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# The impact of temporary occupation and hostilities on the water conditions of the North Crimean and Kakhovka Main Canals

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**Abstract.** The aim was to analyse the dynamics of water resources of the North Crimean and Kakhovka canals from 2013 to 2024 using remote sensing methods. The study utilised satellite imagery from Landsat 8 OLI/TIRS L2 (2013-2015) and Sentinel-2 L1C (2016-2024). The deep learning model "Water Body Extraction (SAR) – USA" based on Sentinel-1 C band SAR GRD VH data was applied. The normalised difference water index was used to detect water surfaces. Manual digitisation of the canals was performed based on time composites of satellite images over the study period. The analysis revealed significant changes in the water conditions of the canals due to natural and anthropogenic factors. Following the annexation of Crimea in 2014, the cessation of water supply from the Dnipro River led to the drying of canals on the peninsula, negatively affecting agriculture and ecosystems through soil salinisation and degradation. In 2015, the length of canals with water in Crimea decreased to 161.65 km. Alternative sources, such as artesian wells, partially compensated for the lack of water but led to groundwater depletion. From 2016 to 2021, the length of canals with water in Crimea continued to decrease, reaching 150.17 km in 2020. In 2022, after the destruction of dams in the Kherson Region, uncontrolled filling of canals with water occurred. Due to infrastructure degradation, a significant portion of water infiltrated into the ground, causing water losses. In 2023, the destruction of the Kakhovka Hydroelectric Power Plant dam led to the shallowing of the Kakhovka Reservoir and changes in the hydrological regime of the canals, reducing the length of canals with water in the Kherson Region to 448.41 km, and in 2024 to 298.98 km. These events caused erosion and lowering of groundwater levels, negatively affecting agriculture due to reduced irrigated areas

**Keywords:** dynamics; irrigation; deep learning; spatial analysis; remote sensing; water security

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## Introduction

In regions with a continental climate characterised by irregular and insufficient precipitation, canals are important not only for the agricultural sector but also for meeting the needs of the local population. Climate change, particularly rising temperatures and decreasing amounts of precipitation, leads to a reduction in the volume of water resources, which is acutely felt in the arid and semi-arid zones of the Ukraine's south. The shortage of fresh water is one of the biggest problems in the territories of the Autonomous Republic of Crimea, Kherson, and Zaporizhzhia regions. Thousands of square kilometres of land require irrigation, which is provided through a branched network of canals such as the North Crimean and the Kakhovka Main Canal. These canals play an important role in ensuring high crop yields and stable water supply. A stable water level in the irrigation system is a critically important aspect for ensuring water resources and maintaining ecological balance in any region. Scientists from various countries are working on improving methods for identifying water bodies and monitoring their changes.

T.V. Bijeesh & K.N. Narasimhamurthy (2020) analysed various methods for detecting water bodies, such as spectral indices, machine learning, and spectral mixture analysis. They concluded that spectral indices are less effective than deep learning models, which better adapt to data but require more resources. To improve the accuracy of water identification, they recommended combining different methods and using synthetic-aperture radar (SAR) and panchromatic images. F. Chen *et al.* (2020) proposed a new method for identifying water bodies in urban areas. Unlike traditional spectral indices that use only two bands (normalised difference water index (NDWI), modified normalised difference water index (MNDWI)), their method uses multiple bands and analyses the interrelationship between visible bands, near-infrared (NIR) and short-wave infrared (SWIR) bands. It increases the accuracy of water identification by relying on the observation that water has a lower reflectance coefficient in the NIR and SWIR ranges and absorbs radiation in the SWIR range. X. Deng *et al.* (2020) used remote sensing to track annual and seasonal changes in water levels in reservoirs of the Yellow River. They determined that the most accurate approach integrates optical and radar images, as SAR images provide stable accuracy under any conditions, and optical images add details in clear weather. Implementing machine learning algorithms can further improve accuracy, especially for detailed classification.

O. Vlasova *et al.* (2023) monitored water bodies and reclaimed lands affected by hostilities, using the example of flooding of the floodplains of the Irpin and Dnipro rivers. They used spectral indices and series of Landsat 8 and Sentinel-2 L2A satellite images to analyse changes in land cover. The method allows for the rapid diagnosis of flooded areas, determining flood extents, and predicting the impact on reclaimed lands. In the study by G. Wang *et al.* (2020), convolutional neural networks (CNN) and the NDWI spectral index were applied to identify water in the area of Lake Poyang. They found that DenseNet performs much better than other CNNs and the NDWI method, considering the accuracy of identification results. H. Guo *et al.* (2020) proposed a new convolutional neural network for semantic segmentation, multi-scale water extraction convolutional neural network (MWEN), for automatic extraction of water bodies from GaoFen-1 (GF-1) remote sensing images. In the article by W. Jiang *et al.* (2021), a new approach to detecting water bodies was proposed using an improved water index for Sentinel-2 images – the Sentinel-2 water index (SWI). The authors developed and evaluated a new water index that demonstrates improved accuracy in water detection compared to traditional indices like NDWI. E. Özelkan (2020) explored the effectiveness of using the spectral index of three NDWI models: NDWI (Green, NIR), NDWI (Green, SWIR1), and NDWI (Green, SWIR2) for detecting water bodies on Landsat-8 OLI images. S. Liu *et al.* (2023) conducted a comparative analysis of 10 spectral indices calculated on Landsat TM/OLI images used for extracting surface water bodies.

