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SPATIAL AND TEMPORAL CHANGES IN THE ECOLOGICAL AND RECLAMATION STATE OF DRAINLESS AREAS

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Abstract. *The article presents the results of studies of spatial and temporal changes in the ecological and land reclamation status of drainless areas based on the use of high and medium spatial resolution satellite data. The authors assessed the geomorphological, hydrogeological, soil and land reclamation conditions of the steppe zone of Ukraine and noted that heterogeneous natural conditions such as relief, geomorphology, groundwater, soils and rocks of the active water exchange zone contributed to the development of processes of harmful effects of water and the nature of their manifestation. A large drainless area, the Petrivskyi depression in the area of the Kakhovka irrigation system, was chosen as the object of study. The processes of land degradation on the territory of the sub were identified by detecting various manifestations of spectral and textural changes in soil and vegetation surfaces under the influence of water and wind erosion, and an unbalanced land use system based on satellite images of various earth surface scanning systems. Changes were identified and studied by vegetation, soil, and water spectral indices, which made it possible to observe the flooding of the territory. Observations were carried out in different years and cover a period of more than 40 years: 1985–2015 – the most active flooding of the territory was observed; 2002, 2003 and 2005 – large-scale winter-spring flooding; 2018–2024 – the absence of a drainage system that is in decline was recorded; 2023, 2024 – the impact of hostilities on the territory of the pad. Based on the results of studies of the spatial differentiation of soil emissions and their temporal dynamics, the authors have developed a complex indicator that is a function of three components – the spectral indices NDVI, NDWI and CM. Verification of the studies of the period 1991–2017 of the averaged values of the spectral indices showed that the closest correlation exists between NDWI and NDVI and is 0,92. The experimental area was analyzed for soil fertility in contrast to the depleted soils of the pudu. It was determined that with the change in humus concentration, the color of the topsoil changes, which in turn causes changes in the spectral characteristics of the satellite image.*

Through long-term observations, the spatial and temporal changes in the ecological and reclamation state of the drainless area and the probability of loss of the functional resource of the reclamation system as a whole were studied.

Keywords: *drainless territories, drainage system, ecological and reclamation state, satellite data, spectral indices, spatial and temporal changes*

Relevance of the research. The restoration of irrigation and drainage, which is a key tool for the development of the agricultural sector of the economy, is emphasized in the current document "Strategy of Irrigation and Drainage in Ukraine for the period up to 2030" [1]. Therefore, first of all, the issue of overcoming the consequences of the war over time and restoring the operation of damaged irrigation and drainage systems that have not lost their resource is acute. To do this, it is necessary to study the operation of the systems in previous years to identify and take into account design flaws, assess their condition, and provide recommendations for future reconstruction and operation.

Without irrigation and drainage in the risky farming zone of the Steppe zone of Ukraine, obtaining stable yields and sustainable development of the agro-industrial complex is virtually impossible [1]. At the same time, out of 924 vertical drainage wells and 119 horizontal drainage pumping stations in the Kherson region, only about 1–15 % were productively operating by 2019. Therefore, this issue should be studied. It is advisable to research and study the operation of irrigation and drainage systems over a long time period using modern technologies in combination with ground observations.

Analysis of previous research and publications. Worldwide experience shows that it is advisable to detect and evaluate the operation of drainage systems using remote sensing [2–4]. In this case, research should be aimed at a comprehensive analysis of applied processes in the spatial localization, classification or assessment of the actual state of subsurface drainage systems using remote sensing methods.

To monitor the state of the drainage system, groundwater levels are usually monitored at pumping stations and hydrogeological observation wells. However, this method helps to observe the state of the system only pointwise or linearly. Therefore, studies on the state of drainage systems should be based on both the analysis of ground-based hydrogeological observations of groundwater levels and their comparison with satellite images [5–9].

Landsat archival satellite images are widely used worldwide to analyze time series of terrain and analyze spatial changes in vegetation around drainage areas [4, 5]. The state of vegetation, as an indicator of biological productivity, is assessed by the normalized difference vegetation index (NDVI) during the peak of the growing season. This approach to assessing the situation based on the use of NDVI [10] is performed during the growing season.

