FLOODED AREAS' MONITORING UNDER THE KAKHOVKA DAM BASED ON MACHINE LEARNING AND SATELLITE DATA

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ABSTRACT

This study analyzed the flooding under the Kakhovka Dam in Ukraine using satellite remote sensing data after the dam was destroyed on June 6, 2023. Maps of the water bodies were created before and after the flooding disaster using Sentinel-1, Sentinel-2, and Landsat-9 imagery. A random forest classifier was used to map the flooded areas. As of June 9, 2023, the total flooded area below the Kakhovka Dam was 47,330 hectares, impacting agricultural lands, forests, grasslands and human settlements. The flooding also affected areas along the Ingulets River, leading to inundation of croplands located close to the river banks which could impact water quality. The disappearance of water canals that were used for irrigation of croplands is also analyzed, showing the far-reaching agricultural impacts of this flooding event. This study demonstrates the utility of satellite remote sensing for rapid monitoring and quantification of the impacts from dam failure flooding disasters.

Index Terms **—** Flooding, Kakhovska HPP, machine learning, satellite monitoring, disaster monitoring.

1. INTRODUCTION

One of the largest and most tragic floods in the history of Ukraine was the flooding of the Kakhovka Reservoir, which occurred on June 6, 2023, as a result of the detonation of the Kakhovka Hydroelectric Power Plant (HPP). Kakhovka HPP was one of the largest hydroelectric power stations in Europe, located on the Dnipro river in the Kherson region and controlling the water level in the Kakhovka Reservoir - the second largest reservoir in Ukraine [1]. The explosion of the Kakhovka HPP led to the destruction of the dam and the leakage of water from the reservoir, which caused a sharp rise in the water level in the lower reaches of the Dnipro and the flooding of dozens of settlements, agricultural lands, infrastructure and natural areas. According to the United Nation [2], [3], more than 700,000 people were affected by the flooding, 58 of them died and 31 went missing. In addition, the flooding caused an environmental disaster, as more than 150 tons of oil spilled from the hydroelectric power plant, which polluted rivers and the Black Sea.

According to the BBC information [4], the flooded area reached its maximum on June 15, 2023 - about 1.5 thousand square kilometers, and the water level in the Kakhovka Reservoir dropped by 16 meters. According to [5], the flooding affected 80 settlements, of which 35 were completely submerged. According to the United Nations, the flooding caused more than $2 billion in economic and agricultural losses.

Based on previous studies [6], scientists have identified the following groups of catastrophic impacts on nature. At the time of the destruction of the dam, there were no less than 43 species of fish in the Kakhovka Reservoir alone, of which 20 species are of industrial importance (annual catch was up to 2.6 thousand tons). It will take at least 7-10 years to restore such reserves. Due to the almost complete Kakhovka Reservoir disappearance, a number of bird species that nest in these places will disappear in this area. Above the Kakhovka Dam, as a result of drainage, a number of nature conservation areas also affected, including at least 11 objects of the nature reserve fund.

Previously, before the destruction of the dam, studies were conducted in which the possible course of events and areas of flooding were modeled, as well as the risks were assessed [7]. After this situation occurs, there is a need for an independent assessment of flooding. In this work, own maps of water bodies before and after flooding were created based on free satellite data Sentinel-1,2 and Landsat-9 and the situation with the water cover as of November 2023 was assessed. This can be useful for analyzing the dynamics of flooding, identifying the most vulnerable areas, assessing the impact of flooding on the environment and developing measures to prevent and eliminate the consequences of flooding in the future.

2. STUDY AREA

In the past the Kakhovka Reservoir was one of the six large reservoirs in the cascade on the Dnipro River, in the Zaporizhzhia, Dnipropetrovsk, and Kherson regions. It was constructed in 1955-1958 and destroyed in June 6, 2023 by the Russian occupiers during a full-scale invasion. The length of the reservoir is 230 km, the average width is 9.4 km. The area was 2155 km², the water volume was 18.2 km³ (Fig. 1).

