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RESEARCH ARTICLE

Initial stages of revegetation at the bottom of the drained Kakhovka Reservoir (Ukraine): synthesis of field surveys and remote sensing

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Abstract. On June 6, 2023, the dam of the Kakhovka Hydroelectric Power Plant was intentionally demolished by Russian troops, who detonated pre-deployed explosives, causing an environmental catastrophe in the Northern Black Sea region. Despite the severe environmental and socioeconomic repercussions, the disaster offered unique opportunities to study vegetation development in the long-flooded but now exposed area. The aim of the present study was to reveal and demonstrate the initial stages of formation of the flora and vegetation in the area of the former Kakhovka Reservoir, combining field research data (flora and vegetation surveys and observations, etc.) and remote sensing techniques (calculation of vegetation indices, supervised machine learning classification, etc.). We visited the area in June and October 2023 and in May 2024; during these visits we georeferenced and outlined various habitat types. These field data were used for geospatial modeling. Our studies found that the number of taxa of vascular plants in the area increased nearly 14 times during the year, thus contradicting initial pessimistic predictions and scenarios of desertification, ruderalization, and large-scale invasions of invasive alien species. We identified main types of newly formed terrestrial habitats, including willow and poplar thickets, marshy habitats, mud-, sand- and shell-covered areas with sparse vegetation. Remote sensing methods, augmented by machine learning techniques, complemented these findings, providing detailed habitat maps for the entire reservoir bed. This study contributes to our understanding of ecological successions and habitat dynamics in post-catastrophic landscapes, informing future management strategies for such areas.

Keywords: dam breach, floodplain, habitats, machine learning, restoration, vegetation

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Introduction

Overexploitation of water resources, including over-regulation of river basins, is a major concern both in terms of water quality and biodiversity loss (Poff et al., 1997). The EU Biodiversity Strategy sets the target to make at least 25,000 km of rivers free-flowing again by 2030, by removing primarily obsolete barriers and restoring floodplains and wetlands (European Commission, 2021).

The drawdown of large and small reservoirs is usually planned and gradual. In the USA, for example, more than 450 dams have been removed during the last century (Graf, 2003; Aube et al., 2007; see also updated information in: American Rivers, 2019–onward). There are positive ecological aspects of reservoir drawdowns, e.g. restoration of natural flow and habitats of wildlife (such as mule deer), no barriers to migratory fish passage, etc. (Poff et al., 1997; Lenhart, 2003; Stanley, Doyle, 2003). Potential risks include the introduction of invasive alien species and slow recovery of natural vegetation (Bednarek, 2001; Stanley, Doyle, 2003; Aube et al., 2007). However, it has been found that invasive species appeared to be much less abundant than initially expected (Prach et al., 2019). Data on the initial stages of succession and the formation of new habitats in drained areas following the release of water as a result of dam failure are reported from the US (Acker et al., 2008; Peterson et al., 2025). Furthermore, various environmental aspects of dams functioning (Johansson, Sellberg, 2006; Schleiss, Boes, 2011) and consequences of deliberate dam removal were also considered (Shafroth et al., 2024, etc.).

However, when the Russians blew up the dam of the Kakhovka Hydroelectric Power Plant on 6 June 2023, similar processes occurred immediately and catastrophically, which triggered a large-scale ecological disaster (Naddaf, 2023; UNEP, 2023; Stone, 2024; Shumilova et al., 2025), directly or indirectly impacting the ecosystems of the Northern Black Sea region in Ukraine and adjacent countries. The socioeconomic connections established in the transformed landscape of the Black Sea lowland over the past 70 years since the reservoir's construction were severed and disrupted. Despite the negative environmental and socioeconomic consequences (Vyshnevskyi et al., 2023), the disaster presented a unique opportunity to observe vegetation development over a vast area that had been flooded for more than six decades. This is what makes the case of Kakhovka so globally remarkable. Unlike the aforementioned examples from the USA, renaturalization in Ukraine was not planned — it is happening naturally, creating a unique "natural testing ground" for science.

Shortly after the water level stabilized, satellite images revealed large drained areas at the Kakhovka Reservoir site. Speculations regarding further scenarios at the reservoir's bed were mostly pessimistic, including the potential release of dried silt contaminated with heavy metals into the air (Naddaf, 2023), and local territorial and ecological expansions of invasive alien plants (UNEP, 2023). The possibility of desertification of this territory is also still being considered (Pichura et al., 2025). These hypotheses could only be tested on-site by examining the actual development of vegetation in the drained areas of the former Kakhovka Reservoir.

However, due to the area's location in the zone of active hostilities (the Right Bank has been liberated by the Ukrainian Armed Forces, while the Left Bank is still occupied by Russian troops), the majority of its territory remains inaccessible to field surveys. In this regard, the role of remote methods for tracking the processes occurring at the bottom of the former reservoir has increased. Multispectral optical images, provided by space missions like Sentinel or Landsat, proved to be valuable data sources for habitat and vegetation mapping (Xie et al., 2008; Fassnacht et al., 2016). Augmented with machine learning techniques for supervised image classification, e.g., Random Forest (RF), Support Vector Machine (SVM), or Classification and Regression Tree (CART), they allow researchers to produce large-scale habitat maps (Gislason et al., 2006; Myroniuk et al., 2020; Kennedy et al., 2021). However, none of these methods can produce accurate habitat maps without reliable and representative on-site training data (Elmes et al., 2020).