For timely inspection of drainage systems, the modified normalized water index (MNDWI) is used, which is a valuable indicator for monitoring waterlogged lands [11]. The index is calculated using Landsat satellite data (Landsat L8 Oli TIRS, Landsat ETM+, Landsat TM). Remote sensing and GIS technologies are used to determine the location and delineation of existing drainage systems [12]. Drainage is localized using color infrared satellite images. Because the soil directly above the drainage surface dries out faster than the surrounding soil, the reflectivity of the drier soil often shows up in the infrared spectrum.

Prolonged irrigation on the massifs led to regional and localized increases in groundwater levels. The regional rise on the background of irrigation occurred with an annual rise rate of about 0,8 m/year. Localized manifestations of flooding are observed at the bottom of the depression, in the riverbed areas and in the area of sprinklers. The effectiveness of drainage in difficult natural and water management conditions on the main irrigation systems and in a number of settlements in the south of Ukraine is covered in [13–16].

The aim of the work is to study the spatial and temporal changes in the ecological and reclamation state of a drainless area based on long-term satellite data observations and to establish the probability of loss of the functional resource of the drainage system as a whole.

Research methods and materials. In conducting research with satellite data, we used the passive method of remote sensing, analytical analysis of scientific papers, spectral and geospatial analysis, system analysis, ground surveys and experimental studies according to generally accepted and certified methods.

To resist the harmful effects of water in the Kherson region, drainage systems of various types were built on the Kakhovska irrigation system on an area of 45 thousand hectares. The irrigated area is characterized by diverse and complex geomorphological, hydrogeological, and soil-reclamation conditions [8].

Regarding the characteristics of the study area, it should be noted that heterogeneity of natural conditions is a characteristic feature of the Kherson region, and such components of the environment as relief, geomorphology, groundwater, soils and rocks of the active water exchange zone contribute to the development of processes of harmful effects of water and determine the nature of their manifestation.

According to the climate zoning, the territory belongs to the steppe Atlantic-continental climate region of the temperate climate zone. The climate is temperate continental, with insufficient moisture, short winters and long hot summers. The climate is formed under the influence of solar radiation and atmospheric circulation, as well as local factors of influence: the proximity of the sea and Lake Syvash. In spring and summer, the effect of solar radiation is manifested in the warming of the earth's surface and the surface layer of the atmosphere.

The study area belongs to the denudation-accumulative forest plain of high riverine and complex terraces with relief forms: drainless areas, saucers, and beams. Drainless territories are shallow (up to 3–5, rarely 10–15 m) enclosed mostly round or oval flat-bottomed areas with an area of hundreds and thousands of square meters. Slightly convex flat pits are clearly defined in the relief. Their diameter is from 0.2 to 3–4 km.

The territory is represented by meadow-dark chestnut gley saline-saline soils and meadow chestnut gley saline-saline soils. The depth of the groundwater table within the drainless area depends on the relief and varies from 0,5 m to 15,0 m.

Among the existing drainage-free areas, the vertical drainage system located within the Petrivskyi depression, which belongs to large asymmetric drainage-free areas with active wind and water erosion, is scientifically noteworthy. Soil erosion is one of the main indicators in a comprehensive assessment of the ecological state of territories. This phenomenon has been studied in the spatial and temporal dimensions using modern methods involving satellite data.

The drainage provides flood protection for the adjacent irrigated area. The catchment area of the pond is more than 30,000 hectares, and the vertical drainage area is 3,190 hectares. The lowest elevation of the bottom of the basin is 12,5 m, and the highest 25,0–30,0 m. On the slopes are agricultural fields that were previously irrigated with modern sprinklers. In the northern part of the pond, the main Kakhovskyi Canal passes through, which affects the groundwater regime.

The location map of the study object was created on the basis of the terrain map available on the Topographic Map of Ukraine website [17], Maxar satellite image (Google Earth Pro) dated 07/14/2021, and the drainage system location scheme (Fig. 1).

