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**APPLICATION OF GEO-INFORMATION TECHNOLOGIES IN
DETERMINING THE AREA OF FLOODED LANDS AS A RESULT OF
THE DESTRUCTION OF THE KAKHOVSKA HPP**

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Abstract. Based on a sample of data from ministries, local authorities and other official open sources of information regarding the consequences of the destruction of the Kakhovska HPP dam and their analysis, it was found that they are inaccurate. Taking into account the above, the scientists of the Institute of Land Use of the National Academy of Sciences developed a methodology for determining the areas of flooded land affected by the destruction of the Kakhovska HPP dam, the territory under the Kakhovska Reservoir, which includes satellite images, geoinformation technologies, and artificial intelligence technologies. To identify and estimate the area of flooded land, satellite images were analysed before the terrorist attack and as of June 9, 2023, according to the results of which it was established that the total area of

flooding according to the ESA WorldCover land cover classes was about 65 thousand hectares.

Investigating the suitability for use of agricultural land for its intended purpose in the regions affected by the destruction, a land database with information on coordinates, intended purpose, form of ownership and other cadastre information was created from open sources of information.

It was found that the number of land plots registered in the State Land Cadastre and located in the flooding zone is 30,325 plots. Other areas that are in the flooding zone are not registered. The total area of these areas affected by the flood is about 25 thousand hectares, including 9.8 thousand hectares (38%) - agricultural land. Only 20% of them are privately owned (three-quarters of them are agricultural land and one-quarter is land for residential and public development).

It was established that the share of the area of land plots in the flooding zone in the total area by forms of ownership is: 56.5% - state property; 22.1% are communal, 20.3% are private, and 1.2% remain unspecified.

Key words: *Kakhovska reservoir, flooded lands, State Land Cadastre, geo-information technologies, artificial intelligence*

Problem statement. Land flooding in Ukraine is influenced by global, regional and local factors. While the global ones depend on global climate change and the natural cyclical nature of water availability (high and low), the regional ones are of man-made origin. Man-made origin is also common for most local (site-specific) flooding factors.

Flooding as a natural and anthropogenic phenomenon causes the intensification of hazardous geological processes. Flooding contaminates surface and groundwater, significantly deteriorates soil quality, and causes waterlogging, which leads to disruption of people's economic and production activities and living conditions.

Since 1982, the area of flooding in Kherson and Mykolaiv regions has increased 17 times, in Odesa region - 10 times, and in Dnipro region - 7 times. Between 1982 and 2004, the average annual increase in the flooded area in Kherson Oblast was 450 km² for each year [1].

The situation was further exacerbated by the terrorist attack of June 06, 2023, which caused the destruction of the Kakhovka hydroelectric power plant dam. This negatively affected land use within the territory of Dnipro, Zaporizhzhia, Mykolaiv, and Kherson regions.

According to the Kherson EMA, as of June 08, 2023, the area of flooded agricultural land in the de-occupied territory of Kherson region increased to 1,323 hectares (arable land - 491 hectares, orchards - 639 hectares, pastures - 193 hectares) located along the coastal zone of the Dnipro River (Kherson, Tyahyn, Bilozersk, Novakokhiv territorial communities). These lands were not used due to their close proximity to the contact line and mined areas. In the area of Odradokaminka village of the Tyahyn territorial community, the water level on agricultural land is decreasing [1].

If the water level continues to rise, there is a threat of increased flooding of 3.5 thousand hectares of agricultural land in the Bilozerska territorial community of Kherson district.

In addition, there are 20 elevators on the liberated territory of Kherson region, 11 of which are flooded (located in the coastal zone of the Dnipro River). The total capacity of the 11 flooded elevators is 358,500 tons. These facilities have not been operating since the de-occupation of the territory, as they are under fire from the occupying forces. There are no products that need to be exported at these facilities.

About 7 thousand hectares of agricultural land are flooded in the occupied territory, and there is a threat of flooding of more than 25 thousand hectares. In addition, 6 elevators and 10 food and processing enterprises are located in the flooded area.

The threat of flooding of agricultural land on the right bank is 9 thousand hectares, and on the left bank - 25 thousand hectares.

According to the Mykolaiv Regional Military Administration, as of June 09, 19 settlements, including the town of Snihurivka, were flooded along the Inhulets River in Snihurivka and Horokhiv communities of Bashtanka district.

No reports of agricultural land being flooded were recorded, and coastal areas (floodplains, gullies) along the Ingulets River channel were flooded.