There were attempts to assess the overgrowth rate at the former reservoir's bed using satellite imagery data only (Dovhanenko et al., 2024; Shumilova et al., 2025) or combined with on-site observations (Vyshnevskyi, Shevchuk, 2024; Pichura et al., 2025). Due to the lack of solid on-site data, that research mostly operated with general or purely descriptive vegetation categories like "willow" or "dense vegetation", and could not reveal exact plant species composition at the site. On the contrary, a few purely on-site research revealing vegetation structure *in situ* (Didukh et al., 2024; Lisovets et al., 2025) were

Table 1. **Characteristics of the studied localities within the bottom of the former Kakhovka Reservoir**

Location number	Location name	Date	Coordinates of the studied locations, DD.DDDDDD°	
			Latitude	Longitude
1	Mylivska gully	30 June and 19 October 2023	47.085307	33.651769
2	Mylivska gully	30 June and 19 October 2023	47.084841	33.642884
3	Kamianka gully	30 June and 19 October 2023	47.004603	33.581268
4	Khortytsia Island	21 May 2024	47.812642	35.142283
5	Khortytsia Island	21 May 2024	47.811732	35.143677
6	Khortytsia Island	21 May 2024	47.791329	35.145560
7	Malokaterynivka village	22 May 2024	47.653495	35.248407
8	Kanivske village	22 May 2024	47.681092	35.112919

unable to extrapolate the obtained results over the whole reservoir's area. Thus, only a fusion of field, satellite and machine learning methods can solve the issue of monitoring of vegetation and habitats at the drained bottom of the Kakhovka Reservoir.

In this article, we provide an overview and description of the flora and habitats forming at the bottom of the former reservoir based on field data. Combining remote sensing and machine learning methods together with collected field data, we also trace habitat dynamics and provide high-resolution habitat maps for the whole reservoir bed for the first year after the dam breach. Additionally, we discuss the habitat transformation processes currently underway.

Methods

Study area

The former Kakhovka Reservoir was 230 km long, with an average width of 9.4 km and the maximum width of 24 km. Its surface area was 2,155 km². The total coastline length was estimated at 896 km (Heohrafichna…, 1989–1993). The climate of the area is warm and temperate. The mean yearly temperatures recorded vary from 10.7 °C (Zaporizhzhia, the northern part of the reservoir) to 11.6 °C (Nova Kakhovka, at the southern part of the reservoir). The mean precipitation varies from 505 mm in Zaporizhzhia to 449 mm in Nova Kakhovka (Climate-Data.org, 2025–onward). In the northern part of the reservoir, particularly on Khortytsia Island, silicate rocks, including granite, are exposed on the surface (Khodosovtsev et al., 2022), while in the southern part, limestone outcrops are exposed (Khodosovtsev et al., 2025). Also, in the northern part of the reservoir within Zaporizhzhia Region (Oblast), the banks of the former reservoir are covered with sand deposits, and in the southern part, thick shell deposits have formed at the bottom of the former reservoir. These are the remains of dead mollusks, mainly taxa of the genus *Dreissena*, which formed in the waters of the reservoir during its existence (Didukh et al., 2024).

An analysis of literature sources showed that before the creation of the reservoir, there were at least 31 types of habitats corresponding to those listed in the *National Catalogue of Habitats of Ukraine* (2018), including 7 types of tree and shrub, 11 types of meadow and marsh, 2 psammophytic, 3 petrophytic, and 8 aquatic habitat types (Vasyliuk et al., 2024).

Field sampling

The field data were collected during three field visits to the territory of the drained reservoir's bed: 25 days after the destruction of the Kakhovka HPP dam (June 30, 2023), Kamianska Sich National Nature Park, then 4.5 months (October 19, 2023), and 11.5 months after the dam breach (May 25, 2024). Eight locations distributed across the two sites were surveyed: the Kamianska and Mylivska gullies within Kamianska Sich National Nature Park in Kherson Region (Oblast), the southwestern part of the reservoir, and Khortytsia Island, vicinities of Malokaterynivka and Kanivske villages in Zaporizhzhia Region (Oblast), the northern part of the reservoir (Table 1, Fig. 1).

To ensure a comprehensive detection of all vascular plant species, transects were randomly established along and across the bottom of the former bays. Within the surveyed sites, we mapped habitats using GPS and high-resolution satellite images to prepare ground truth data for machine learning habitat mapping.