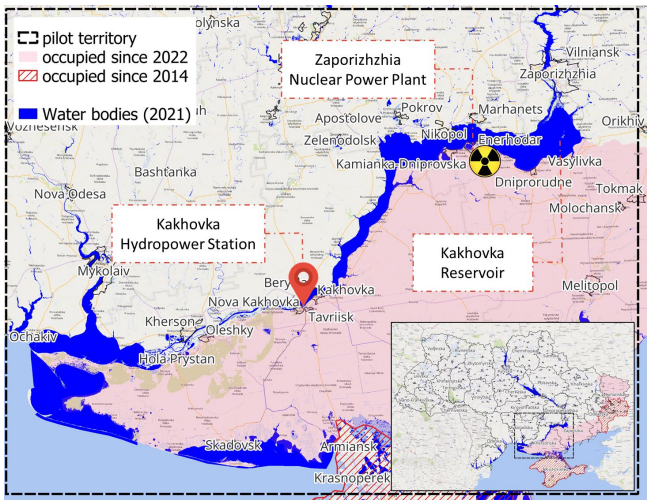


Fig. 1. Study area - Kakhovka reservoir, Kherson region.

3. SATELLITE DATA USED

For the territory of Ukraine, 12-day mean composites of SAR Sentinel-1 satellite data with VV, VH bands with 10-meters spatial resolution were used [8]. The preprocessing steps were: apply orbit, border noise removal, thermal noise removal, radiometric calibration, orthorectification, filter box 3x3 were performed as preliminary processing. As a result, the Sentinel-1 stack was formed every 12 days. Optically corrected Sentinel-2 Level 2A satellite data [9] was used for water bodies classification before and after dam destroy. The spectral bands with 10 meters resolution (red, green blue and NIR) were used and the cloud free composites were created. A Landsat-9 image with red, green blue, NIR, SWIR-1,2 bands was also used [10]. Although the spatial resolution of Landsat-9 data is 30 m, it has a panchromatic band of 15 m, which made it possible to improve the spatial resolution of other bands for more effective monitoring of water bodies. The dates of satellite images are presented in the Table 1.

Table 1. Satellite data used.

Satellite	Dates
Before the dam destroy	
Sentinel-1	01.03 – 05.06.2023
Sentinel-2	01.03 – 30.05.2023, 01.06 – 05.06.2023
After the dam destroy	
Sentinel-1	06.06 – 30.06.2023
Sentinel-2	06.06 – 30.06.2023; 01.10 – 31.10.2023 01.01 – 11.01.2024
Landsat-9	09.06.2023

4. METHODOLOGY

To assess the consequences of the destruction of the Kakhovka HPP, a map of water bodies was created before the flood (as of June 5, 2023), during the flood (June 9, 2023) and a map of water bodies at the moment when the water level in the reservoir stabilized (October 31, 2023). Free satellite images of Landsat-9, Sentinel-1 and Sentinel-2 were used for this (Table 1). To create the maps, classification was carried out in the Google Earth Engine (GEE) cloud platform based on the Random Forest (RF) method [11]. The RF method uses an ensemble of decision trees that vote for the best class for each pixel. The training data is created based on the interpretation of satellite data.

In order to identify flooded cultivated agricultural lands, our own method [12] and land cover classification map for the year 2023 was used [13]. Water canals were also investigated, the water from which disappeared due to the destruction of the dam and the emptying of the reservoir. Information about water canals for the Kherson region was obtained from Open Street Map. Canals that lost water were identified by comparing with water bodies maps before and after the dam broke.

5. RESULTS

With the use of satellite data and a cloud platform, maps of the water cover as of June 05 (before flooding), June 09 (during flooding), and October 31 (when the water level stabilized) were constructed for the Kakhovka reservoir. In Fig. 2 the obtained results are presented, where it can be seen that the water from the reservoir has almost disappeared, and after passing the dam, the water has returned to its usual way.