As for the Southern Bug and Dnipro-Bug estuary, where the water level also rose to 104 cm, there were no threats to agricultural land. The consequences of the rise in the water level in the Bug estuary are the flooding of the coastal strip in the Namyv district, Alyauda Peninsula, Raketne tract, Varvarivka district, Matviivka district, and V. Korenykha district, which are located within the city of Mykolaiv. Also, in Mykolaiv district, Kutsurubska territorial community, Parutyne village, and a beam were flooded, and the coastline was flooded.

Given the above data from ministries, local authorities and other official open sources of information on the consequences of the destruction of the Kakhovka HPP dam, which turned out to be rather approximate and inaccurate, and given the lack of land use records, the question arose of determining the area of flooded land affected by the destruction of this dam.

Analysis of recent research and publications. Hurytskyi D.S. analyzed the main trends in the process of land flooding in Ukraine at the regional level and proposed preventive measures to overcome the negative impact of these processes [2]. Dubniak S.S. revealed the issues related to the elimination of land flooding in protected areas in the zone of influence of the Dnipro reservoirs, the issues of reorganization of monitoring of flooding processes and conditions based on ecohydromorphological zoning, periodization, and appropriate approaches to the selection of monitoring indicators [3]. Savchuk D.P., Kharlamov O.I., Kotykovych I.V. studied the experience of protecting rural

settlements from flooding in the irrigation zone and proposed ways to improve the system of protection of these territories [4]. Assessment of the impact of regional and territorial flooding on engineering and geological conditions and the structure and level of engineering and geological risk of cities and urban-type settlements, improvement of their methodological basis, and transition to modern technologies (GIS, remote sensing, etc.) were carried out by Y. Zakharchuk, V.O. Slyadnev [5]. K.Y. Danko and his team of authors developed various scenarios of zones of probable flooding of the territory within which the number of agricultural land plots of the corresponding designated purpose was determined [6]. However, issues related to the flooding of land affected by the destruction of the Kakhovka HPP dam require in-depth study under martial law.

The purpose of the study is to determine the area of flooded land affected by the destruction of the Kakhovka HPP dam based on the developed methodology, which includes satellite imagery, geographic information technologies and artificial intelligence technologies.

Data collection and methodology. Both optical and radar satellite images can be used for the purposes of our study. The best way to determine the flooded area is to calculate the NDWI (Normalized Difference Water Index) if you are using optical satellite imagery. Since 1995, the NDWI, as defined by S.C. McPheeters, has been a valuable tool for identifying open water features and improving their visibility in digital remote sensing imagery. NDWI relies on the contrast between reflected near-infrared and visible green light to enhance the presence of these water features, effectively minimizing the visibility of ground features and terrestrial vegetation. In addition to its primary function, the NDWI has the potential to provide researchers with estimates of water body turbidity through the use of digital remote sensing data [7].

The study can use Landsat satellite images from either Sentinel-2 or Sentinel-3. All three satellites provide optical imagery. We prioritized the use of Sentinel-2 images because, according to our colleagues (Yang X. et al. 2017),

they make it possible to determine the boundaries of water bodies with high accuracy, in particular, due to the 10-meter resolution. However, we used Landsat images, even though they have a pixel size of 30 meters.

Research results and discussion. To identify the area of flooded lands and assess them as a result of the destruction of the Kakhovka HPP dam, satellite images were analyzed before the terrorist attack and as of June 09, 2023, which revealed that the total area of flooding was about 65 thousand hectares (Table 1, Figs. 1, 2, 3).

Table 1.

Total area of flooded land by ESA WorldCover* land cover classes

Class of land cover	hectares	%
Bare / sparse vegetation	82	0,1%
Arable land	2 606	4,0%
Built-up land	4 088	6,3%
Meadows and pastures	12 177	18,7%
Forested areas	13 577	20,9%
Grassy and marshy areas	32 473	50,0%
Total	65 004	100,0%

* Source: based on calculations of the Institute of Land Use of the National Academy of Sciences of Ukraine.

While investigating the suitability for the intended use of agricultural land in the regions affected by the destruction of the Kakhovka HPP, scientists from the Institute of Land Management of the National Academy of Sciences of Ukraine created a land database with information on coordinates, intended use, ownership, and other cadastral data from open sources (Figures 4, 5).