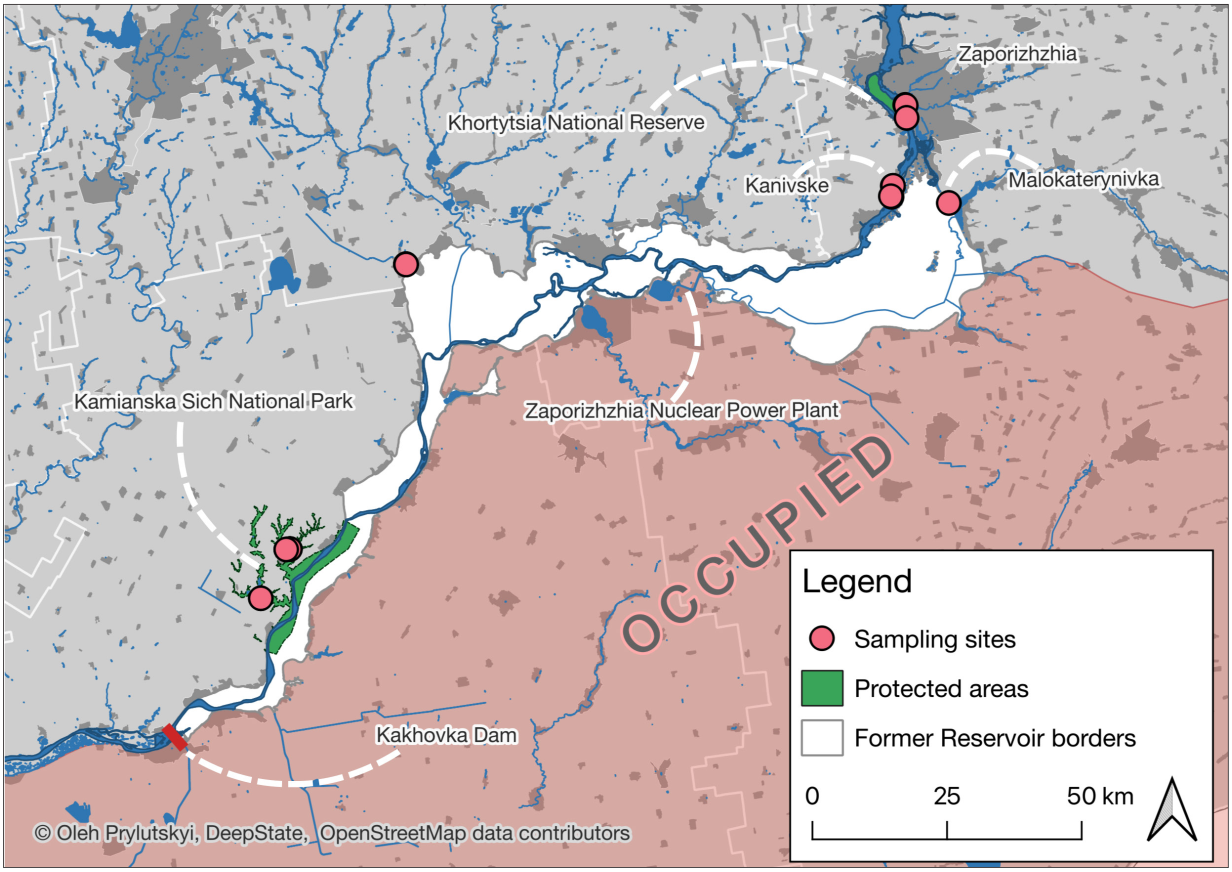

Fig. 1. The map of the surveyed locations

The nomenclature of higher vascular plants mainly follows the *Plants of the World Online* (POWO, 2024–onward). Habitat identification was based on the EUNIS (European Nature Information System) classification (Schaminée et al., 2018; EUNIS…, 2019), as well as the Interpretation Manual of European Union Habitats (2013).

Vegetation indices

To analyse the dynamics of water discharge and vegetation development at the bottom of the reservoir, we used a time series of multispectral data from the Sentinel-2 Level 2A satellite with a spatial resolution of 10 meters (Copernicus, 2023). The criteria for selecting the images for analysis were correspondence to the on-site surveys, as well as the absence of optical obstacles (clouds) that prevent the reflection of the land/water surface. We acquired five images in total: taken a day before the dam was blown up (5 June 2023), closest to the first (20 June 2023), second (7 November 2023) and third (25 May 2024) surveys, as well as intermediate between the first and second survey (19 August 2023). For all images, we calculated two common spectral indices: the Normalized Difference Water Index (NDWI) and the Normalized Difference Vegetation Index (NDVI). NDWI index is defined as the normalized difference between near-infrared and green bands, while NDVI index uses the normalized difference between near-infrared and red bands. Both indices are widely used for mapping water and vegetation, respectively (Gao, 1996; Pettorelli et al., 2005), and they can be used for differentiating moist and vegetated areas (Rogers, Kearney, 2004). We chose this combined approach because NDWI effectively masks water bodies before terrestrial habitat analysis, while NDVI index allows us to distinguish between vegetated and sparsely vegetated surfaces. We calculated both indices using the raster calculator tool in QGIS 3.4.5-Madeira (QGIS.org, 2024).

To determine the threshold value of the NDWI index separating water from other habitat types (set at -0.04), we performed a visual verification. This process involved field photographs and high-resolution satellite imagery to accurately delineate water and land areas along the Dnipro River and its tributaries. The absence of urban surfaces allowed us to clearly separate water surfaces, including shallow water surfaces overgrown with vegetation. To interpret the vegetation index NDVI, we used habitat mapping data based on the results of field surveys, as well as on the identification of photographic materials and their exact location by characteristic terrain features for locations inaccessible to the survey.

We first established distinct training areas for subsequent classification, relying on on-site habitat mapping and ground-truthing photographs that were verified based on precise location and time. By calculating the average spectral reflectance (NDVI) within these verified habitat samples, we were able to identify more generalized habitat classes with clearly discrete NDVI values. As a result, the generalized classes included habitats with closed vegetation (Habitat Group 1), including marshy vegetation (Habitat 1.2) and willow thickets (Habitat 1.1), with an average NDVI value of 0.74 as of 7 November 2023, and habitats with open vegetation (Habitat Group 2), including shell and sandy sediments (Habitat 2.2) with an average NDVI value of 0.08, as well as muddy sediments with sparse vegetation (Habitat 2.1) with an average NDVI value of 0.22 at the date. Also, based on the values of all pixels in the field study and photograph verified areas, we identified the threshold values of the index that can be used to separate Habitat Group 1 from Habitat Group 2 — 0.37, which corresponds to the minimum values of the index for marshy vegetation and effectively matches the maximum values of the index for sparse vegetation on shell, sandy, or muddy sediments. In addition, a group of water bodies and watercourses (Habitat Group 3) was identified.