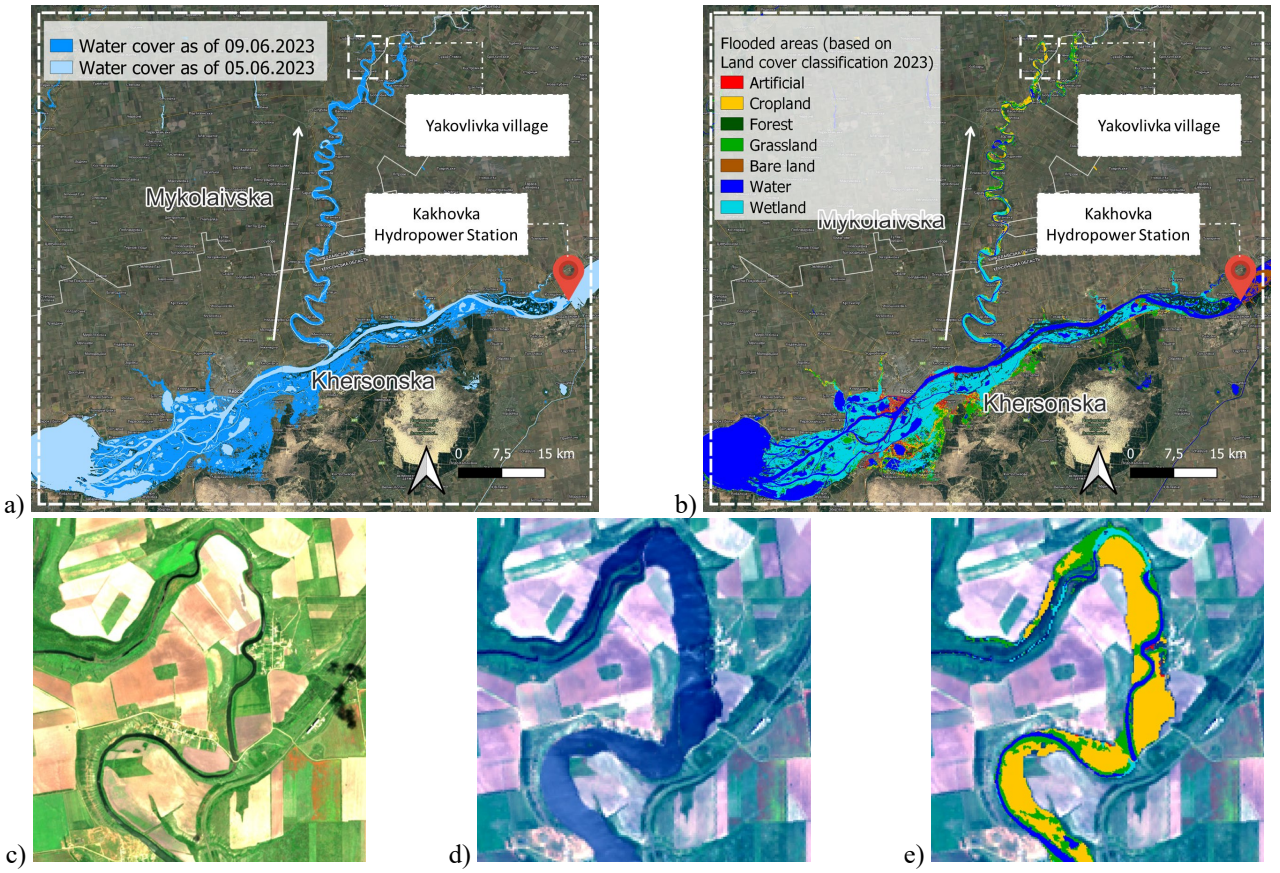
Fig. 2. Comparison of the water cover before the dam damage (June 5, 2023) and after (October 31, 2023).

5.1. Flooded area

The Fig. 3-a shows the identified water cover on June 9, 2023 compared to the pre-dam damage water cover on June 5, 2023. Areas that were flooded are marked in dark blue.

The combination of flooded areas with the land cover map is shown in the Fig. 3-b. According to satellite observation as of June 9, 2023 the total flooded area to the Kakhovka Dam is 47.33 th. hectares. This includes 1.85 th. hectares of artificial objects, 1.67 th. hectares of cropland, 0.97 th. hectares of forest, 12.3 th. hectares of grassland and noncultivated lands, 1.14 th. hectares of bareland, and 29.4 th. hectares of wetland.

It is interesting that the flooding occurred not only below the dam. On the contrary, the water rose significantly along the Ingulets river bed up to the Yakovlivka village, Mykolaiv region. It is in this zone that there is flooding of the coastal river zone and agricultural territories that were cultivated at a distance of up to 1 kilometer from the river bed. An example of a Sentinel-2 image before flooding is shown in Fig. 3-c, Landsat-9 is during flooding - Fig. 3-d, as well as identified flooded agricultural areas - in Fig. 3-e. Given that fertilizers and pesticides are used in agriculture, such flooding can affect the quality of water in the river, and as a result in the sea.



Sentinel-2, 05.06.2023 Landsat-9, 09.06.2023 Land cover map of flooded area

Fig. 3. Flooded areas after damage to Kakhovka Dam as of June 9, 2023 (a), flooded area with LC distribution (b), example of Sentinel-2 before the Dam destroy (c), Landsat-9 data after Dam destroy (d), flooded land cover types (e).