The water supply situation in the territory of the Autonomous Republic of Crimea became especially difficult after the annexation of the peninsula in 2014 and, as a result, the closure of the channel of the North Crimean Canal in the southern part of the Kherson Region, which significantly complicated the provision of water to the peninsula. With the start of the full-scale invasion of the Russian Federation into the territory of Ukraine in 2022, dams in the Kherson Region that blocked the channel of the North Crimean Canal were destroyed, resulting in uncontrolled filling with water of part of the North Crimean Canal, whose channel had degraded since annexation. A significant part of the water from the Dnipro infiltrated into groundwater horizons, leading to substantial water losses. Under such conditions, the issue of determining and forecasting the dynamics of water in river channels has acquired a new level of relevance. Therefore, the aim was to analyse the dynamics of water resources of these canals from 2013 to 2024, to identify factors influencing their condition, and to propose ways to restore irrigation systems.

## Materials and Methods

**Description of the research area.** The North Crimean and Kakhovka Main Canals are located in three regions of Ukraine: the Autonomous Republic of Crimea, Kherson, and Zaporizhzhia regions. The area where the canals are located has a moderately continental climate characterised by significant seasonal temperature fluctuations and uneven distribution of precipitation throughout the year, ranging from 350-500 mm. The unstable level of precipitation leads to droughts, affecting agricultural practices and causing a shortage of water resources. The total length of the North Crimean and Kakhovka Main Canals along with their branches is 1,219.64 km in the Kherson Region, 171.23 km in Zaporizhzhia, and 2,177.55 km in the Autonomous Republic of Crimea (Fig. 1).

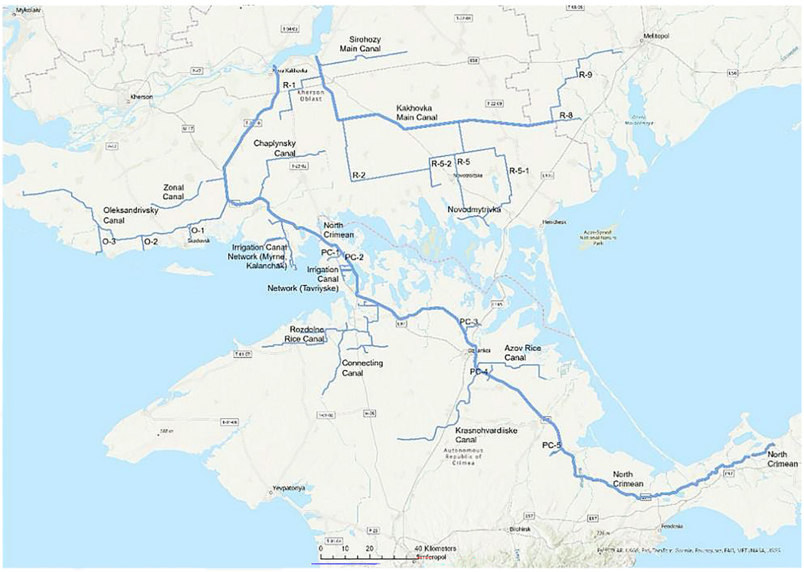



**Figure 1.** Map-scheme of the location of the North Crimean and Kakhovka Main canals
**Source:** created by the authors

The North Crimean Canal is a hydraulic engineering structure that, until 2014, provided water for irrigation to approximately 400,000 hectares of agricultural land and covered about 85% of the peninsula's water supply needs. The canal begins from the Kakhovka Reservoir, near the city of Tavriisk, and stretches south through the Black Sea Lowland and the Perekop Isthmus to Crimea. The total length of the North Crimean Main Canal is 402.6 km. The width of the canal varies from 110-120 m (up to the Krasnoznamenskyi Canal) to 25-30 m (near Dzhankoi), and the average depth is 4.6 m. The maximum capacity of the canal is 380 $m^3$/s. On average, about 1.5-2 $km^3$ of water flowed through the canal per year, ensuring the maintenance of ecosystems and water supply for 1.9-2.1 million people in Crimea (Mankovska, 2021). The main branches that depart from the North Crimean Canal include the Krasnoznamenskyi and Chaplynskyi canals in the Kherson Region, and the Rozdolnenska branch, Chervonogvardeiska branch, and Azov Rice Canal in Crimea.

The Kakhovka Main Canal is located mainly in the Kherson Region. The primary purpose of the canal is to irrigate agricultural lands covering an area of 216,000 hectares (190,100 ha in Kherson and 25,900 ha in Zaporizhzhia regions) and to supply water to the cities of Melitopol, Berdiansk, and 27 rural settlements in Kherson and Zaporizhzhia regions. The Kakhovka Main Canal has a total length of about 130 km. The width of the canal varies but averages from 10 to 20 m. The depth of the canal, depending on the section and season, is up to 10 m (A unique…, n.d.). From the Kakhovka Main Canal originate the Pryazov, Sirogoz, Henichesk, Kalanchak, and Perekop irrigation systems.

**Methodology and its selection.** The paper has employed a number of remote sensing methods for analysing water resources, particularly for monitoring the dynamics of the water cover of the North Crimean and Kakhovka canals. The main methods used in the study include comparison, measurement, change analysis, interpolation, extrapolation, geostatistics, linear regression, spectral indices, and deep learning methods. The comparison method involved comparing different datasets or images obtained at different times or from different sources. The measurement method was applied to obtain the lengths of canals with identified water. The analysis method was used to detect changes in the water conditions of canals over different years.

For the analysis and assessment of the water conditions of the canals in Southern Ukraine, images from Landsat 8 OLI/TIRS L2 satellites (for 2013-2015) with a spatial resolution of 30 m (USGS, n.d.), Sentinel-2 L1C (for 2016-2024) with a spatial resolution of 10 m, and Sentinel-1 C band SAR GRD VH with a spatial resolution of 10 m (Copernicus…, n.d.) were used. Open-source data from catalogued state and international sources included layers from OpenStreetMap (n.d.), Sentinel-2 Land Cover Explorer (n.d.) water cover obtained based on Sentinel-2 L2A images with a spatial resolution of 10 m, and OCHA Services (administrative boundaries of Ukraine level 1 – regions) (Ukraine…, n.d.).