Geospatial modelling

Using the Google Earth Engine (GEE) cloud computing platform (Gorelick et al., 2017), we applied supervised machine learning classification of satellite multispectral image to make a fine-scale (10 m per pixel) habitat maps of the former Kakhovka Reservoir bed. As input data, we choose harmonized Sentinel-2 Level 2A Surface Reflectance images (Copernicus, 2023) obtained through the GEE Data Catalog (https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR_HARMONIZED), for two dates: 18 October 2023 (second survey) and 25 May 2024 (third survey). Optical bands (B2-B12) were selected, clipped by the contour of the pre-dam burst water surface boundaries, defined based on NDWI at the previous step, cleaned from remaining clouds and cloud shadows, and mosaicked following GEE's Sentinel-2 routine.

As ground truth data, we used spatial polygons of the four terrestrial habitat types, mapped during field sampling (25 for the year of 2023, 31 for 2024). To expand spatial coverage of training data, we also added six polygons with known habitat types from the northern part of the reservoir. To be used for the modeling, such polygons must have met the following criteria: (i) be applicable to accurate georeferencing from input photographic materials and (ii) represent habitat types that corresponded to habitat types delineated during field surveys. The total area of ground truth was 40.3 ha. Ground truth data were randomly split into the 70% training data used further for model fitting, and 30% validation data saved for testing model performance. Since we had only survey data for terrestrial habitat types, we manually added training data for water bodies using natural colors Sentinel-2 images and NDWI values for them, 33 polygons in total. Then, we classified the composite using a Random Forest algorithm (Ho, 1995) with 30 trees, estimating classification performance through the confusion matrix, overall accuracy, and Cohen's Kappa. The number of trees was chosen based on preliminary exploration data, as though the values over 30 did not result in accuracy increase, but caused heavier computational load. The resulting maps did not change with higher parameters.

Data and code availability

All data, including plant survey results, rasters of vegetation and water indices, ground truth polygons for Random Forest training, as well as codes to reproduce satellite image preparation and classification, are publicly available at https://github.com/olehprylutskyi/kakhovka_vegetation_habitats under the MIT license. The high-resolution habitat maps for October 2023 and May 2024 are accessible online at https://ee-olegpril12.projects.earthengine.app/view/kakhovka-habitat-map-oct-2023.

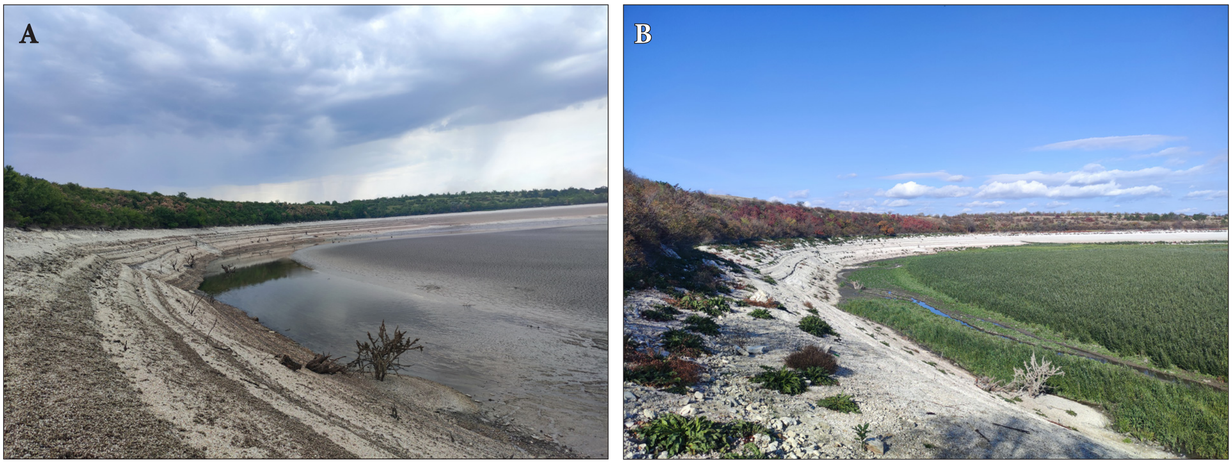

Fig. 2. General view of the bottom of the former Kakhovka Reservoir in the drained Respublikanets Bay in the Kamianka Gully. A: 30 June 2023, with the watercourse (Kamianka River) and shell sediments; B: 19 October 2023, with the willow forest and marshy vegetation along the watercourse. Photo: O. Khodosovtsev

Results

Plant species composition

In June 2023, we detected 10 species of higher vascular plants in the surveyed areas of the former reservoir bottom, while in October 2023 we recorded 68 species (see Supplementary Table S1). The total number of species detected by the end of the third survey reached 147, including 145 taxa of vascular plants and two identified species of bryophytes.

Interpretation of habitats based on survey data

Based on the data from our field surveys, we identified three distinct habitat groups at the bottom of the former reservoir: habitats with closed vegetation (Habitat Group 1), habitats with open vegetation (Habitat Group 2), and ponds and watercourses (Habitat Group 3).

The most prevalent habitat type within the first group was willow and poplar thickets (Habitat 1.1), characterized by the dominance of willow, a hybrid of the native species *Salix alba* L. and the long-naturalized alien species *Salix fragilis* L., known as *Salix ×rubens* Schrank. Alternatively, this hybrid is treated as *Salix ×fragilis* L. s. str., resulting from supposed crosses between *S. alba* and *S. euxina* I.V. Belyaeva (*S. fragilis* sensu auct.) (Belyaeva, 2009; POWO, 2025–onward); for an overview of the problem, see Marchenko and Kuzovkina (2022) and Stalažs (2024), and references therein. Resolution of these nomenclatural and taxonomic controversies is beyond the scope of the present research; thus, for purely pragmatic reasons, we follow here the traditional nomenclatural convention and use the name *S. ×rubens* for this hybrid that dominates the willow thickets in the study area.

