the entire landscape complex.

Two plants are currently operating at the site. The first is the Tengiz oil and gas processing plant and reservoir, which started operating on 6 April 1991. The plant marked the beginning of commercial production in the area and was designed to clean oil from hydrogen sulphide and mercaptans.

Since 1993, oil production at the site has increased 30 times—up to 30 million tons of oil per year. Therefore, in 2008, a second oil and gas processing plant was built. It was designed for pumping sour gas into the reservoir. The plant stabilises the oil and removes sulphur-containing components from it. It also separates natural gas and sulphur. After the plant construction, the resultant oil production at the site amounted to 75 tons × day^{-1}, and natural gas production to 22 million m^3 × day^{-1}. The plant is presumed to be the world's largest sour oil processing line.

Currently, the construction of the third plant is nearly completed, as a result of which the increase in oil production is expected to reach up to 39 million tons × year^{-1}. This plant will be 20–30% larger than the first and second plants. There will be no sulphur production at the third plant since gas will be injected back into the reservoir to maintain reservoir pressure. The plant is designed to operate for 30 years.

During the construction of the plants, a large area of the site, amounting to 5.5 km^2, was affected and disrupted. There are accidents, fires and hydrogen sulphide emissions which often occur at the plant. The last release of hydrogen sulphide at Tengiz occurred on 7 April 2021, which affected the ecological state of the natural environment and pollution of the natural components of the landscape.

In addition to factories, disturbance of the soil cover is also influenced by other industrial facilities. For example, the area of one plot of prepared wells for drilling is on average 275 m^2 (150 m × 180 m). If this indicator is multiplied by the number of wells, then the total area of affected soils (only by wells) will be about 7,000 km^2. This results in almost a complete replacement of the natural landscape with technogenic elements.

During the construction of the pipeline, the lithogenic basis of landscape changes, and geomorphological processes (pore formation, salinisation, takyr formation, etc.) are activated, leading to a change in or destruction of the entire natural complex. The wells in the area are interconnected by pipelines, which are then connected to a common pipeline built in 2001 by the so-called Caspian Pipeline Consortium (CPC). Through this pipeline, all Tengiz oil was sent to Novorossiysk (Russia). The length of the pipelines in the Tengiz field is 150 km.

In addition to disturbing the soil and vegetation complex, oil storage in drilling pits, accidents and pipeline ruptures create the threat of oil contamination of both the upper layer of soil and groundwater aquifers. The size of the contaminated areas depends on the landscape features of the area. One such site is found in the southwestern part of the study area, where the oil is poured into a 300-m^2 pore depression.

The territory of the site is crossed by a network of unpaved roads, which have completely disturbed the entire soil and vegetation cover and increased the bare (takyr-like) areas. The impact of the highway road located nearby is not as high.

There is a 38-km long single-track railroad in the area, along the western part of the site. This road transports Tengiz oil. The railroad is also prone to accidents and results in leaks of oil products, polluting the soil and vegetation cover. Along the railroad, the soil cover is completely bare.

As we know, Tengiz oil has a high hydrogen-sulphide content (Table 2) and also contains other harmful compounds. During the development, the oil purifies from sulphur, which immediately solidifies in the air. For a long time (since the beginning of operation), a huge mass of sulphur, with a volume of 9 million tons and an area of 612 m^2, was stored on the territory (recorded on the space image and is highlighted in yellow).

It created an insoluble problem for the environment. Sulphur does not dissolve but accumulates in the air, soil and groundwater (Nadim et al. 2006). As a solution, a processing plant was built to eliminate the sulphur, but the elimination was completed successfully only in 2015, after 20 years of operation. These days, the soil area where the sulphur was stored has been heavily contaminated under the influence of hydrometeorological factors, and erosion and destruction processes have accelerated.

We can also mention the story at the Tengiz field on 23 June 1985 at well No. 37, when oil and gas were released into the atmosphere from a depth of over 4 km. The fire at the field was extinguished one year later (400 days) – on 27 July 1986. Some people compare this catastrophe to the Chernobyl tragedy in 1986. A big flare of fire reached a height of 200 m and a diameter of 50 m. The temperature around the well reached 15,000°C and the soil turned into a vitreous mass. As a result of the fire, 3.4 million tons of oil, 1.7 billion m^3 of gas, 850 tons of mercaptans, and 900,000 tons of soot and other products of combustion were released into the air, poisoning the entire area around the field. The environment was heavily damaged, and the air, soil and water surfaces were polluted within 100–125 km from the well. The ground surface turned into black soot. The radius of the negative impact of the accident reached 450–500 km. The sickness rate of the Atyrau region population increased by 50%, and about one million birds died.