For automatic identification of canals in the territories of Kherson and Zaporizhzhia regions, and the Autonomous Republic of Crimea, the deep learning model "Water Body Extraction (SAR) – USA" (2022) was used. This model employs SAR data to determine water surfaces based on processing radio images obtained from SAR satellites. The model classifies the pixels of the input raster and assigns them a class identifier. Pixel classification was carried out on the input 3-band composite raster Sentinel-1 C band SAR GRD VH with parameters: padding – 128, batch size – 4. This is because the number of image fragments processed at each step of the model's operation (batch size) depends on the video card's memory and only affects the processing time, and padding is a parameter that determines the size of the overlap of image fragments, with a maximum value of 256 for this model. However, the model proved insufficiently effective for extracting irrigation systems (Fig. 2).

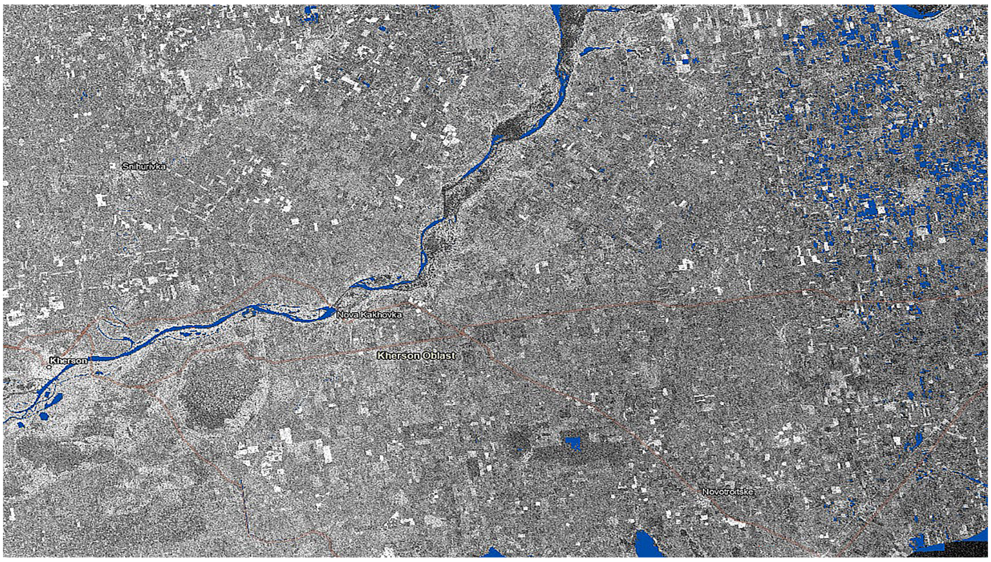



**Figure 2.** Identified water resulting from the operation of the water body extraction model on a part of the Kherson Region

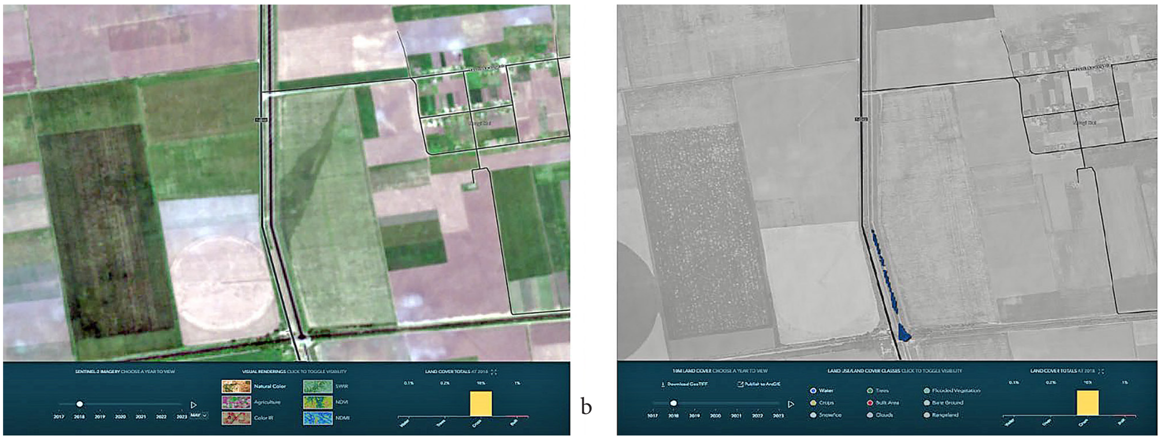
**Source:** created by the authors

Therefore, an attempt was made to improve the results by retraining the model. Considering the specifics of the land cover types and the width of the irrigation system objects, a training sample was created with parameters: image format – TIFF, tile size X, Y – 512, metadata format – Classified Tiles (Fig. 3). Despite retraining, water objects in the image were not fully identified. The model mainly detected objects like rivers and reservoirs because most irrigation canals have a small width, complicating their recognition on images with a spatial resolution of 10 m.


**Figure 3.** Training sample for retraining the water body extraction model

**Source:** created by the authors

The Esri Sentinel-2 Land Cover Explorer (n.d.) resource was then also considered, where global land cover is identified and classified based on Sentinel-2 satellite images with a resolution of 10 m using the Impact Observatory deep learning model into nine types, including water resources. However, identifying water in canals, especially their smaller branches, was a more complex task for the model. Therefore, the model did not always identify water in the image that the human eye can distinguish. In the 2018 image, it is evident that the Perekop Canal is filled with water (Fig. 4a), but the water in the canal was not identified by the model (Fig. 4b).



a b

**Figure 4.** Perekop Canal images

**Note:** a – canal with water in Sentinel-2 images, true colour composition; b – identified water in the canal according to Sentinel-2 Land Cover Explorer