As we know, the flood reached its peak on June 9, 2023, and it was on this day that cloudless Landsat images were available for the entire study area. Unfortunately, there are no Sentinel-2 images for June 9, or for June 8 or 10 for

the entire study area. Figure 1 shows a Landsat image classified by the NDWI index as of June 5, 2023, i.e. less than a day before the dam was blown up. The image clearly identifies the lower reaches of the Dnipro River from the reservoir to the mouth and the Dnipro-Bug estuary. The Inhulets riverbed is difficult to identify in this image.

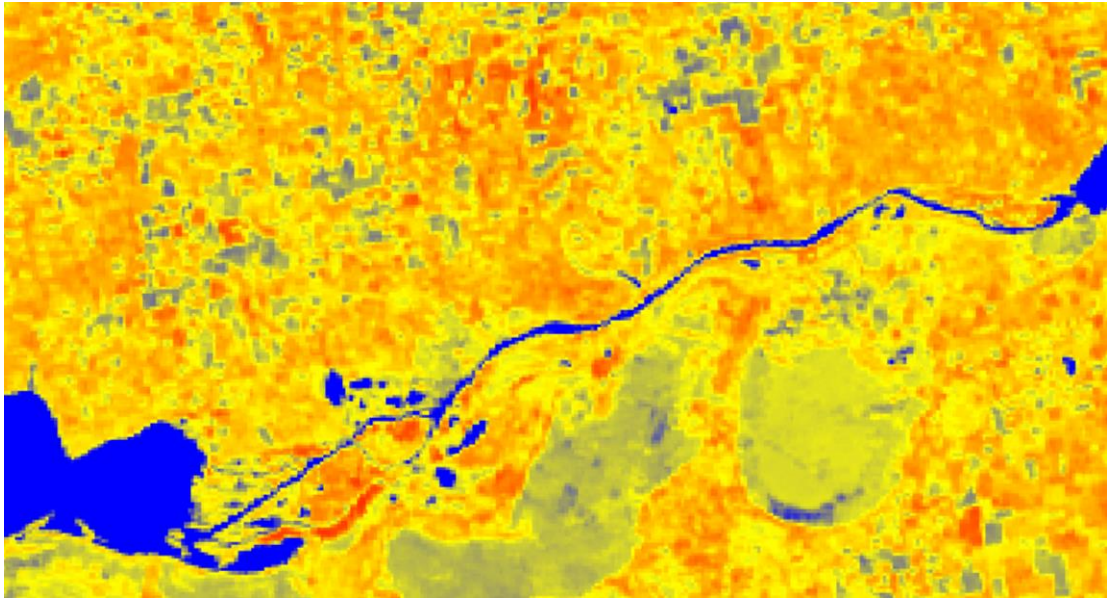


Figure 1 – NDWI water index of the flooded area based on Sentinel-3 images as of June 5, 2023

In Figure 2, you can see a Landsat image classified ("normalized") by the NDWI index as of June 9, 2023, the day the flood reached its peak. The width of the river has increased significantly, exceeding 10 km in some places. The image also clearly identifies the channel of the Inhulets River, which has also overflowed its banks.