More than 30 years have passed since the accident, but the consequences are still seen to this day, both in the polluted air and in geosystems. After this catastrophe, we can firmly state that the landscape complex of the Tengiz field and adjacent territories has been completely transformed and has a technogenic appearance. In this regard, it is impossible to assess the sustainability of modern natural–territorial complexes in the area. However, in the field, the landscapes are not very stable (pore depressions, loose sediments, and close groundwater occurrence [1–1.5 m]). Therefore, one of the complicated tasks in the ecological analysis of oil and gas fields is to identify the real degree of disturbance

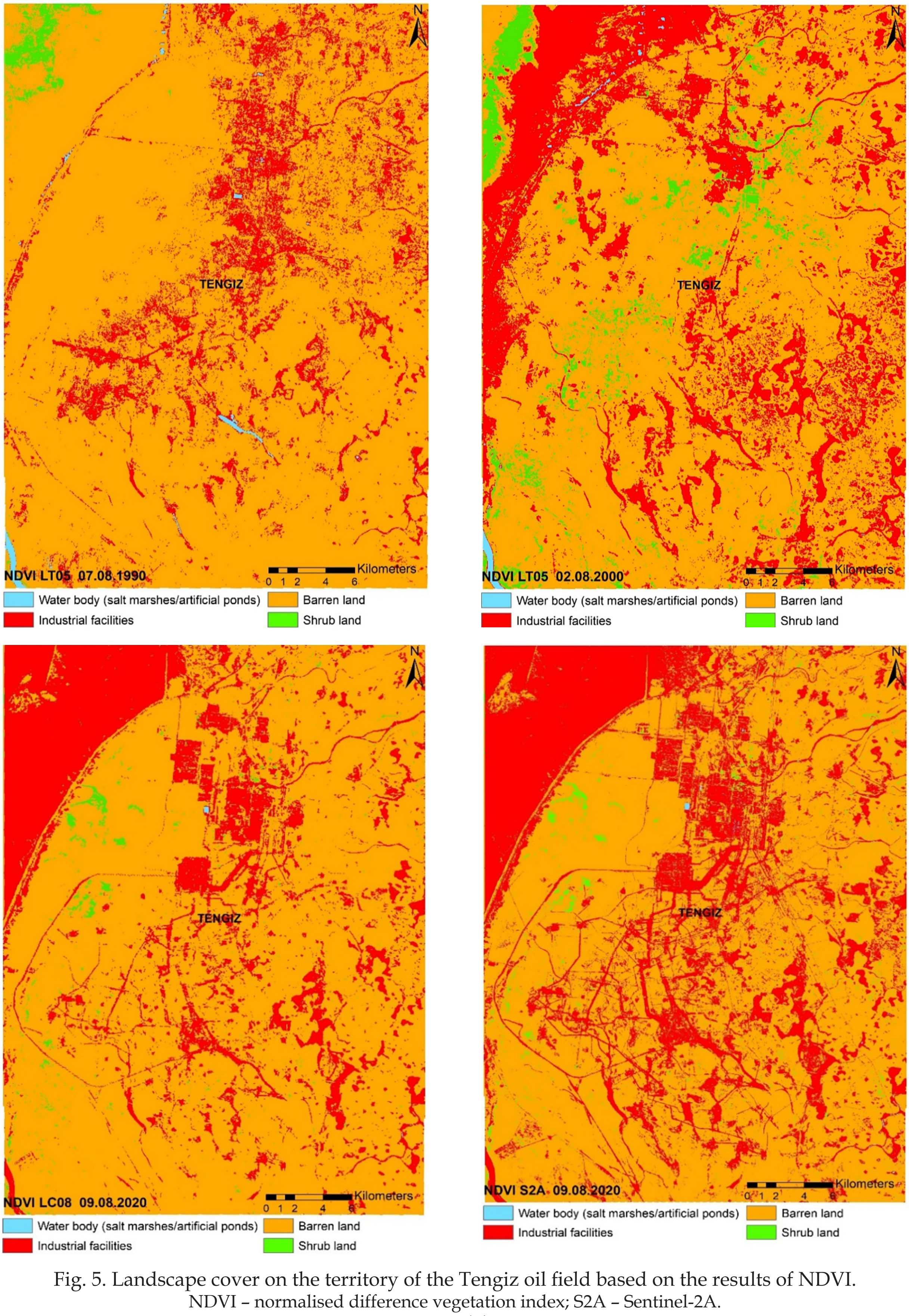

Fig. 5. Landscape cover on the territory of the Tengiz oil field based on the results of NDVI.
NDVI – normalised difference vegetation index; S2A – Sentinel-2A.
Source: own elaboration.