**Source:** created by the authors

Using the EO Browser (n.d.) resource, the NDWI has been applied to monitor changes related to water content in water bodies. However, this method did not yield the desired results and did not identify water even in the largest canals. In Figure 5a, a part of the North Crimean Canal is presented in a true colour composition based on Sentinel-2 satellite images. The image shows that the canal is filled with water. However, when the NDWI visualisation was applied to the same section of canal, the water was not identified (Fig. 5b).

a b

**Figure 5.** North Crimean Canal in Sentinel-2 satellite images

**Note:** a – true colour composition; b – NDWI index composition

**Source:** created by the authors

Due to unsatisfactory model results and incomplete data from third-party resources, it was decided to supplement previous methods with the method of manual delineation of water levels in the canals. Delineation was carried out based on time composites of satellite images over a 12-year period from 2013 to 2024. Sentinel-2 satellite images have better spatial resolution than Landsat 8 images, but the Sentinel-2 mission was launched in 2015. Therefore, for the period from 2013 to 2015, Landsat 8 images were used, and from 2016 to 2024 – Sentinel-2 images. The imaging period was chosen based on the period of water supply to the North Crimean Canal, approximately from March to May. However, considering the availability of images and their cloudiness, the period was extended to June for Sentinel-2 images and to August for Landsat 8 images.

## Results and Discussion

An analysis of satellite images from 2013 to 2024 allowed for the assessment of changes in the water conditions of canals in the southern regions of Ukraine due to factors such as climate change, variability of atmospheric precipitation, hostilities, and the impact of temporary occupation. One of the main reasons for the change in the water conditions of the North Crimean Canal was the annexation of Crimea by Russia in 2014, which significantly affected the functioning of the canal that had previously supplied water from the Dnipro River to the peninsula. After the annexation, Ukraine ceased the supply of water to the North Crimean Canal; from April 2014 to March 2022, water from the Dnipro did not flow through the canal. Without water from the main source, the canal lost its functionality, leading to its drying up and negatively impacting agriculture and the state of the natural environment of the peninsula. The absence of water supply from the Dnipro caused ecological problems, including secondary soil salinisation and degradation of steppe, water, and agro-ecosystems.

As of mid-2013, the total length of canal channels with water in the North Crimean and Kakhovka Main Canals, along with their branches, reached: in the Kherson Region 772.16 km, in the Zaporizhzhia Region 66.75 km, in the Autonomous Republic of Crimea 561.34 km (Fig. 6). In 2014, after the annexation of Crimea and the shutdown of the North Crimean Canal supply, the total length of channels with water in the North Crimean and Kakhovka Main Canals, along with their branches, was: in the Kherson Region 582.04 km, in the Zaporizhzhia Region 73.41 km, and in the Autonomous Republic of Crimea 389.60 km.

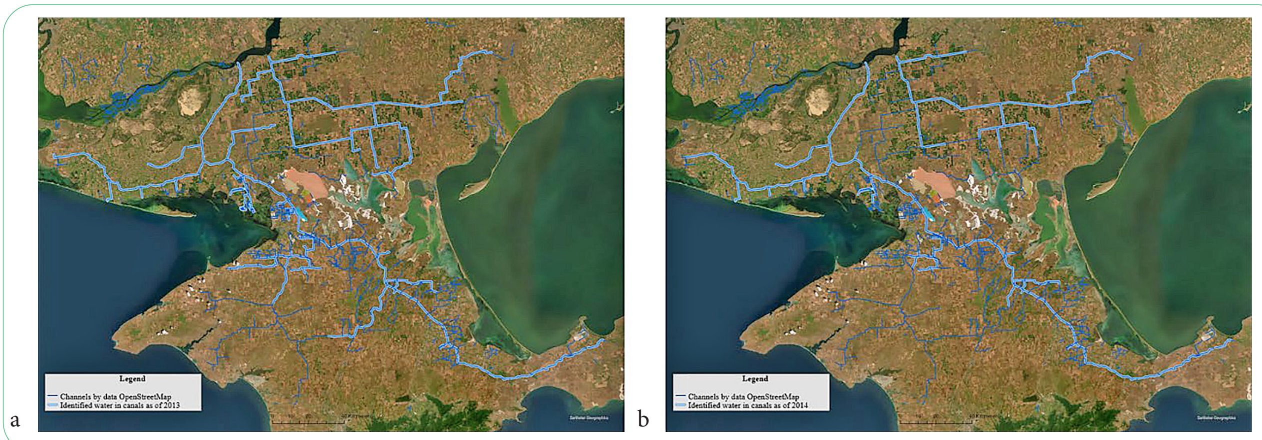



**Figure 6.** Identified water in canals, 2013-2014

**Source:** created by the authors

Since the North Crimean Canal stopped receiving water from the Kakhovka Reservoir, the water level in the Kakhovka Canal began to decrease. This happened because the portion of water that previously flowed into the canal for irrigation in Crimea was no longer used, and the water level in the canal started to fluctuate. This led to the need to rebalance water resources and changes in water use for irrigation and other needs. After the occupation of the peninsula in 2014, the volume of fresh water consumption decreased fivefold – to 310 million m$^3$, with losses up to 16 million m$^3$. The total volume of water intake in 2015 amounted to 253.46 million m$^3$, including: 138.47 million m$^3$ from fresh surface sources (55%); 95.13 million m$^3$ from groundwater (37%); 19.86 million m$^3$ of seawater (8%). Water losses amounted to 13 million m$^3$ (about 6%). Of this volume, 50% was used for industrial needs, 39% for domestic and drinking needs, and 6% for irrigation (Hai-Nyzhnyk, 2017). Due to a decrease in the average annual precipitation to 300-350 mm in 2015, droughts were observed, which was one of the factors affecting the water conditions of the canals during this period. The total length of canal channels with water in the North Crimean and Kakhovka Main Canals, along with their branches, in 2015 was: in the Kherson Region 457.63 km, in the Zaporizhzhia Region 28.57 km, in the Autonomous Republic of Crimea 161.65 km (Fig. 7).