In other areas, usually with light sandy soils, *Populus nigra* L. prevails. Among shrubs, *Tamarix ramosissima* Ledeb. is the most widespread taxon. The herb layer is dominated by species characteristic of natural floodplain willow-poplar forests, such as *Carex otrubae* Podp., *Epilobium hirsutum* L., *Lycopus europaeus* L., *Phalaris arundinacea* L., *Mentha aquatica* L., *Lythrum salicaria* L. These habitats also host two species of bryophytes, *Funaria hydrometrica* Hedw. and *Marchantia polymorpha* L.

During our initial visit to the former reservoir, we observed the first stage of formation of this habitat type, with the entire bottom covered in willow seedlings at a very high density — averaging 90 per 1 m^2. Upon our second visit, we witnessed dense willow thickets spanning large areas of the former reservoir bottom (see Fig. 2). Over the 111-day period between our first and second surveys, the average plant height increased from 0.5 cm to 190 cm, with a maximum height of 309 cm. This indicates highly favorable conditions for the formation of this habitat type, with an average daily growth rate of 1.7 cm. In May 2024, the average height of the willows was already about 3 m, with the maximum height of 4.7 m recorded. In the northern part of the former reservoir, we also observed pure poplar thickets formed by young plants of *Populus nigra* L., which are formed mainly on sandy sediments and in drier conditions as compared to those of willow thickets. The average height of poplar thickets was about 1.5 m, with the maximum measured height of 1.97 m.

Visually, much smaller areas were occupied by another type of habitat with closed vegetation, namely, the marshy habitat (Habitat 1.2). We did not observe such habitats during our first visit in June 2023, only noted a few reed seedlings at that time. However, these habitats were already well-formed by October 2023 along the permanent watercourses. The most common species in these communities are *Phragmites australis* (Cav.) Trin. ex Steud. s.l., *Typha angustifolia* L., *T. latifolia* L., *Oenanthe aquatica* (L.) Poir., and *Rumex hydrolapathum* Huds.

The second group of habitats (Habitat Group 2) consisted of the muddy sediments with sparse vegetation (Habitat 2.1), as well as communities formed on shell and sandy sediments (Habitat 2.2). These substrates are generally composed of alluvial fine- and medium-grained sandy, sandy-loamy, and silty bottom sediments. Polygonal, fissure-divided plates, mostly pentagonal and hexagonal, are clearly visible on the redeposited, well-dried sandy loam-clay deposits. The cracks between these plates were deep due to the thick drying layer, which represented the entire thickness of the bottom silt. In June 2023, the depth and width of the cracks on the still-wet substrates ranged from 3 to 25 cm and 0.5 to 4 cm, respectively. The plates of cracked silt averaged 43 cm wide. After 3.5 months, the average depth and width of the cracks increased by an average of seven times. This structure indicates intensive drying of the dense, viscous substrate and insufficient precipitation during the season of 2023. While the silts, despite their structural features and moisture regime, are intensively overgrown with willow, the vegetation on the shell and sandy deposits was rather sparse and mainly consisted of annuals, e.g., *Lactuca tatarica* (L.) C.A. Mey. or *Portulaca oleracea* L. s.l. In addition, species of plants characteristic of wet grasslands have been observed on muddy deposits. These include, for example, *Alopecurus aequalis* Sobol., *Dactylis glomerata* L., *Geum rivale* L., *Poa palustris* L., *Ranunculus sceleratus* L., etc. We also found terrestrial forms of *Nuphar lutea* (L.) Sm. on muddy deposits. The species composition on shell deposits is interesting. In addition to annuals that are not demanding on soil fertility (e.g., *Amaranthus albus* L., *A. retroflexus* L., *Digitaria sanguinalis* (L.) Scop., *Eragrostis minor* Host), species of plants characteristic of steppe habitats (*Glycyrrhiza echinata* L., *Medicago falcata* L., *Coronilla varia* L., etc.) were found here, whose diaspores were obviously washed away from the surrounding steppe slopes. *Bromus tectorum* L., *Calamagrostis epigejos* (L.) Roth, *Cynodon dactylon* (L.) Pers., *Plantago indica* L., *Trifolium arvense* L. are the most characteristic species for sandy deposits. It should be noted that shell sediments prevailed in the southern part of the reservoir, and sandy sediments in the northern part.

Reservoirs and watercourses (Habitat Group 3) consisted of the riverbeds of the Dnipro River and its tributaries, which were flooded by the reservoir and have re-established their beds following its disappearance. An example is the Kamianka River, whose restored riverbed we observed in June and which, at least visually, remained stable until October 2023, except for the formation of riparian vegetation along its banks. In certain areas of the floodplain, depressions formed temporary reservoirs that dried out rather quickly and were also overgrown with riparian vegetation on their periphery. However, during the year of observation, we did not find any aquatic macrophytes in these reservoirs and watercourses.

Habitat mapping based on remote sensing data

By utilizing an empirically derived threshold value of the Normalized Difference Vegetation Index (NDVI), we identified two composite classes of surface covering the entire territory of the former reservoir bed, corresponding to the terrestrial habitats that we identified during field surveys. These classes included conditionally closed vegetation (Habitat Group 1), comprising willow and poplar thickets and marshy communities, and conditionally open vegetation (Habitat Group 2), encompassing sparse vegetation on muddy, shell, or sandy sediments. We also utilized NDWI water index thresholds to map open water surfaces, constituting Habitat Group 3. Four months after the dam's destruction, the total area of open water surfaces was 256.5 km^2.