Two settlements are located in the central part of the pud – Petrivka and Pavlivka. The area of Pavlivka village is more than 500 hectares, and Petrivka village is 1000 hectares. Their territory has absolute ground surface elevations of mostly 12–20 meters. In the village of Petrivka, a vertical drainage system was built on an area of 190 hectares. The drainage wells are located in the lowest parts of the settlement. The constructed drainage includes 7 wells (Table 1).

It should be noted that vertical drainages protect the territory from flooding on an area of 300, 600, 2100 and 600 hectares.

a b c

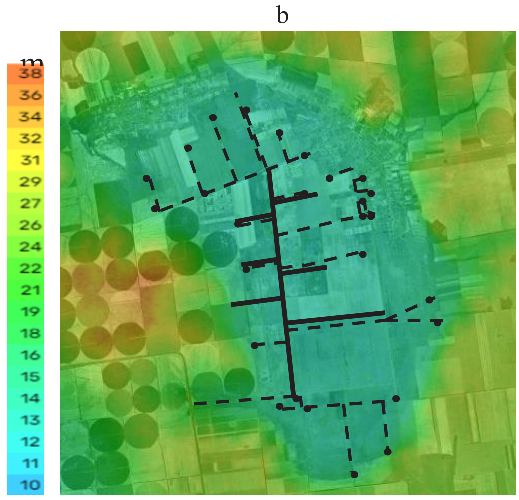

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Fig. 1. The collector-drainage system of the Petrivskyi depression in the area of the Kakhovska irrigation system:

a – terrain map (“Topographic Map of Ukraine” [17]); b – Maxar satellite image (Google Earth Pro geospatial analysis service) dated 14.07.2021; c – drainage system layout; d – integrated image of the terrain, satellite image and drainage system layout

1. Hydrogeological parameters of the aquifer in the areas of vertical drainage within the Petrivskyi depression

Drainage area, ha	Number of wells, pcs.	Water permeability, m^2/day	Filtration coefficient of the upper layer, m/day	Filtration coefficient of the separation layer, m/day	Water return	Mineralization of drainage water, g/l
300	3	240	0,14	0,0030	0,002	1,1–5,2
2100	9	–	–	–		1,1–5,2
600	6	300	0,14	0,0004	0,002	2,0–3,0
190	7	–	–	–	–	–
600	5	–	–	–	–	–
Total 3790	30	–	–	–	–	–

On an area of 300 hectares, two wells protect the village of Petrivka and one protects the village of Pavlivka. Drainage on an area of 600 hectares has a positive impact on flood protection in Pavlivka village. The main part of the drainage is built in the central lowest part of the pond. The drainage area here is 2100 and 600 hectares. The drainage system includes 14 vertical drainage wells, an open drainage channel, a drainage pumping station and a pressure pipeline for drainage from the pit.

The drainage covers the highest areas of the pit. The total drainage area is 3790 hectares. There are 30 vertical wells in the drainage area. The distance between the wells is generally 1–3 km. The depth of the wells is 34 meters. Some wells are 20 meters deep.

The Petrivskyi depression is characterized by a significant saturation of the territory with irrigation systems. Thus, the territory of the sub is intensively used in terms of land reclamation.

Research results and their discussion. Observations were made in different years and generally cover a period of more than 40 years. Thus, during 1985–2015, the most active flooding of the territory was observed, as evidenced by Landsat 2–7 satellite images (Fig. 2).

Regarding the period of large-scale flooding and inundation of the Kherson region in 2005, it is advisable to provide a NOAA, IR (infrared) image as of March 1 (Fig. 3).

The climate change observed in recent decades has caused a sharp increase in average annual air temperatures in Ukraine, especially in its steppe regions [19]. According to observations at the Askania Nova weather station, the current climatic norm for air temperature (1991–2020) is 10,79 °C, which is 0,93 °C higher than the previous climatic norm (1961–1990). A particularly intense increase in air temperature has been observed since 2000. While the average annual temperature averaged 9,79 °C between 1910 and 2000, in the following period its value increased to 11,2 °C, i.e. by 1,41 °C.