In Figure 7, it is evident that despite the cessation of Dnipro water supply to the North Crimean Canal, some of its sections still had water. Russia was forced to seek alternative water supply sources. Construction of new water intake facilities and infrastructure to meet the peninsula's needs began. However, these measures could not fully compensate for the loss of water from the North Crimean Canal. One such project was the extraction of groundwater from Crimea, which included the development of new artesian wells (Hai-Nyzhnyk, 2014). By extracting water from artesian wells, water was transferred along the canal bed to the eastern part of Crimea, in the area of Feodosia and surrounding territories. Figure 7 shows that from 2015 to 2022, there was water consistently in the bed of the North Crimean Canal. This allowed for partially compensating for the absence of water from the Dnipro and providing irrigation of lands and water supply for local needs. However, this method led to negative consequences, such as lowering groundwater levels, soil salinisation, and a decrease in the amount of water in rivers and reservoirs.

After the cessation of water supply, the North Crimean Canal effectively lost its functionality. Its infrastructure, including concrete reinforcements, dams, and locks, began to gradually deteriorate due to the lack of maintenance and natural factors. This included issues with erosion, pollution, and a decline in the technical condition of canals and pumping stations. The total length of canal channels with water on the territory of Crimea gradually decreased from 2016, reaching minimal values in 2020. As of 2016, the total length of canal channels with water was: in the Kherson Region 723.68 km, in the Zaporizhzhia Region 91.90 km, in the Autonomous Republic of Crimea 335.52 km. In 2020, the lengths of canals with water were: in the Kherson Region 643.79 km, in the Zaporizhzhia Region 88.02 km, in the Autonomous Republic of Crimea 150.17 km (Fig. 8).