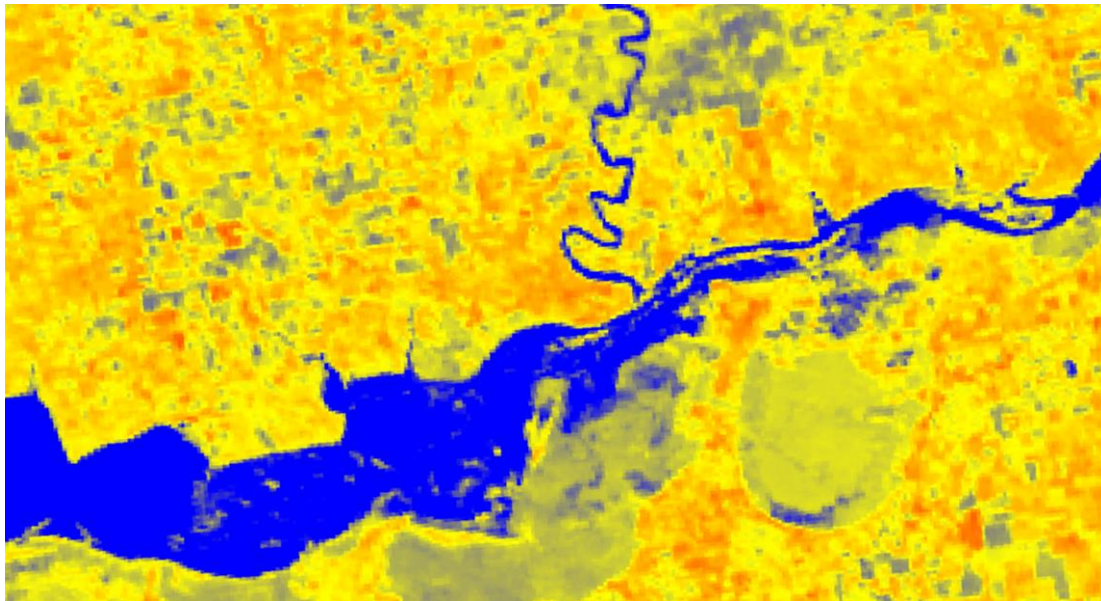


Figure 2 – NDWI water index of the flooded area based on Sentinel-3 images as of June 9, 2023

Subsequently, we digitized the flood zone and exported it to a shapefile to determine the flooded area and conduct further research. We superimposed the shapefile on the ESA WorldCover 10m classified land cover map (Fig. 3).

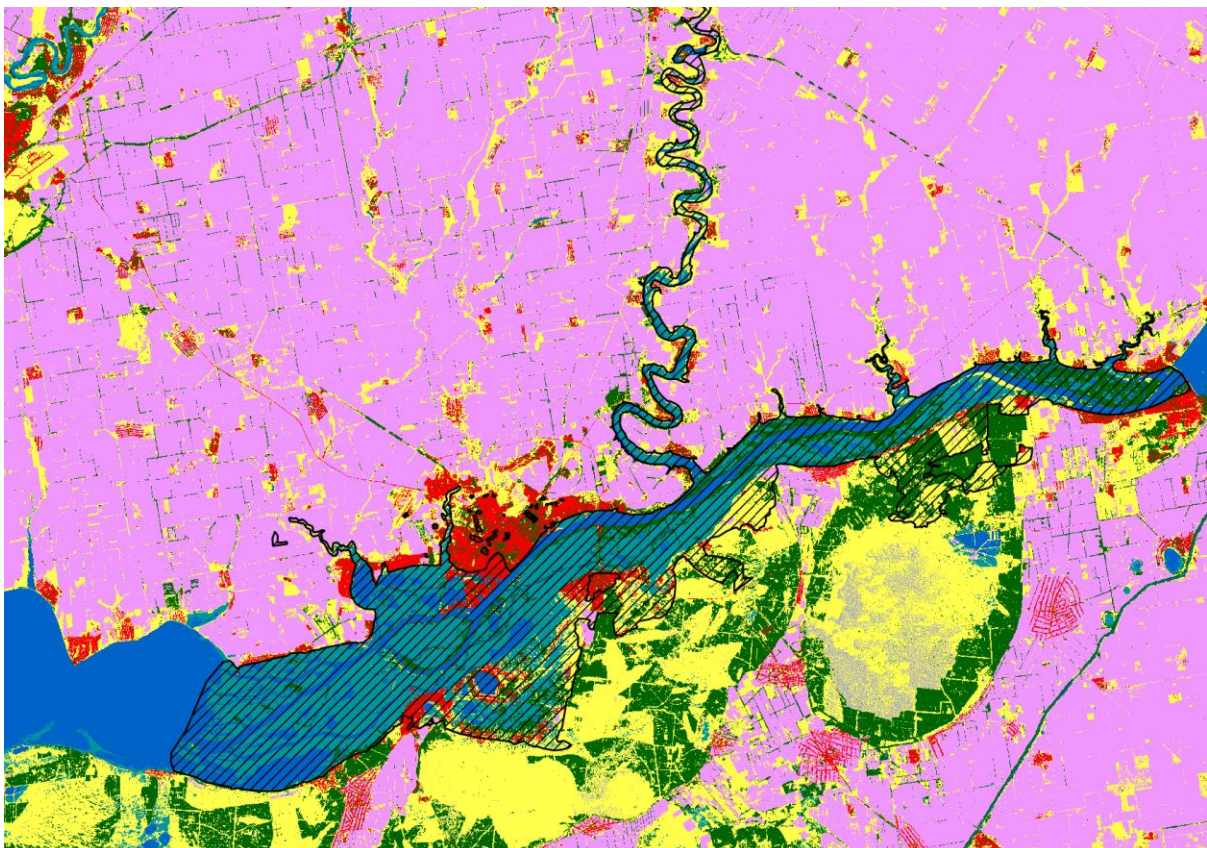


Figure 3 – Determination of the boundaries of the flood zone by comparing the flood area with Sentinel-3 images as of June 9, 2023 and ESA WorldCover 10m v200 land cover map