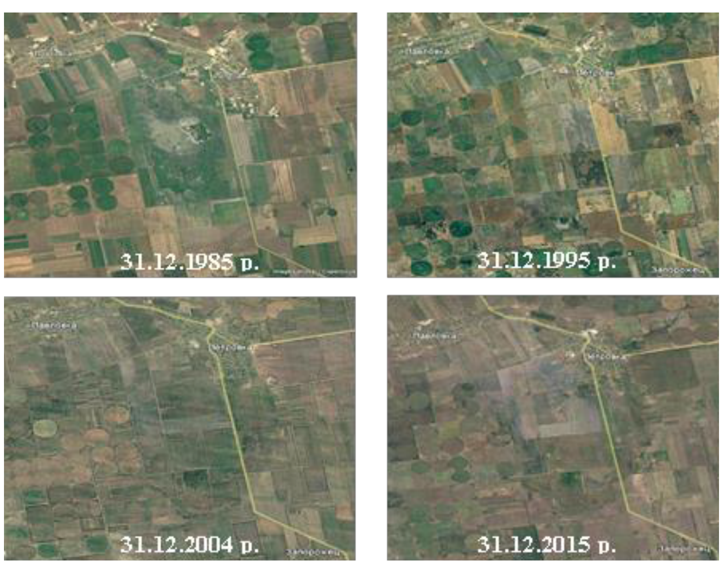

Fig. 2. The territory of the floodplain during the period of active flooding according to the images (Google Earth Pro geospatial analysis service)

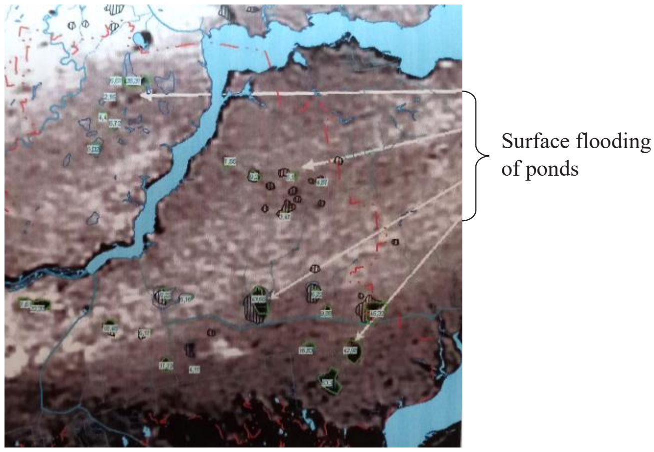

Fig. 3. Territories of the Kherson region affected by flooding and inundation as of March 1, 2005 [18].

The increase in air temperature led to a sharp increase in potential total evaporation, which, according to research [20], increases by 9 % with an increase in temperature by 1 °C. At the same time, an analysis of long-term precipitation observations at the Askania Nova weather station shows that since 1945, their amount has remained almost constant (Fig. 4). The average amount of precipitation over the past 77 years (until 2021) was 401 mm, the previous climatic precipitation rate (1961–1990) was 399 mm, and for the period from 1991 to 2020 it increased to 409 mm. Such an increase in precipitation is not typical for the entire Kherson region, in particular, in Kherson, the climatic precipitation rate decreased by 9 mm.

The highest amount of precipitation is observed in May-July (an average of 44 mm per month), and the lowest in December-March (an average of 28 mm per month). The largest increase in precipitation over the past 30 years compared to the previous climatic norm was recorded in June – by 6.4 mm per month, and the largest decrease – in December, by 7 mm (Fig. 5).