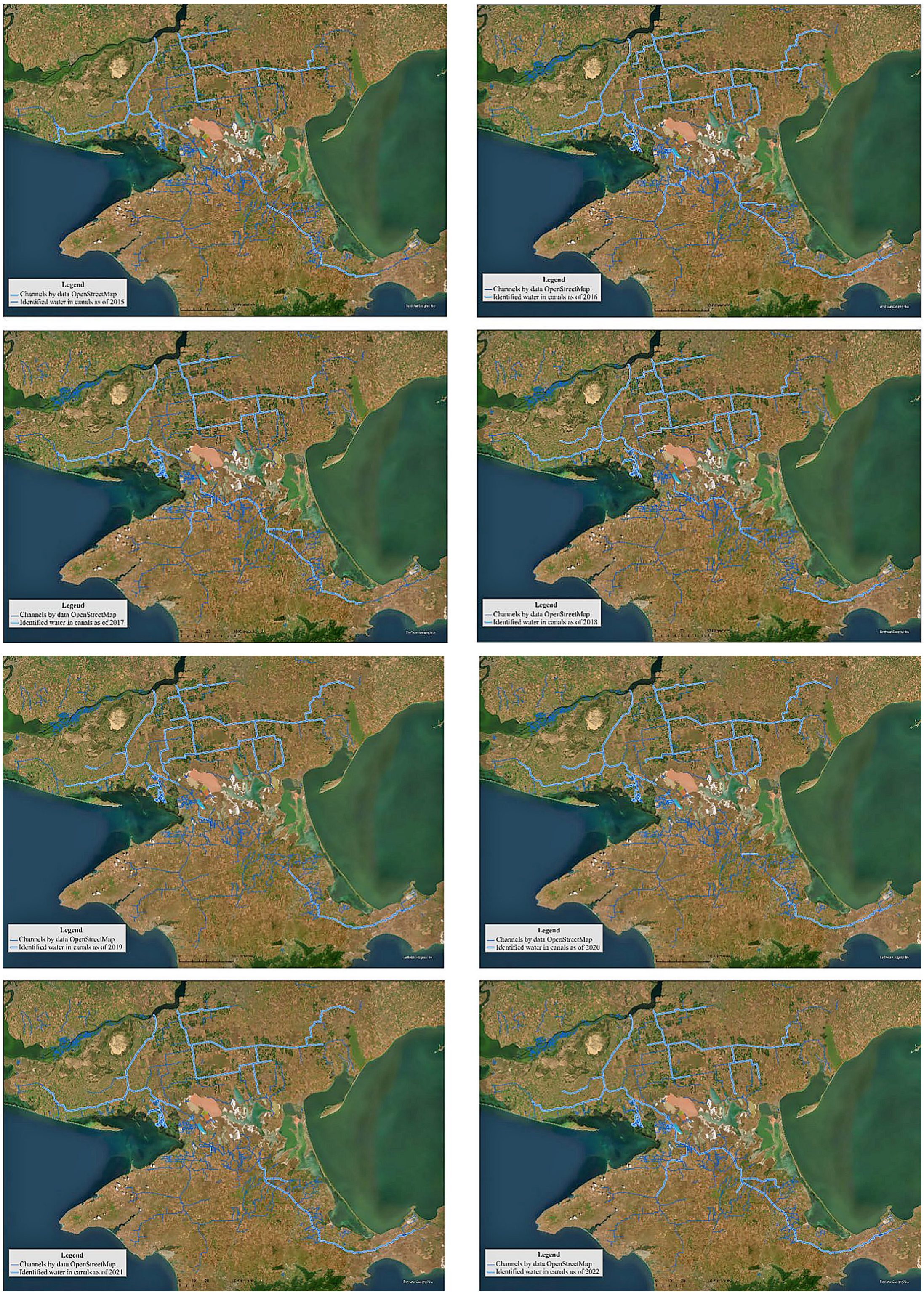



**Figure 7.** Identified water in canals, 2015-2022

**Source:** created by the authors

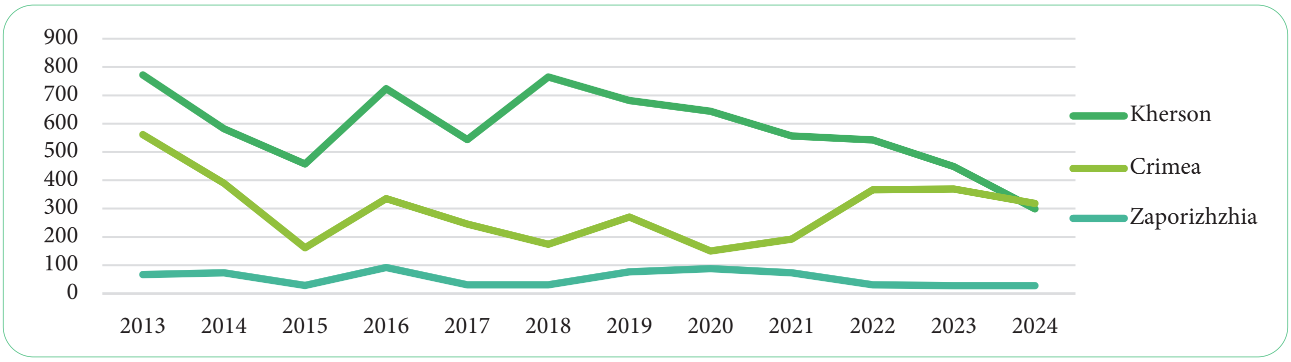



**Figure 8.** Graph of the dynamics of the total length of canals with identified water, 2015-2024, km
**Source:** created by the authors

The main reasons for the decrease in water level and reduction in canal lengths with water from 2015 to 2021 were the absence of Dnipro water supply and the depletion of alternative water sources. However, fluctuations in precipitation and periods of extremely high temperatures recorded in the summers of 2017, 2018, and 2020 affected the water conditions, leading to changes in water levels. Until 2022, the North Crimean Canal was used only partially for water transportation, mainly in the eastern part of Crimea. Its primary function as a water transport canal was lost. At the end of February 2022, a dam in the Kherson Region blocking water supply to the North Crimean Canal was destroyed. However, water began to reach Crimea in the second half of March after the demolition of a stationary hydraulic structure. After the destruction of the hydraulic unit, water began to flow uncontrollably, without adhering to necessary speed regimes. The unsatisfactory technical condition of the canal contributed to rapid infiltration of water into the soil and led to deformation of structures and faster wear of pumps. The release of water through the North Crimean Canal coincided with a period of intense atmospheric precipitation. As a result, the supply of water proved ineffective, as water resources were not optimally used for agricultural needs. Additionally, the destruction of the dam caused serious environmental problems, including flooding of lands, which negatively impacted agriculture and natural ecosystems in the region (Kitowski *et al.*, 2023).

In 2022, the total length of channels with water was: Kherson Region 542.65 km, Zaporizhzhia Region 30.89 km, and Autonomous Republic of Crimea 366.70 km (Fig. 7). In June 2023, Russian forces destroyed the dam of the Kakhovka Hydroelectric Power Plant, causing a rapid shallowing of the Kakhovka Reservoir and flooding of the Dnipro's banks downstream (Vyshnevskyi *et al.*, 2023). The destruction led to massive water discharge, altering the hydrological regime of the canal and surrounding areas (Zgurovsky *et al.*, 2023). After the dam's destruction, the reservoir level dropped, stopping water inflow into the canal. The intensive water discharge provoked erosion of canal banks, water pollution, and changes in the regional ecosystem. Local flora and fauna suffered, and water quality issues arose. Rising water levels damaged pumping stations, hydraulic structures, and other infrastructure elements. In 2023, the total length of canal channels with water was: Kherson Region 448.41 km, Zaporizhzhia Region 27.73 km, and Autonomous Republic of Crimea 369.39 km (Fig. 9). In 2024, the total length of channels with water was: Kherson Region 298.98 km, Zaporizhzhia Region 27.73 km, and Autonomous Republic of Crimea 318.26 km (Fig. 10).


**Figure 9.** Identified water in canals, 2023
**Source:** created by the authors


**Figure 10.** Identified water in canals, 2024

**Source:** created by the authors

After the destruction of the Kakhovka Hydroelectric Power Plant, precipitation amounts and temperature fluctuations became the main factors affecting reservoir levels on the peninsula. Crimea's moderate climate means any changes in precipitation can significantly impact water availability. Rising temperatures may increase water evaporation, affecting reservoir levels. A similar situation occurred in 2020, when extremely high temperatures and insufficient precipitation caused drought and lowered reservoir levels (Table 1).