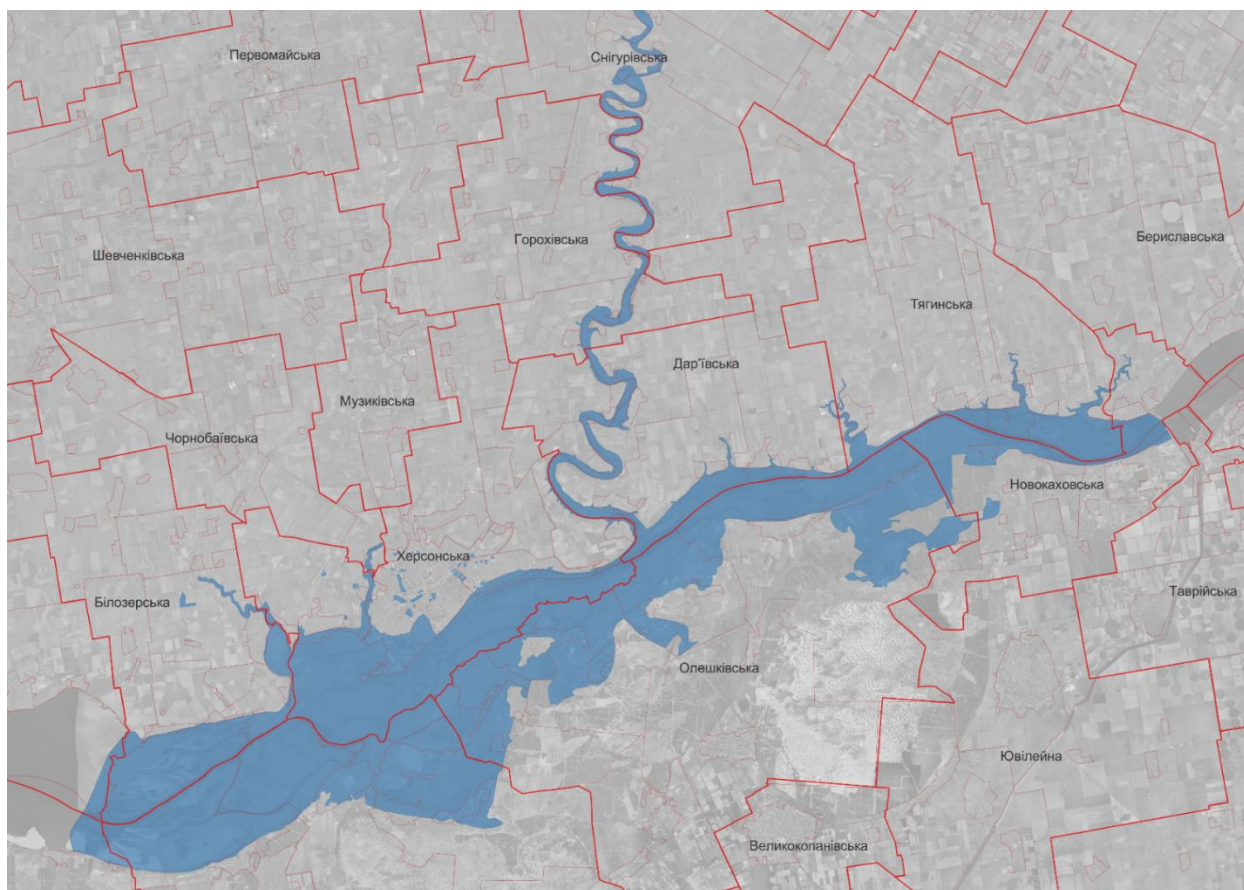


Figure 4 – Boundaries of territorial communities and administrative units in the flood zone *

* Source: compiled using these resources [8,9]

The total number of land plots registered in the State Land Cadastre that are in the flood zone is 30,325. All other plots located in the flood zone are not registered in the State Land Cadastre.

The total area of land affected by the flood is about 25 thousand hectares (Table 2, Figure 5). Among them, 9.8 thousand hectares (38%) are agricultural land.

Table 2.