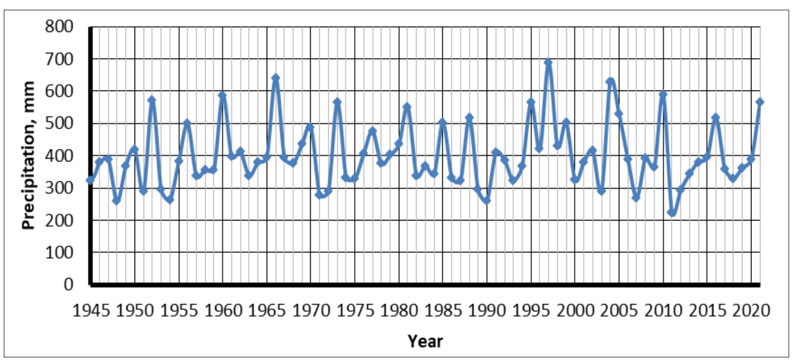

Fig. 4. Long-term precipitation dynamics at Askania Nova weather station

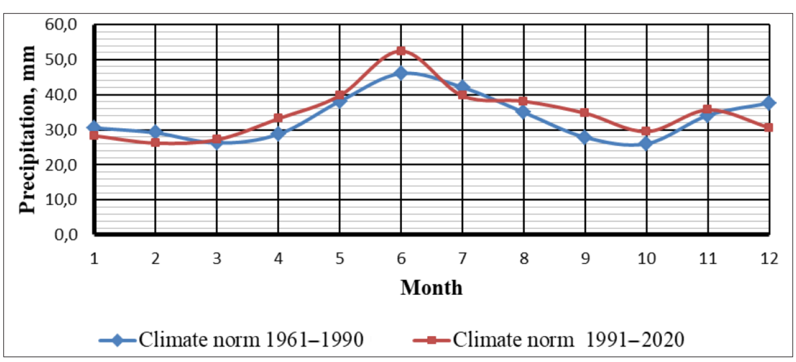

Fig. 5. Intra-annual distribution of precipitation at Askania Nova weather station for different observation periods

The analysis of climatic factors shows that the increase in flooding levels in the floodplain during 1985–2015 is not related to climate change, but is caused by anthropogenic factors, in particular, the deterioration of the drainage system.

Water and wind erosion of the soil in the bed was assessed by a complex indicator containing various spectral indices.

During this period, we used spectral indices calculated on the basis of Landsat satellite images as a comprehensive indicator of the state of the bedrock under water and wind erosion**.**

The periods with more favorable weather conditions were studied separately. For this purpose, the territory of the Petrivskyi depression was surveyed using satellite data in 1991, 2000, 2007, and 2017. The spectral indices CM (clay content in soils), NDVI (vegetation index), and NDWI (moisture index) were calculated based on Landsat images. The experimental area was analyzed for the condition of the soils of the irrigated massif in contrast to the depleted soils of the pond. For this purpose, the sub-floor depression was identified and thematic maps were constructed to record differences in the composition of fertile (irrigated crops) and infertile soils (smoothing of the relief, loosening of soils in the lowlands).

Based on the results of the study of the spatial differentiation of soil emissions and their temporal dynamics, a complex indicator was developed, which is a function of three components: I comp. = *f* (NDVI, NDWI, CM).

The degradation processes were identified by detecting various manifestations of spectral and textural changes in the soil and vegetation surface, which are affected by water and wind erosion, unbalanced land use, etc. It was found that heterogeneous natural conditions such as relief, geomorphology, groundwater, soils and rocks of the active water exchange zone contributed to the development of processes of harmful effects of water and determined the nature of their manifestation. The NDVI vegetation index calculated from satellite images made it possible to identify the types of soil degradation that cause a decrease in the concentration of humus in the upper biologically active soil layer.

Maps of the territory's NDVI images for 1991, 2000, and 2007 are shown in Figure 6.

Based on the images from January 13 to June 24, 2003 (NOAA) and decadal SPOT VGT satellite data, a joint graph of the dynamics of changes in the flooded area of the Petrivskyi depression and the vegetation index averaged over the low area was constructed. The period of the greatest flooding occurred on March 16-18, 2003. The territory of the floodplain was surveyed using retrospective satellite data from 1991, 2000, 2006, and 2007, and the most unfavorable climate impact on hydrothermal and agricultural conditions was revealed. Based on the data obtained, the spectral soil indices IO and SM, as well as additional indices, were calculated: NDWI – moisture content for certain subsoil depressions. The dynamics of changes in the average values of the indices is shown in Figure 7.