**Table 1.** Length of canal channels where water was identified, km

| Area | 2013 | 2016 | 2020 | 2024 |
|---|---|---|---|---|
| **Autonomous Republic of Crimea** | **561.34** | **335.52** | **150.17** | **318.26** |
| Azov Rice Canal | 36.51 | 30.78 | 13.65 | 28.70 |
| Connecting Canal | 30.96 | 26.77 | | |
| Krasnohvardiiskyi Canal | 58.84 | | | |
| Irrigation Canal Network (Tavriisk) | 20.74 | 19.74 | 14.47 | 15.54 |
| North Crimean Canal | 256.53 | 234.55 | 117.81 | 245.97 |
| PC-1 | 7.05 | | 2.92 | 2.92 |
| PC-2 | 1.31 | | 1.31 | 1.31 |
| PC-3 | 9.47 | | | |
| PC-4 | 7.23 | | | |
| PC-5 | 8.50 | | | |
| Rozdolne Rice Canal | 124.19 | 23.69 | | 23.82 |
| **Zaporizhzhia** | **66.75** | **91.90** | **88.02** | **27.73** |
| R-8 | 10.66 | 21.72 | 21.72 | |
| R-8-1 | | 14.09 | 3.55 | |
| R-9 | 55.68 | 55.68 | 62.34 | 16.70 |
| Kakhovka Main Canal | 0.41 | 0.41 | 0.41 | 11.03 |
| **Kherson** | **772.16** | **723.68** | **643.79** | **298.98** |
| R-1 | 33.61 | 28.94 | | |
| R-1-1 | | | | |
| R-2 | 58.41 | 58.41 | 38.58 | 38.99 |
| R-2-1 | | 25.11 | 25.13 | |
| R-5 | 40.55 | 40.58 | 40.58 | |
| R-5-1 | 54.17 | 54.17 | 54.16 | |
| R-5-2 | 25.82 | 25.86 | 25.86 | |
| R-8 | 1.27 | 1.34 | 1.34 | |
| R-9 | 0.05 | 0.05 | 0.05 | 0.05 |
| Zonal Canal | 34.62 | 36.27 | 36.27 | 7.69 |
| Kakhovka Main Canal | 117.85 | 117.85 | 117.85 | 119.18 |
| Irrigation Canal Network (Myrne, Kalanchak) | 67.70 | 77.50 | 60.59 | 39.53 |
| Novodmytrivka | 14.85 | | 12.26 | |
| O-1 | 6.97 | | | |

Table 1. Continued

| Area | 2013 | 2016 | 2020 | 2024 |
|---|---|---|---|---|
| O-2 | 5.97 | | | |
| O-3 | 14.46 | | | |
| Oleksandrivskyi Canal | 104.61 | 51.82 | 81.04 | |
| Perekopskyi Canal | | 55.25 | | |
| North Crimean Canal | 110.22 | 110.22 | 109.76 | 93.54 |
| Sirohozy Main Canal | 38.50 | 40.33 | 40.33 | |
| Chaplynskyi Canal | 42.54 | | | |

**Note:** codes indicate the branches of the channels, see Figure 1
**Source:** created by the authors

The majority of water resources necessary for the peninsula are directed towards agriculture and production. In water deficit conditions, cultivating crops like rice, vegetables, and garden plants becomes impossible. This leads to a shift towards less demanding but low-profitability crops due to reduced yields without irrigation, potentially causing a gradual decline in agricultural production. Since other water sources in Crimea are insufficient, utilising underground wells becomes a possible option for agriculture. Over the past 10 years, transporting artesian water via branches of the North Crimean Canal to eastern Crimea has been practiced. However, using this resource negatively affects both the soils irrigated and the underground sources themselves. Depleting groundwater reserves, especially for agricultural needs, will lead to the loss of this source for many decades. Additionally, changes in groundwater levels can harm regional ecosystems. Lower groundwater levels may increase salt concentrations due to infiltration of brackish water from the Black and Azov Seas, affecting water quality and availability for the population.

To ensure sustainable water supply and restore the region's agricultural potential, it is necessary to do the following. The canal infrastructure needs to be restored by repairing and modernising hydraulic structures, dams, and pumping stations to control water levels and prevent losses caused by infiltration and damage. Effective water management methods should be implemented by utilising modern technologies for monitoring and forecasting canal water levels, as well as distributing water resources efficiently among consumers. Climate adaptation strategies must also be developed, considering projected climate scenarios in water supply and irrigation planning, and introducing drought-resistant crops. Ensuring environmental safety is crucial, which involves implementing protective measures to prevent soil salinisation and water pollution. The international cooperation should be strengthened, engaging international organisations and experts to exchange experiences and resources in water management and the restoration of affected areas. Joint efforts at local, national, and international levels can overcome these challenges and ensure the region's sustainable development.

Research on the dynamics of water resources using remote sensing methods is extremely relevant due to the growing need for monitoring water systems. Under martial law conditions, commercial high-resolution images of the territory of Ukraine are not publicly available and are often inaccessible to scientific institutions even on a commercial basis for security reasons. Therefore, studying this problem can only be conducted based on open sources, which significantly complicates monitoring. Images available in open access have medium resolution, which does not provide sufficient accuracy for identifying small water bodies such as small irrigation canals. The results of the research showed significant changes in the water level of the North Crimean and Kakhovka Main Canals as a result of the temporary occupation and hostilities. These changes affected not only the water supply of the region, but also the ecological condition and agricultural activity.

Comparing obtained results with other studies, both commonalities and differences in conclusions and approaches were detected. S. Velychko & O. Dupliak (2023) studied the impact of the full-scale aggression on water bodies as sources of water supply. It was emphasised that the conduct of hostilities has a direct impact on the state of water bodies due to the destruction of water intake structures and the contamination of water with chemical substances. Obtained results confirm these conclusions, especially regarding the destruction of hydrotechnical structures in the Kherson Region and the uncontrolled inflow of water into the North Crimean Canal after the detonation of the dams.

O. Shumilova *et al*. (2023), in their analysis of the impact of the Russian-Ukrainian armed conflict on water resources, indicated multiple negative consequences for the availability and quality of fresh water for the civilian population. Threats to water infrastructure and ecosystems were identified. Paper's findings are consistent with their ones, especially regarding the risks to public water supply and agriculture from infrastructure destruction. V. Strokal & A. Kovpak (2022) emphasised military actions that negatively affected the state of water bodies and can lead to disruption of processes in water ecosystems. They noted that the destruction of water infrastructure and water pollution by heavy metals are the main consequences. Provided research confirms these aspects, in particular, regarding the pollution of water bodies due to the conduct of hostilities and the destruction of hydrotechnical structures.