Flooded land plots as a result of the destruction of the Kakhovka HPP dam by

land category and region of Ukraine, ha *

Land category	Mykolaiv region	Kherson region	Total
Lands of the water fund	105,83	724,65	830,48
Residential and public development land	29,54	1 549,45	1 578,98
Lands of historical and cultural designation		1,39	1,39
Forestry lands	38,72	10 799,57	10 838,28
Lands for recreational purposes		6,78	6,78
Lands of nature reserve and other environmental protection purposes		5,67	5,67
Lands for industry, transport, communications, energy, defense and other purposes	68,19	2 653,02	2 721,21
Recreational lands		132,37	132,37
Agricultural land	2 544,97	7 297,82	9 842,79
Not defined		3,96	3,96
Total	2 787,23	23 174,67	25 961,90

* Source: calculations by the Institute of Land Use of the National Academy of Sciences of Ukraine.

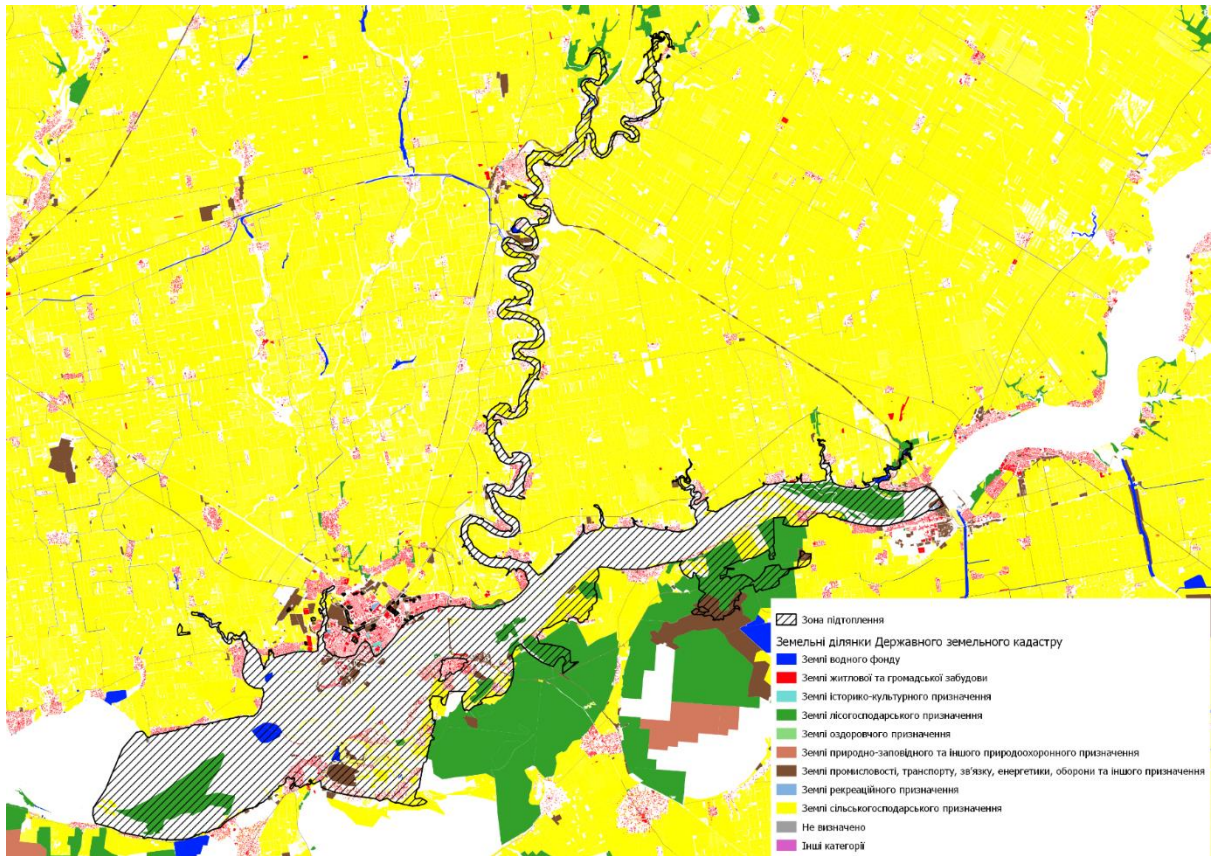


Figure 5 – Land plots in the flood zone due to the destruction of Kakhovka
HPP*

* Source of data for [10]

Of the 25,000 hectares of flooded land, only 20% are privately owned (of which three quarters are agricultural land and one quarter are residential and public land) (Table 3).