Table 3. The ratio of landscape cover elements in the territory of the Tengiz oil field according to the results of NDVI.

Lulc classes based on NDVI	1990	2000	2020	2020_sent
Water body (salt marshes/artificial ponds)	0.4	0.3	0.0	0.1
Industrial facilities	12.9	20.9	23.8	28.1
Barren land	85.8	74.2	75.5	72.0
Shrub land	0.9	3.6	0.7	0.7

NDVI – normalised difference vegetation index.
Source: own elaboration.

of landscape complexes. To solve this problem, we use space images, which are widely used in solving practical tasks.

Four images were used in the work (Table 3). The space images of Landsat 5 from 7 August 1990 and 2 August 2000, Landsat 8 from 9 August 2020 and S2A from 8 August 2020 were used. It was not always possible to get clear days, which is why the weather influenced the choice of these images.

According to the available data, the natural-climatic conditions on these dates were not out of the norm. So it was assumed that the landscape-vegetation cover of the Tengiz field for the periods of 1990–2020 should not differ significantly, unless, in the last 30 years, there was an impressive intervention of technogenic factors (in the period after the accident). In addition, our area is quite localised in the scale of the region. Therefore, we can assert that, in any case, anthropogenic objects are the most significant factor determining the state of the landscape complex as a whole.

A visual study of the current ecological state of the Tengiz field on modern satellite images shows significant mechanical changes and fragmentation of the landscape cover.

Automated interpretation of satellite images consisted of calculation of NDVI for the studied area (Fig. 5). The NDVI method enables us to obtain quantitative assessments of vegetation cover. Also, it is the most convenient for landscape cover assessment since it indicates the ratio of multispectral scanner data in the near-infrared and visible red regions (Cherepanov, Druzhinina 2009; Myachina, Krasnov 2021). Green vegetation has a relatively high vegetation index, due to the absorption of chlorophyll in the red region of the spectrum, unlike soils or artificial materials (for example, concrete cover around wells) having a low value of vegetation index.

Analysing the classified space images of Landsat 5 TM for 1990 and 2000, Landsat 8 OLI for 2020 and S2A for 2020 using NDVI, the following conclusions can be made:

- In 2020, compared to 1990, the percentage of water availability was 0.1 (according to Sentinel) or 0.0%, i.e. it almost disappeared. The water objects in this area are wet solonchaks or artificial reservoirs;
- The percentage of grass cover has decreased by 2020, even though 2000 was the rainiest year in Kazakhstan (Annual bulletin for monitoring the state and climate change of Kazakhstan, 2020). The area of vegetation has increased to three, and then six times, but within 20 years it decreased again and was only 0.7%;
- The area of barren land in 2020 decreased compared to 1990. This is explained by the occupation of industrial and technological facilities in the area;
- The area of industrial facilities in 2020 increased by 2.2 times, which is associated with intensive development of road networks, construction of numerous well sites and factories, and technological facilities.

The results obtained are preliminary, and the research requires further development. To obtain more accurate conclusions, it is planned to use a reference area located close to the site but not experiencing its influence. The use of space images in geoecological studies, in combination with traditional ground surveys, allows us to objectively assess the situation at the site and interpret the obtained results for other oil fields not only in the region but all of Western Kazakhstan, located mainly in the Caspian lowlands.

Conclusion

Based on the analysis of technogenic sources on the territory of the Tengiz oil field and establishing the degree of their impact on natural components, we can say that the landscape of the field (1990) is completely changed or transformed into another type.

The use of remote sensing data made it possible to compensate for the lack of field studies. Satellite imagery allowed a detailed study of the dynamics of landscape changes in the territory. The data obtained indicate the vulnerability of the landscape to anthropogenic impacts, which leads to significant dynamics of landscape-forming processes. Dryness of natural conditions contributes to the monotony, instability, and inconstancy of landscapes. The remote sensing data confirm that the landscape connections are unstable, and thus changes in the states of landscapes occur quickly.

As mentioned previously, in 1993, a contract was signed with Tengizchevroil to develop Tengiz until 2033. The company is in a hurry to meet the deadline, increasing production by expanding the number of drilling wells and commissioning a third gas processing plant with greater capacity.

Undoubtedly, the intensive exploitation of the field will affect its ecological condition, which will require further research and the solving of a whole group of problems related to functional zoning of the territory, landscape assessment, identification of anthropogenic forms of landscapes and their mapping. All these tasks, one way or another, will be based on the indispensable use of aerospace information.

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