The study proved that as the humus concentration changes, the color of the topsoil changes, which in turn causes changes in the spectral characteristics of the satellite image. If soil erosion is calculated individually for each pixel, the NDVI and surface slope gradient can be used to calculate the degree of soil erosion per year. Vegetation indices of redness RI and brightness BI and their correlation with ground data and spectral indicators of soil erosion can be used to classify erosion degradation – to determine the extent of planar erosion.

Another indicator of land degradation is the reflectivity of the earth's surface (albedo). If the albedo increases by 6-14 %, the area with this type of soil is classified as unstable, by 15–20 % as a zone with mild degradation, by 21–50 % as moderate degradation, by 51–75 % as severe degradation, and by 76–100 % as extreme degradation.

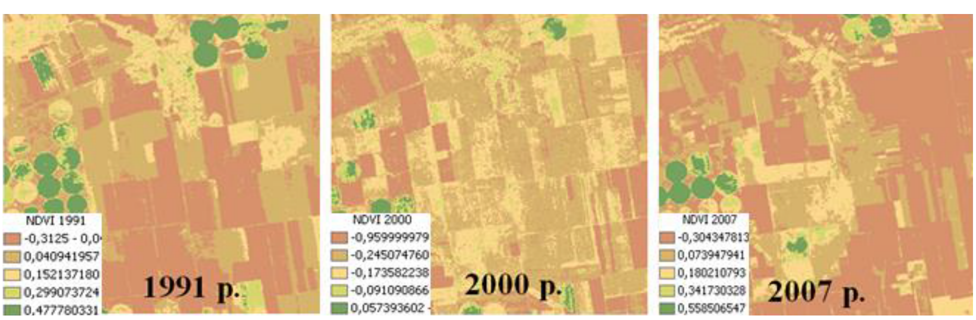

Fig. 6. Maps of NDVI spectral index of the Petrovskyi depression according to research conducted in 1991–2007