By evaluating threshold values of spectral indices from multi-temporal images, we tracked the dynamics of water level decline and the concurrent development of closed vegetation (Fig. 3). The chronological sequence of vegetation and water conditions demonstrated an evident and

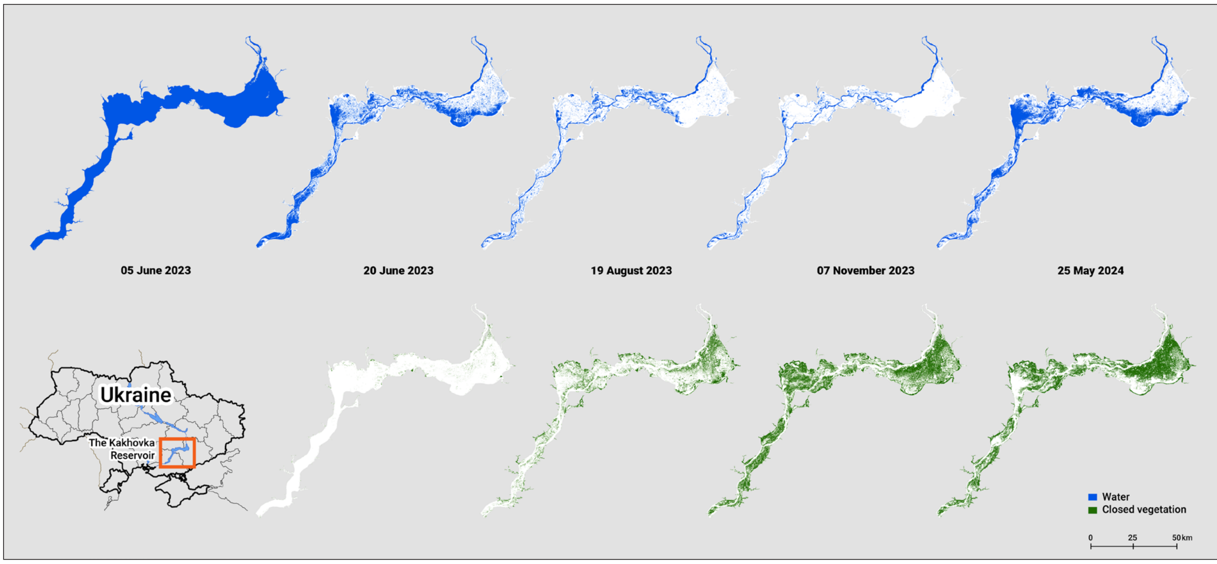

Fig. 3. Water release from the Kakhovka Reservoir bed and vegetation growth on the exposed area (based on NDWI index). In the initial months following the Kakhovka dam breach, the water receded swiftly, gradually revealing old streams and swampy areas that existed before the reservoir was constructed. As the water drained rapidly at first and then more slowly, vast stretches of newly formed land became accessible, creating prime conditions for rapid vegetation colonization (based on NDVI index). In the spring of 2024, the seasonal flood of the Dnipro River has raised the water level again

anticipated restoration process of the natural hydrological state of the river floodplain, accompanied by rapid development of green photosynthetic mass, which correlated with the first group of habitats featuring closed vegetation.

To generate a detailed habitat map for the entire territory of the former reservoir at the moments of the second field surveys (refer to Fig. 4, available for viewing online at https://ee-olegpril12.projects.earthengine.app/view/kakhovka-habitat-map-oct-2023), we leveraged supervised classification of Sentinel-2 multispectral satellite images. The results of the field survey, extended with additional sites from the northern part of the reservoir with known habitat types, served as ground truth for training the Random Forest model. The diagnostic performance of the model was exceptionally high, with an overall accuracy of 0.99 and Cohen's Kappa coefficient of 0.98. The Confusion matrices built on validation datasets (Supplementary Tables S2, S3) indicated only minor confusion between willow thickets and marshy vegetation. The distinction among the other classes was very robust.

The model confirms the findings of the vegetation indices analysis, indicating that as of October 2023, half of the bottom was covered with closed vegetation. Different habitat types are distributed in a mosaic pattern across the territory. Willow and poplar thickets (Habitat 1.1) covered a total area of 614.6 km^2, mostly located in the southern part of the former reservoir, as well as in coastal areas along its entire length. Marshy vegetation (Habitat 1.2) is estimated to cover 332.1 km^2 and tends to occur in near-terrace depressions and bottom hollows. Drying muddy sediments (Habitat 2.1) comprised a total of 70 km^2, with the highest density observed in the central part of the former reservoir, on the right bank of the restored Dnipro riverbed. The largest surface class was shell and sand sediments (totalling 718.5 km^2) (Habitat 2.2), mostly localized on the left bank of the restored Dnipro riverbed in the central and northern, the widest, parts of the former reservoir. The remaining water-covered areas constituted 406.8 km^2.