Table 3
Structure of land plots in the flood zone by land category, ha*

Land category	State property	Communal property	Not defined	Private property	Total
Lands of the water fund	769,2	20,6	40,4	0,3	830,5
Residential and public development land	29,7	357,9	76,3	1 115,2	1 579,0
Lands of historical and cultural designation		1,4			1,4
Forestry lands	10 838,3				10 838,3
Lands for recreational purposes		6,8			6,8

Land category	State property	Communal property	Not defined	Private property	Total
Lands of nature reserve and other environmental protection purposes	1,6	4,0			5,7
Lands for industry, transport, communications, energy, defense and other purposes	1 818,2	754,0	10,1	138,9	2 721,2
Recreational lands	39,7	51,1	8,4	33,1	132,4
Agricultural land	1 158,5	4 544,0	164,7	3 975,6	9 842,8
Not defined	1,9		2,1		4,0
Total	14 657,1	5 739,8	302,0	5 263,0	25 961,9
Share in the total area by type of ownership, %.	56,5	22,1	1,2	20,3	100,0

* Source: based on calculations of the Institute of Land Use of the National Academy of Sciences of Ukraine

Further in-depth research is needed to obtain more complete information on the structure of the land and assess the extent of its damage due to flooding.

To identify and assess the area under the Kakhovka Reservoir, scientists from the Institute of Land Use of the National Academy of Sciences of Ukraine also analyzed satellite images based on the developed methodology. The study found that as of July 4, 2023, only 371 square kilometers (17%) of the 2,155 square kilometers covered by the reservoir was water surface (Figs. 6, 7).



21st of May– 5th of June 2023



2nd–8th of July 2023

Figure 6 – Kakhovka Reservoir based on Sentinel-2 satellite images
(mosaic of cloudless images by periods)

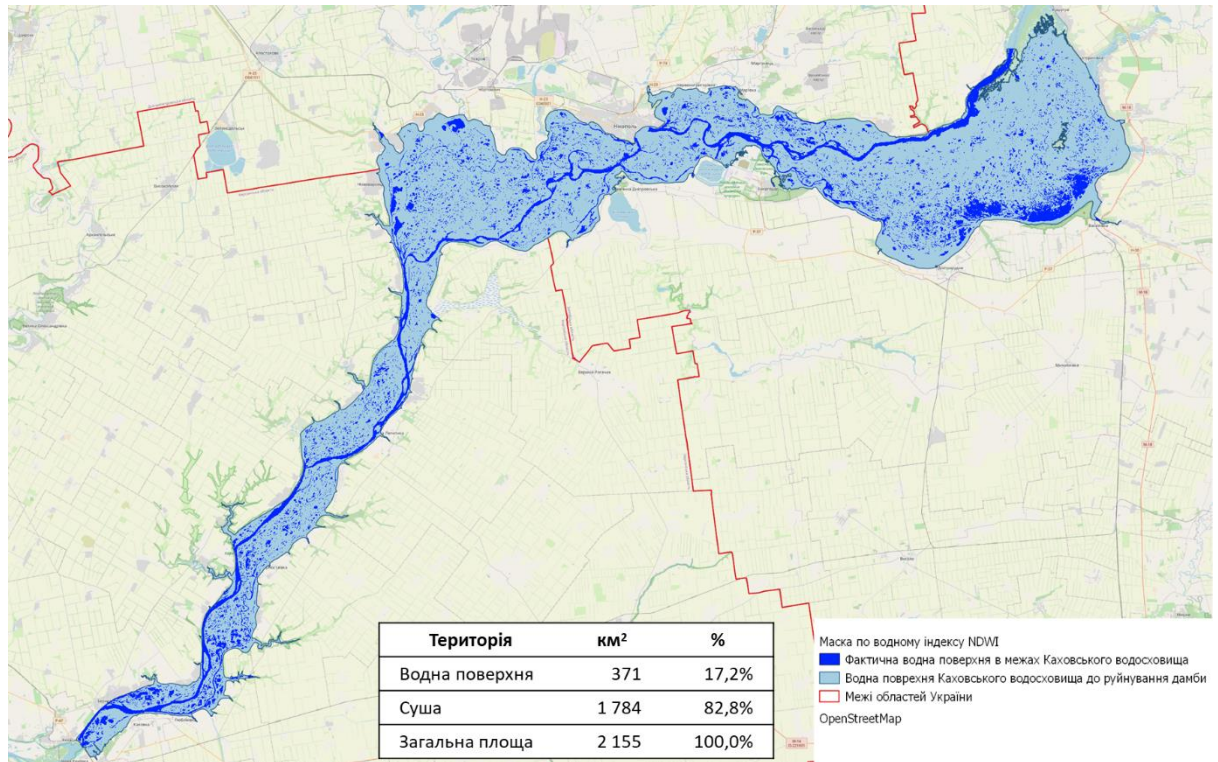


Figure 7. Water surface of the Kakhovka Reservoir as of July 04, 2023 according to Landsat-9 satellite images

About 83% of the area under the reservoir has been freed from water. This process is ongoing, and some water bodies without water inflow will continue to dry up.