A. Zubko (2022) conducted an analysis of the water-related dimensions of Russian aggression in Southern Ukraine, emphasising the critical role of water as a strategic factor in the conflict. The study highlights the strategic importance of controlling water resources, aligning with the current study conclusion that the occupation of the North Crimean Canal served not only military objectives but also economic and environmental purposes. T. Khaing & T.P.L. Nguyen (2022) examined water management in the context of armed conflict in Rakhine State, Myanmar, concluding that such conflicts exacerbate challenges in managing water resources and necessitate adaptive strategies that incorporate local community participation. While their study focused on a different region, the authors concur that conflict-driven approaches to water management must be re-evaluated, emphasising the involvement of local communities and the adaptation of strategies to evolving circumstances.

O. Zemlianska *et al.* (2023) evaluated the environmental damage to Ukraine's water resources caused by Russia's military aggression, emphasising the long-term consequences of water body pollution, infrastructure destruction, and other adverse effects on the environment and public health. The findings of this study verify these conclusions, particularly in relation to soil salinisation, ecosystem degradation, and the health risks associated with deteriorating water quality. In contrast to some experts, e.g., O. Vasyliuk & E. Simonov (2024), who proposed groundwater extraction as a sustainable long-term solution, the authors assume that it may have negative environmental consequences and is not a sustainable solution.

Based on the analysis of the above studies, several key conclusions can be drawn. Comprehensive approach to restoration: consistent with the findings of O. Shumilova *et al.* (2023), the continuation of the conflict will have negative consequences not only at the national level, but also at the global level. Therefore, a comprehensive approach to the restoration of water infrastructure is necessary, taking into account ecological, social and economic aspects. Involvement of local communities: as noted by T. Khaing & T.P.L. Nguyen (2022), the participation of local communities in water management is critical. This will help to adapt management strategies to the real needs and conditions of the region. Monitoring and assessment of environmental damage: O. Zemlianska *et al.* (2023) emphasised the importance of systematic monitoring and analysis of the consequences of military aggression. The authors support this perspective, as it is necessary to develop algorithms for assessing losses and mechanisms for minimising economic losses. Restoration of irrigation systems: given the importance of irrigation for agriculture, restoration and modernisation of irrigation systems to ensure food security should be a priority.

## Conclusions

The study results demonstrated the significant impact of temporary occupation and hostilities on the water conditions of the North Crimean and Kakhovka Main Canals. Analysis of satellite images from 2013 to 2024 revealed substantial changes in the lengths of water-filled canal channels, directly correlating with geopolitical events and military conflicts in the region. The annexation of Crimea in 2014 led to the cessation of Dnipro water supply through the North Crimean Canal, causing a sharp decrease in water availability and negatively impacting agriculture and the ecological state of Crimea and the Kherson Region. The total length of channels with water decreased from 561.34 km in 2013 to 389.60 km in 2014. The shallowing and drying up of the canal's branches led to degradation of agricultural lands, reduced yields, and deterioration of the region's ecological state. To compensate for the absence of Dnipro water, alternative sources like groundwater were developed. However, these measures could not meet regional needs and led to aquifer depletion and soil salinisation.

Following the full-scale invasion in 2022, dams in the Kherson Region were destroyed to fill the North Crimean Canal – the canal's water-filled length increased from 192.02 km in 2021 to 366.70 km in 2022. However, uncontrolled water inflow led to flooding, bank erosion, and infrastructure damage, negatively affecting ecosystems, water quality, and posing threats to the local population and agriculture. Climate change, particularly rising temperatures and uneven precipitation distribution, further complicates water supply in Ukraine's southern regions. Increased temperatures boost evaporation rates, reducing available water resources and intensifying arid conditions. Further research in this area is critically important for understanding the long-term consequences of occupation and military actions on the region's water resources. A comprehensive approach to solving canal water issues will aid in restoring the economic potential of Ukraine's southern regions and improving the quality of life for the local population.

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## Conflict of Interest

None.

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# Вплив тимчасової окупації та бойових дій на водний стан Північно-Кримського та Каховського магістральних каналів

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**Анотація.** Мета роботи полягала в дослідженні динаміки водних ресурсів Північно-Кримського та Каховського каналів із 2013 по 2024 роки за допомогою методів дистанційного зондування. У дослідженні використано супутникові знімки Landsat 8 OLI/TIRS L2 (2013-2015) та Sentinel-2 L1C (2016-2024). Застосовано модель глибинного навчання «Water Body Extraction (SAR) – USA» на основі даних Sentinel-1 C band SAR GRD VH. Використано нормований різницевий водний індекс для виявлення водних поверхонь. Виконано ручне оцифрування каналів на основі часових композитів супутникових знімків за досліджуваний період. Аналіз супутникових знімків показав суттєві зміни у водних умовах каналів через природні та антропогенні фактори. Після анексії Криму у 2014 році припинення постачання води з Дніпра призвело до висихання каналів на півострові, негативно вплинувши на сільське господарство та екосистеми через засолення та деградацію ґрунтів. У 2015 році довжина каналів із водою в Криму зменшилася до 161,65 км. Альтернативні джерела, такі як артезіанські свердловини, частково компенсували відсутність води, але призвели до виснаження підземних вод. З 2016 по 2021 рік довжина каналів із водою в Криму продовжувала зменшуватися, досягнувши 150,17 км у 2020 році. У 2022 році, після руйнування дамб у Херсонській області, відбулося неконтрольоване заповнення каналів водою. Через деградацію інфраструктури значна частина води інфільтрувалася у ґрунт, спричиняючи втрати водних ресурсів. У 2023 році руйнування дамби Каховської ГЕС призвело до обміління Каховського водосховища та змін у гідрологічному режимі каналів, зменшивши довжину каналів із водою у Херсонській області до 448,41 км, а у 2024 році до 298,98 км. Ці події спричинили ерозію берегів та зниження рівня підземних вод, що негативно вплинуло на сільське господарство через зменшення зрошуваних площ

**Ключові слова:** динаміка; зрошення; глибинне навчання; просторовий аналіз; дистанційне зондування; водна безпека