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# Surface Water Transitions of the Former Kakhovka Reservoir, 2021-2026, Based on Sentinel-1 Data at Annual Temporal Resolution

*Ye. Sazonenko, L. Pidgorodetska, L. Kolos, O. Fedorov. *(Space Research Institute of the NAS of Ukraine and SSA of Ukraine)*

## SUMMARY

This paper presents the results of mapping the surface water transitions of the bed of the former Kakhovka Reservoir, based on Sentinel-1 radar imagery covering the period from January 2021 to May 2026 - before and after the demolition of the Kakhovka Hydroelectric Power Station dam in June 2023. The calculations are based on a methodology for classifying surface water features using a modified algorithm for the automatic extraction of water surface data from Sentinel-1 satellite images, based on the OTSU method implemented in Google Earth Engine. The proposed approach utilizes all-weather radar data with improved spatial resolution (10 m), which is independent of cloud cover and time of day, and constructs transitions at an annual resolution for a specific territory, updated through to 2026. The results show a sharp reduction in the area of permanent water - from approximately 1,715.1 km$^2$ in 2021 to 204.1 km$^2$ in 2026 - and the transformation of the bed of the former reservoir predominantly into seasonal water: the dominant type of transition in 2023 was the conversion of permanent water to seasonal water (1,474.0 km$^2$). The accuracy of the 'water/land' classification was confirmed by pixel-by-pixel comparison with cloud-free Sentinel-2 imagery and by comparing areas with an independent CLMS dataset. The results obtained are suitable for monitoring Sustainable Development Goal indicator 6.6.1 and for planning the post-war restoration of water management systems in southern Ukraine.

*Keywords:* Water transition map; Sentinel-1; Kakhovka Reservoir.

*Corresponding Author*: sazon.eugene@gmail.com

## Introduction

Earth observation data play a crucial role in monitoring aquatic ecosystems, and the use of satellite data to assess the impact of natural and anthropogenic factors on their state covers a wide range of scientific works (Lehmann et al., 2014; Dörnhöfer et al., 2016; Tomchenko et al., 2013). The destruction of the Kakhovka HPP dam in June 2023 caused an unprecedented ecological disaster, prolonged and dynamic transformations of the former reservoir bed, and further deterioration of the water supply and of the ecological state of the natural and agricultural lands of southern Ukraine (Lischenko et al., 2025; Yailymov et al., 2026).

This study aims to investigate the dynamics of surface water transitions of the former Kakhovka Reservoir from Sentinel-1 radar imagery over 2021 to May 2026, and is based on the methodology for determining permanent and seasonal water (United Nations, 2025; Sazonenko et al., 2024) and on the classification of surface water transitions (Pekel et al., 2016; Global Surface Water Explorer, 2026).

The closest analogue is the global Global Surface Water Explorer product (Global Surface Water Explorer, 2026; Nagel et al., 2025). However, it has insufficient temporal resolution, presenting transition maps only between the first (1984) and last (2024) years of observation, and is based on optical and thermal Landsat data at 30 m resolution that are sensitive to cloudiness (Pekel et al., 2016). The proposed approach instead uses all-weather Sentinel-1 radar data at 10 m resolution, with annual monitoring of a specific area updated to 2026.

## Method

The analysis of the annual-resolution surface water dynamics in the bed of the former Kakhovka Reservoir is based on a classification of 11 types of surface water change between the baseline observation period and the most recent year of data update (Pekel et al., 2016):

- **No change**: the surface state has not changed (stable land).
- **Permanent**: permanent water that has undergone no change.
- **New permanent**: conversion of land to permanent water.
- **Lost permanent**: conversion of permanent water to land.
- **Seasonal**: seasonal water whose regime has remained stable from year to year.
- **New seasonal**: land that has turned into seasonal water.
- **Lost seasonal**: conversion of seasonal water or floodplain to land.
- **Seasonal to permanent**: a shift of a water body from seasonal filling to a permanent state.
- **Permanent to seasonal**: a shift from a year-round regime to a seasonal one.
- **Ephemeral permanent**: an appearance of permanent water on land that later disappeared.
- **Ephemeral seasonal**: an appearance of seasonal water that later disappeared.

In the proposed study, this classification was applied not only to compare the baseline observation year with the most recent one, but also to examine the annual dynamics of the surface water of the former reservoir over consecutive pairs of years from January 2021 to May 2026.

A modified algorithm for the automatic extraction of water-surface data from Sentinel-1 satellite imagery using the OTSU method was applied (Sazonenko et al., 2024). C-band Sentinel-1 SAR (synthetic aperture radar) images are used as input, since Sentinel-1 sensors acquire imagery at any time of day and under any weather conditions and are openly available for download from various platforms. They are Level-1 Ground Range Detected (GRD) products with a spatial resolution of 10×10 m and cover the entire study area. Pre-processing and the algorithm were implemented in the Google Earth Engine environment using the Python programming language (Google Earth Engine, 2026).