5.2. Irrigation area

In a study [14] using vegetation indices that show soil moisture and thermal channels of the Landsat satellite, the area of potentially irrigated areas for 2019 was determined for the Kherson region (Fig. 4- central part). The area of such fields was about 350,000 hectares. Such lands are more productive [15] than those territories, which are not irrigated, and accordingly give a higher yield. This figure also shows the water canals that were used to irrigate the fields (according to OSM data). Through the layer of irrigated fields, it can be seen that these canals supplied water to many agricultural lands that are now threatened with water scarcity. In Fig. 4, the left column shows an example of a completely emptied water canal after the dam was blown up. However, if you look at the right column, you can see that this canal continues to be filled with water, however, to optimize the water resource, some of the branches from the main canal bed have been blocked.

6. CONCLUSIONS

The catastrophic flooding along the Dnipro River and its tributaries in southern Ukraine was a direct result of the destruction of the Kakhovka Dam during the war on June 6, 2023. Using high resolution Sentinel and Landsat satellite imagery combined with machine learning methods, we quantitatively mapped the extent of flooded areas before and after this event. As of June 9, over 47,000 hectares of croplands, forests, grasslands and human settlements were inundated.

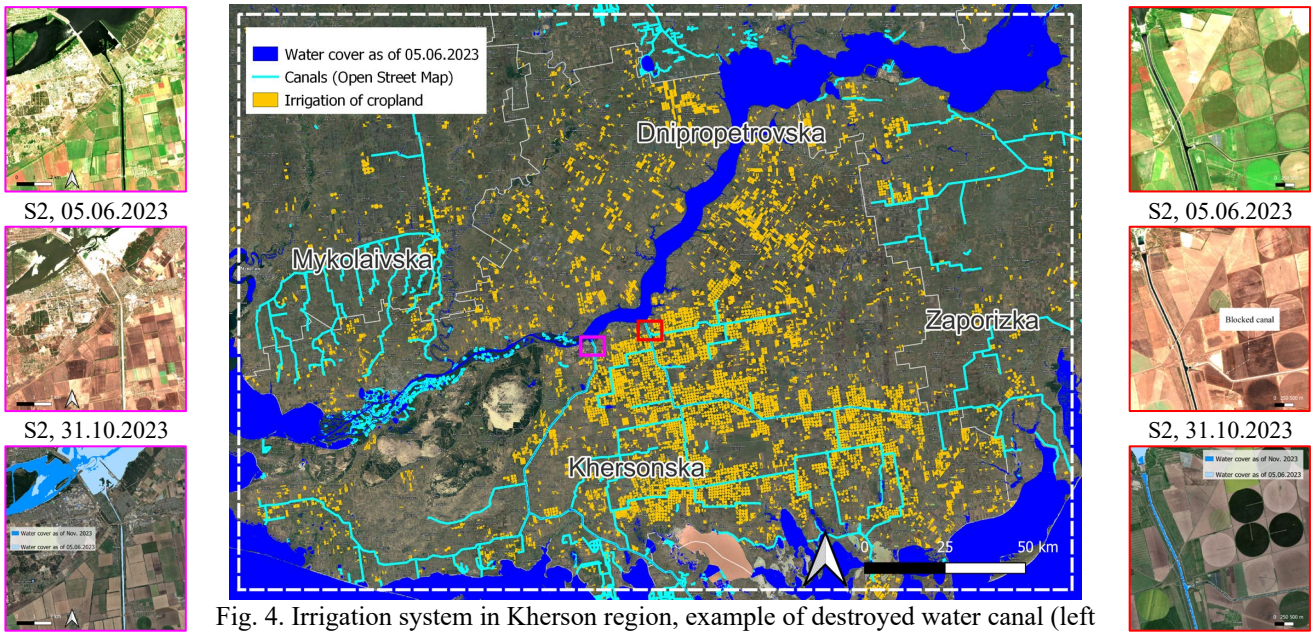


Fig. 4. Irrigation system in Kherson region, example of destroyed water canal (left column), and the canal is filled with water in autumn 2023

This study demonstrates the usefulness of frequently updated global satellite data for rapidly detecting, delineating, and assessing the damages from flooding disasters linked to dam failures. Continued high resolution optical and radar remote sensing monitoring is needed to support recovery efforts and redevelopment planning after this catastrophic event. The integrated application of satellite earth observations and geospatial analysis has proven invaluable for independent and timely monitoring of the humanitarian and environmental impacts of war-related flooding.

7. AKNOWLEDGEMENTS

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