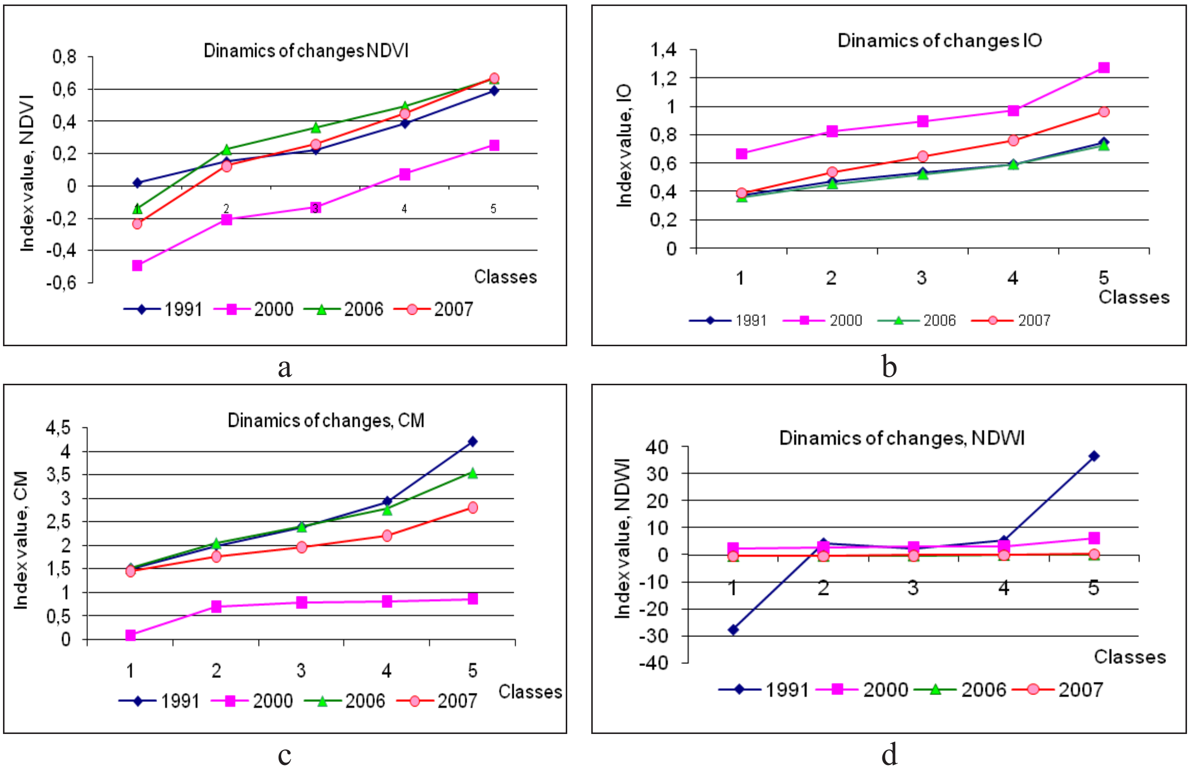

Fig. 7. Diagrams of changes in the averaged values within the Petrivskyi depression according to the 1991–2007 studies:

a – NDVI; b – IO; c – SM; d – NDWI

In further studies conducted in 2017, Landsat 8 image for the month of August was used to identify the study area and calculate the NDVI, IO, CM indices (Fig. 8). Separately, we calculated the humidification by NDWI. The experimental area was analyzed for soil fertility of the irrigated area in contrast to the depleted soils of the subsoil. For this purpose, the subsoil depression was isolated by an isoline (black outline).

The thematic maps show the differences in the composition of fertile (irrigated crops) and infertile soils (smoothing of the relief, loosening of soils in the lowlands).

After completing the studies of the period 1991–2007 and 2017, the results of the averaged values of the spectral indices were verified, which showed that the closest correlation $R^2 = 0{,}92$ exists between NDWI and NDVI, which is indisputable. A new stage of research was launched in 2018 with the involvement of CNES/Airbus and Maxar Technologies imagery. The involved high-resolution images of the study area are shown in Fig. 9.

The images show a fuzzy blurred image of the bedding even in the summer and autumn, which indicates that the drainage system is not working and is in poor condition.

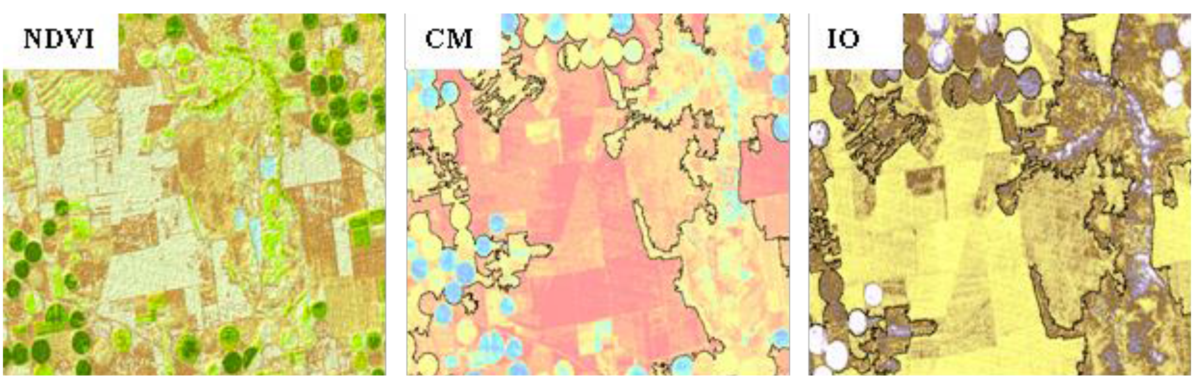

Fig. 8. Maps of the spectral indices of the Petrivskyi depression NDVI, SM, IO for the period of research in 2017

Fig. 9. High-resolution images of the study area by Maxar Technologies and CNES/Airbus

The latest studies of reclaimed land in drainless areas were conducted in 2023–2024 to determine the impact of hostilities on the territory of the depression. For this purpose, Sentinel-2 L2A imagery for 20.06.2023 and 01.01.2024 was used. No changes were detected (Fig. 10).