The processing of Sentinel-1 imagery comprises several stages, described in detail in (Sazonenko et al., 2024), followed by the direct computation of surface water transition maps according to the classification of (Pekel et al., 2016):

1. Speckle noise filtering to remove image graininess.

2. Segmentation into water and land classes using the optimal OTSU threshold.
3. Building a monthly water mask as the union of the segmented masks of all images for the month (monthly water extent).
4. Computing seasonal water – the surface that is under water for fewer than 12 months a year.
5. Computing permanent water – the surface that is under water throughout the year.
6. Building surface water transition maps by comparing the water-regime classes of two years following the scheme of (Pekel et al., 2016).
To analyze the annual dynamics of the transitions, 201 images were processed for January 2021 – May 2026: 72 before and 129 after the dam breach.

The water/land classification accuracy was assessed by two independent methods: pixel-wise – for each Sentinel-1 scene with a cloud-free Sentinel-2 image within ±1 day, by comparison with a reference water mask based on the MNDWI index; and by area – by comparing the total monthly water areas with the independent CLMS dataset using the sMAPE metric.

**Results**

The results of the annual surface water transition computations for 2021–2026, based on the classification of surface water transition types after (Pekel et al., 2016), are presented in Figure 1.

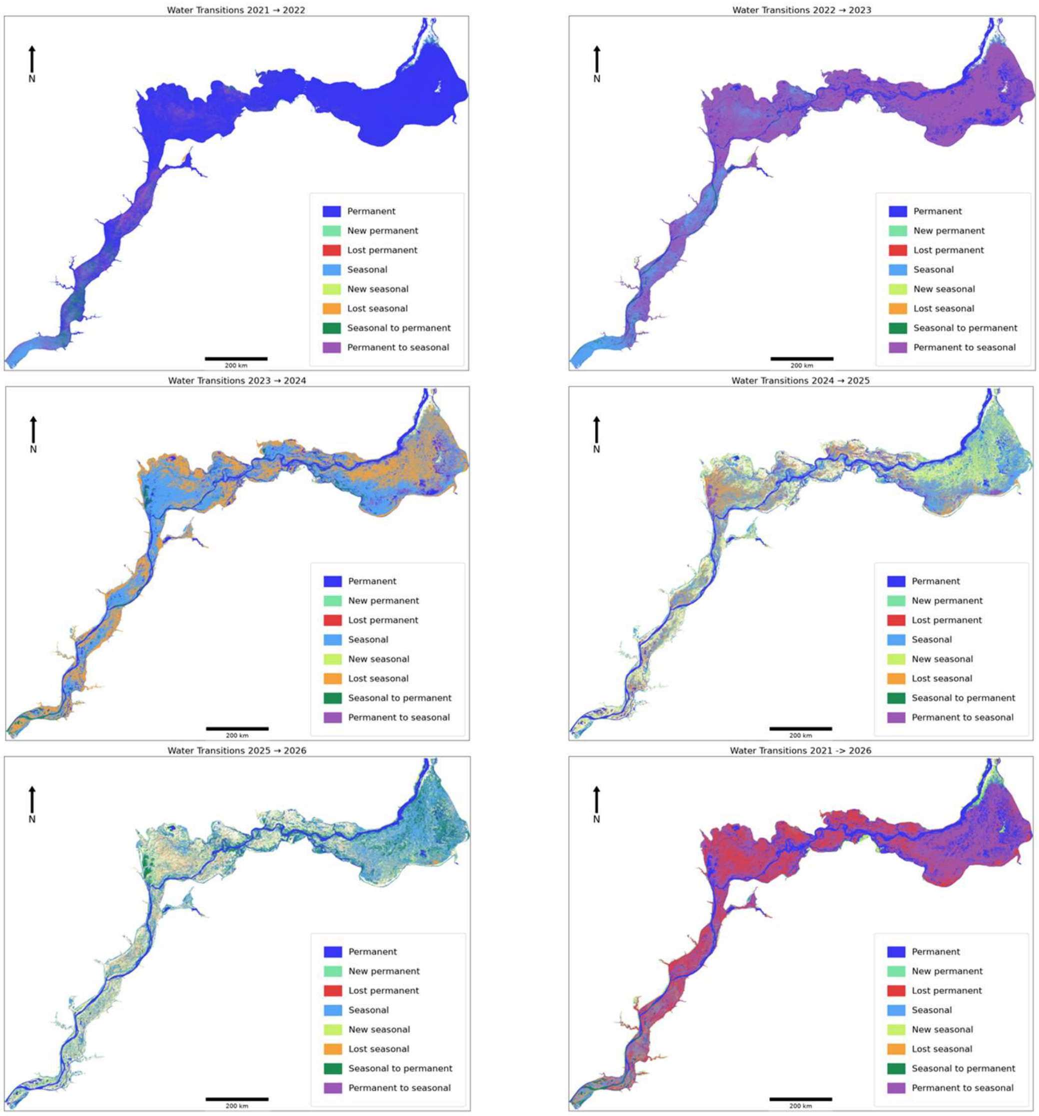


***Figure 1.*** *Maps of surface water flow in the former Kakhovka Reservoir for 2021-2026, based on Sentinel-1 data at annual resolution*