Seven months later, in May 2024, 48% of the former reservoir (1031.1 km^2) were covered by water due to a seasonal spring flood of the Dnipro River. The area covered by sparse vegetation on shell and sandy sediments decreased near triple (to 247.9 km^2), whereas other terrestrial habitat types remains generally of the same areas (willow and poplar thickets — 611.8 km^2, marshy vegetation — 188.6 km^2, sparse vegetation on muddy sediments — 62.6 km^2). At the same time, by-pixel

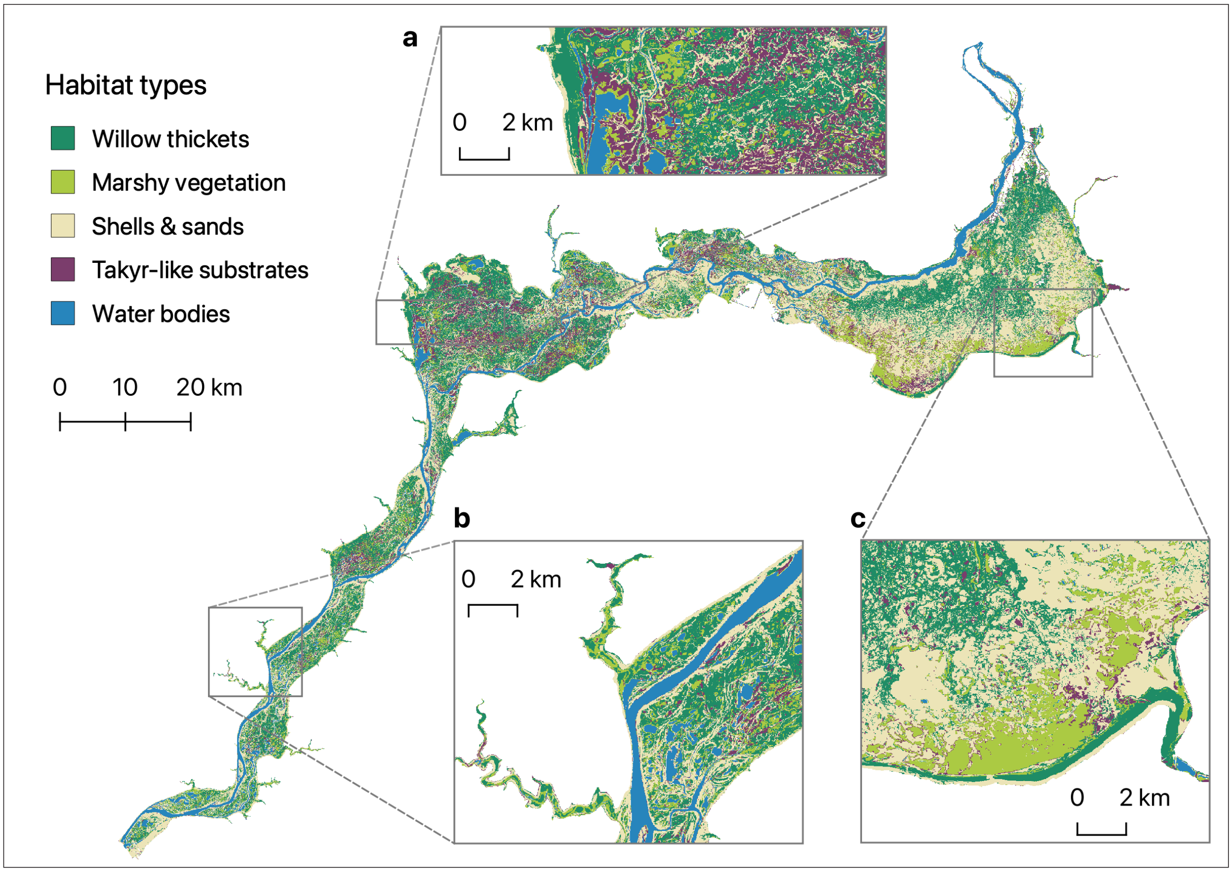

Fig. 4. Distribution of habitat types of the former Kakhovka Reservoir, as of the end of the first vegetation season since the dam breach (October 2023). Pioneer land cover types there seemed to follow the original geomorphology of the Dnipro River valley. In the central part of the former reservoir (a), mostly on the right bank of the Dnipro River, sparse vegetation on muddy sediments prevailed. The southern part (b) with narrower valleys got the most developed vegetation cover, primary willow and poplar thickets. The eastern part (c), which mostly extended across the left bank of the Dnipro River, followed typical floodplain morphology, with willow and poplar thickets on elevated central part of the terrace, followed by sparse vegetation on shell and sand sediments, then marshy vegetation on near-terrace depressions, bordered by willow thickets stretched along the older and higher, not flooded terrace. Spatial prediction based on Random Forest supervised classification of Sentinel-2 satellite imagery, trained by ground truth data collected in October 2023. A scalable high-resolution web maps for October 2023 and May 2024 are available online at https://ee-olegpril12.projects.earthengine.app/view/kakhovka-habitat-map-oct-2023

change detection (Supplementary Fig. S1) showed between-class transmission, supposedly owing to changes in water cover, continuing growing of established willow and poplar trees, and alluvial processes.

Discussion

The environmental catastrophe resulting from the blowing up the dam of the Kakhovka Hydroelectric Power Plant provided us with a unique opportunity to observe the restoration of vegetation at the bottom of the former Kakhovka Reservoir. Our research has revealed that the vegetation cover formation in this area is remarkably rapid. This is facilitated by the presence of a seed bank and the relatively high moisture content of the nutrient-rich substrate. The rapid regeneration of vegetation, which stabilizes the soil structure, makes it unlikely for dried soil contaminated with heavy metals and other potentially hazardous chemicals to disperse, as concerned in some publications (Naddaf, 2023).

The timing of the dam's detonation in early June, coinciding with the ripening of willow seeds, undoubtedly contributed to the success and competitiveness of this particular plant species in colonizing newly formed substrates and establishing pioneer communities.

We have observed a clear differentiation of habitats in the surveyed areas, with significant areas of willow thickets supporting the hypothesis that it is possible to restore the vegetation cover present in this area before the reservoir was filled, known as the Velykyi Luh (meaning the "Great Meadow"), an area directly related to the history of the Ukrainian Cossacks. We believe that assertions suggesting that these primary habitats will be replaced by something entirely different in the coming years (as mentioned in Stone, 2024) are premature.