The most pressing issues today regarding the territory under the Kakhovka Reservoir and the land plots adjacent to the reservoir are the determination and consolidation of their legal status. First of all, it is about determining and regulating the use of this territory in the absence of water in this water body and the water protection zone around the former reservoir.

Conclusions and suggestions. Based on the methodology developed by the scientists of the Institute of Land Management of the National Academy of Sciences of Ukraine for determining the area of flooded land affected by the destruction of the Kakhovka HPP dam and the area under the Kakhovka Reservoir, satellite images were analyzed before the terrorist attack and as of June 09, 2023, which concluded

that the total area of flooding by ESA WorldCover land cover classes was about 65 thousand hectares.

In order to study the suitability of agricultural land for its intended use in the regions affected by the destruction, a land database was created from open sources of information with information on coordinates, intended use, ownership, and other cadastral data.

It was discovered that the number of land plots registered in the State Land Cadastre that are in the flood zone is 30,325. No other plots in the flood zone have been registered. The total area of these plots affected by the flood is about 25 thousand hectares, including 9.8 thousand hectares (38%) of agricultural land. Of these, only 20% are privately owned (of which three quarters are agricultural land and one quarter are residential and public land).

It has been established that the share of the area of land plots in the flood zone in the total area by ownership is as follows: 56.5% - state ownership; 22.1 - communal ownership; 20.3% - private ownership; and 1.2% remains undetermined.

The most pressing issues today regarding the territory under the Kakhovka Reservoir and the land plots adjacent to the reservoir are the definition and consolidation of their legal status. First of all, it is about determining and regulating the use of this territory in the absence of water in this water body and the water protection zone around the former reservoir.

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ЗАСТОСУВАННЯ ГЕОІНФОРМАЦІЙНИХ ТЕХНОЛОГІЙ ПРИ ВИЗНАЧЕННІ ПЛОЩ ПІДТОПЛЕНИХ ЗЕМЕЛЬ УНАСЛІДОК РУЙНУВАННЯ ДАМБИ КАХОВСЬКОЇ ГЕС

Анотація. На підставі вибірки даних міністерств, місцевих органів влади та інших офіційних відкритих джерел інформації щодо наслідків руйнування дамби Каховської ГЕС та їх аналізування з'ясовано, що вони є неточними. З урахуванням наведеного, науковцями Інституту землекористування НААН розроблено методологію визначення площ підтоплених земель, що постраждали внаслідок руйнування дамби Каховської ГЕС, території під Каховським водосховищем, складовими якої є супутникові знімки, геоінформаційні технології та технології штучного інтелекту. Для виявлення та оцінки площі підтоплених земель проаналізовано супутникові знімки до скоєння теракту й станом на 09 червня 2023 року, за результатами якого встановлено, що загальна площа підтоплення за класами земельного покриття ESA WorldCover становила близько 65 тис. га.

Досліджуючи придатність до використання земель сільськогосподарського призначення за цільовим призначенням у постраждалих внаслідок руйнування регіонах із відкритих джерел інформації створено базу даних земель із відомостями про координати, цільове призначення, форму власності та інші відомості кадастру.

З'ясовано, що кількість земельних ділянок, зареєстрованих у Державному земельному кадастрі й опинились у зоні підтоплення, становить 30 325 ділянок. Інші ділянки, які знаходяться у зоні підтоплення, не зареєстровано. Загальна площа цих ділянок, що потрапили під вплив повені, становить близько 25 тис. га, в тому числі 9,8 тис. га (38%) – це землі сільськогосподарського призначення. Із них лише 20% знаходяться у приватній власності (з них три чверті – землі

сільськогосподарського призначення та одна чверть – землі житлової та громадської забудови).

Встановлено, що частка площі земельних ділянок у зоні підтоплення у загальній площі за формами власності становить: 56,5% – державна власність; 22,1 – комунальна, 20,3% – приватна й не визначеними залишається 1,2%.

Ключові слова: *Каховське водосховище, підтоплені землі, Державний земельний кадастр, геоінформаційні технології, штучний інтелект*