The combination of healthy vegetation channels SWIR1, Red8, Blue of the Sentinel satellite made it possible to assess the current state of the Petrivskyi depression. The soil structure does not appear to be eroded during the wettest winter period.

Conclusions and further research. It is advisable to identify soil degradation processes by identifying various manifestations of spectral and textural changes in the soil-plant surface, which are affected by water and wind erosion, unbalanced land use, etc.

It has been established that heterogeneous natural conditions such as relief, geomorphology, groundwater, soils and rocks of the active water exchange zone contributed to the development of processes of harmful effects of water and determined the nature of their manifestation.

It is determined that with the change in humus concentration, the color of the topsoil changes, which in turn causes changes in the spectral characteristics of the satellite image.

The study area was analyzed for soil fertility in contrast to the depleted soils of the piedmont. For this purpose, the subsoil depression was isolated (black outline). The thematic maps showed the difference in the composition of fertile (irrigated crops) and infertile soils (smoothing of the relief, loosening of soils in the lowlands).

Further research should be directed at studying the transformation of the soil cover and the manifestation of unfavorable soil degradation processes observed in this area. This is especially true for changes in the conditions of economic activity of agricultural enterprises located within the Petrivskyi depression.

Fig. 10. Thematic maps showing the impact of hostilities on the study area:
a – NDVI, 06/20/2023, Sentinel-2 L2A; b – SWIR1_ Red8_ Blue, 01/01/2024 Sentinel-2 L2A

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ПРОСТОРОВО-ЧАСОВІ ЗМІНИ ЕКОЛОГО-МЕЛІОРАТИВНОГО СТАНУ БЕЗСТІЧНИХ ТЕРИТОРІЙ

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Анотація. *У статті викладено результати досліджень просторово-часових змін еколого-меліоративного стану безстічних територій, які ґрунтуються на використанні супутникових даних високого та середнього просторового розрізнення. Автори оцінили геоморфологічні, гідрогеологічні та ґрунтово-меліоративними умови степової зони України та зазначили, що неоднорідні природні умови такі як рельєф, геоморфологія, підземні води, ґрунти та породи зони активного водообміну, сприяли розвитку процесів шкідливої дії вод та характеру їх прояву. За об'єкт дослідження обрано велику безстічну територію – Петрівський под в районі Каховської зрошувальної системи. Процеси деградації земель на території поду ідентифіковано шляхом виявлення різноманітних проявів спектрально-текстурних змін ґрунтово-рослинних поверхонь під дією водної та вітрової ерозії, незбалансованої системи землекористування на основі супутникових знімків різних систем сканування земної поверхні. Зміни визначали і вивчалися за вегетаційними, ґрунтовими і водними спектральними індексами, що дозволило спостерігати за підтопленням території. Спостереження велися в різні роки і в цілому охоплюють період у понад 40 років: 1985–2015 рр. – спостерігалися найактивніші підтоплення території; 2002, 2003 і 2005 рр. – масштабні зимово-весняні затоплення;*

2018–2024 рр. – зафіксована відсутність роботи дренажної системи, яка знаходиться у занепаді; 2023, 2024 рр. – вплив ведення бойових дій на територію поду. За результатами досліджень просторової диференціації ґрунтових виділів, а також їх часової динаміки авторами розроблено комплексний показник, який є функцією трьох складових – спектральних індексів NDVI, NDWI та CM. Верифікація досліджень періоду 1991–2017 рр. усереднених значень спектральних індексів показала, що найбільш тісний кореляційний зв'язок існує між NDWI та NDVI і становить 0,92. Дослідну територію було проаналізовано щодо родючості ґрунтів на контрасті зі збідненими ґрунтами поду. Визначено, що із зміною концентрації гумусу змінюється забарвлення верхнього шару ґрунту, що в свою чергу викликає зміни в спектральних характеристиках супутникового знімка. Шляхом багаторічних спостережень вивчено просторово-часові зміни еколого-меліоративного стану безстічної території та ймовірність втрати функціонального ресурсу меліоративної системи в цілому.

Ключові слова: *безстічні території, осушувальна система, еколого-меліоративний стан, супутникові дані, спектральні індекси, просторово-часові зміни*