Whereas the habitats observed at the bottom of the drained reservoir are currently in the process of formation, they can already be classified according to different European habitat classification systems. Thus, the willow and poplar thickets predominant in the area can be classified as G1.11 Riverine *Salix* woodland in Resolution 4 of the Bern Convention (Revised…, 2019), as well as listed in Annex I of the EU Habitats Directive under 91E0: Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion*, *Alnion incanae*, *Salicion albae*), and 92A0: *Salix alba* and *Populus alba* galleries (Revised…, 2019), and in the *European Red List of Habitats* as G1.1 Temperate and boreal softwood riparian woodland (Janssen et al., 2016). Consequently, this habitat type is protected at the European level. Its significance lies in its ability to structure and purify soils and water by filtering nitrogen and phosphorus compounds, oil products, and adsorbing heavy and toxic metals (Gray, Sotir, 1996; Thompson, 1998; Klang-Westin, Eriksson, 2003; Vervaeke et al., 2003; Mohsin et al., 2021). Similar to the previous habitat type, marshy vegetation is protected at the European level, as it is listed in Resolution 4 of the Bern Convention as C3.2 Water-fringing reedbeds and tall helophytes other than canes, and as type C5.1a Tall-helophyte bed in the *European Red List of Habitats* (Janssen et al., 2016).

The main limitation for mapping habitats at the bottom of the former reservoir is the fact that the majority of the territory remains inaccessible due to the Russian occupation of a significant part of its left (eastern) bank and ongoing hostilities. Most of the territory is reachable for drone attacks, making field surveys dangerous. Under these circumstances, remote methods remain the only reasonable option. Supervised machine learning classifications of Earth Observation data are robust solutions (Rodriguez-Galiano et al., 2012), but they require extensive and representative ground-truth data. In our case, the data point locations were primarily determined by safety concerns. Hence, they better represent the habitats of the southwestern, western, and northern banks of the former reservoir as compared to the eastern part. For this reason, we had to treat the communities formed on shell and sandy sediments (Habitat 2.2) as a single class, since the majority of sandy sediments were allocated close to the left, still occupied bank.

The confusion matrix built upon validation data showed good class separability (Supplementary Tables S2, S3), likely due to the system's simplicity and the low number of classes. Minor intermixture took place only for closed willow and poplar thickets and marshy vegetation (0.007% of misidentifications for 2023, 0.01% for 2024). The main cause of confusion is supposedly the tendency for some sites covered by marshy vegetation to overgrow with willow and poplar thickets over time and drying.

We can expect the formation of a more complex habitat system over time, with diverse transitions among types due to different histories of patch initiation and flooding/overgrowth. That will require revising the habitat type classification and collecting new ground-truth data for future habitat mapping attempts.

The further development of habitats at the bottom of the former reservoir will depend on various factors, primarily weather conditions in winter and spring and the magnitude of spring floods. In the spring–early summer of 2024 we already witnessed the latter, and detected respective changes in the vegetation cover. The main changes included expansion of willow and poplar thickets and shrinking of other habitats, like areas with sparse vegetation on muddy, shell, and sandy substrated, and marshes. Some of these habitats were overgrown with willow and poplar, while others were flooded. Spring floods, alongside with the progressive growth of willow and poplar trees, disproves the idea that this area is destined to be turned into a desert. We intend to continue monitoring the processes of vegetation and habitat formation in the areas we surveyed, as well as in other areas of the former reservoir bottom, as they become available for scientific research. This information is an important component of the overall situation and will help in establishing the scientific basis for developing scenarios and options for the future destiny of this territory.

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SUPPLEMENTARY MATERIAL

This article includes Supplementary Material (Fig. S1, Tables S1–S3) available as: ukrbotj82-05-488-S1.pdf (325 KB).

ETHICS DECLARATION

The authors declare no competing interests.

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Початкові стадії відновлення рослинності на дні осушеного Каховського водосховища (Україна): синтез польових досліджень та дистанційного зондування

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Реферат. 6 червня 2023 року гребля Каховської ГЕС була підірвана російськими військами, що спричинило екологічну катастрофу в Північному Причорномор'ї. Незважаючи на важкі екологічні та соціально-економічні наслідки, катастрофа надала унікальну можливість вивчити розвиток рослинності на території, яка тривалий час була затоплена. Ми відвідали цю територію тричі: через три тижні, 3,5 місяці та 11,5 місяців після катастрофи. Наші дослідження показали, що кількість судинних рослин на цій території збільшилася майже в 14 разів за рік, що суперечить початковим песимістичним прогнозам про опустелювання. Як малорічники, так і багаторічні рослини були представлені майже однаковою кількістю, для більшості з них характерним було поширення вітром. Низька питома вага чужорідних видів спростовує гіпотезу про те, що колишнє водосховище стане джерелом інвазій чужорідних рослин. Ми виділили основні типи новоутворених наземних біотопів, включаючи зарості верб і тополь, прибережні біотопи, мулисті, піщані та вкриті черепашками території з розрідженою рослинністю. Ці дослідження були доповнені даними дистанційного зондування із використанням методів машинного навчання, що дозволило створити детальні карти біотопів для всього дна водосховища. Проведене дослідження сприяє розумінню екологічної сукцесії та динаміки біотопів у пост-катастрофічних ландшафтах, а також формуванню майбутніх стратегій управління такими територіями.

Ключові слова: біотопи, відновлення, заплава, машинне навчання, рослинність, руйнування греблі