The maps produced provide an insight into the general trends in the surface waters transitions of the former Kakhovka Reservoir before and after the dam was breached. The 2021→2022 transition map indicates that the permanent water body remained stable during this period. The sharpest transformation occurred in the dam breach year: the 2022→2023 map shows a predominant shift from permanent water to seasonal water, with the area of permanent water decreasing from approximately 1,715 km$^2$ (2022) to 303 km$^2$ (2023). It should be noted that the 2023 period combines two regimes (a full reservoir until June and a dry bed thereafter); therefore, in this pair, the retreat of water is reflected primarily as a transition to the seasonal class, rather than as a loss of permanent water. The 2023→2024 map shows both a gradual stabilization of seasonal water and its partial loss with a transition to dry land. The 2024→2025 and 2025→2026 maps indicate a stabilization of areas of dry land, permanent water and seasonal water.

Figure 2 shows the general trends in changes in the areas (km$^2$) of various types of surface water transitions in the former Kakhovka Reservoir over the period from January 2021 to May 2026.

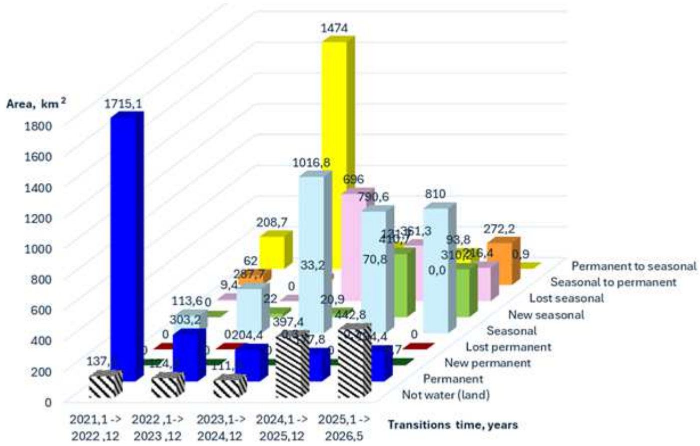


***Figure 2.*** *Trends in the areas of different types of surface water crossings over the period from January 2021 to May 2026*

The ephemeral permanent and ephemeral seasonal types were not recorded within the study area, since they describe the appearance of temporary water on plots that were land both at the beginning and at the end of the observation period; instead, processes of loss and degradation of permanent water (transition to seasonal water and to land) prevailed within the bed of the former reservoir.

Pixel-wise comparison with the Sentinel-2 reference masks (MNDWI) over 88 cloud-free matching dates yielded an overall accuracy of 83.6%. Comparison of the total monthly water areas with Copernicus Land Monitoring Service data gave an sMAPE of 23.72% (5.80% before the destruction, 38.52% after); the higher errors in the post-destruction period are explained mainly by the lower spatial resolution of the CLMS product (100 m), which underestimates the narrow channels and the branched channel network of the Dnipro river.

## Conclusions

This study analyzed the surface water transitions of the former Kakhovka Reservoir from January 2021 to May 2026, both before and after the demolition of the Kakhovka HPP dam. During the study:

The methodology (Sazonenko et al., 2024), based on Sentinel-1 radar satellite imagery, was modified to identify surface water transitions (Pekel et al., 2016) on an annual time scale, with a spatial resolution of 10 m, and implemented in the Google Earth Engine cloud platform.

Quantitative evidence has been provided of trends showing a sharp decrease in the area of permanent water in the former reservoir, an increase in the area of seasonal water, and its subsequent partial conversion to land in the first two years following the breaching of the Kakhovka HPP dam in June 2023, as well as trends towards an increase in land areas and a certain stabilization of permanent and seasonal water bodies during 2025-2026.

The proposed approach enables the rapid acquisition of data on surface water dynamics with superior spatial resolution, whilst complying with the requirements of the methodology for assessing Sustainable Development Goal indicator 6.6.1.

In the future, the research results may be used in planning the post-war restoration of water supply and irrigation systems in southern Ukraine, as they are based on a continuous set of radar data.

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