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Recovery of Velykyi Luh through ecological restoration of the Kakhovka Reservoir

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Abstract. The relevance of modern environmental issues requires comprehensive approaches to the restoration and preservation of natural ecosystems, specifically through ecological restoration as a tool to eliminate the effects of anthropogenic interventions. The purpose of this study was to survey the territory of the Kakhovka Reservoir using remote sensing and to propose a way to restore the historical territory of the Kakhovka Reservoir of Velykyi Luh. The following research methods were employed: empirical, analysis and systematisation, remote sensing, geographic information systems. The study consisted of two main stages. The first stage included an analysis of the dynamics of the historical territory of Veliky Luh, from the end of the 19th century to the present day. The second stage involved comparing the dynamics of the area's restoration using 19th-century mapping data and 21st-century satellite imagery. The use of modern technologies, including the analysis of satellite images of the degraded area and three indices of the EO Browser software, such as the differential vegetation index, the normalised differential humidity index, and the differential water index, helped to obtain data on the state of vegetation and water resources in the study area. The analysis of the patterns between these indicators made it possible to determine the close interaction between plant growth rates and their moisture availability. The biomass growth on the territory of the Kakhovka Reservoir was measured from the moment of dewatering to

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November 2023. The results obtained indicate that it is possible to effectively restore the ecosystem of the Velykyi Luh through ecological restoration. This process involves the selection of optimal biotopes for the restoration of the historic area, which is a crucial step in conserving biodiversity and stabilising the natural environment in the Kakhovka Reservoir. The findings of the study on a new approach to ecological restoration based on high-precision technologies and in-depth analysis of ecosystem dynamics will contribute to the development of scientific approaches to the restoration of natural landscapes and will be an important contribution to modern environmental practice

Keywords: remote sensing of land; vegetation; ecology; regeneration; historical area

Introduction

In the light of current environmental challenges, addressing the loss and degradation of natural ecosystems requires the implementation of comprehensive measures, including the active use of ecological restoration. The key purpose of this aspect is to restore ecosystems affected by anthropogenic interventions and identify opportunities to use restoration as a means of eliminating the effects of human activity that adversely affects the natural environment.

It is possible to obtain information about any object or process without direct contact with them using remote sensing (RS). According to S.O. Dovhyi *et al*. (2019), remote sensing is a thematic analysis of both natural and artificially generated radiation of the earth's surface in the ultraviolet to radio wave ranges. The development of geodetic and cartographic knowledge has made it possible to link a satellite image to a concrete location on the earth's surface that it represents. S.A. Shevchuk (2022) showed that monitoring remote sensing data allows identifying hydraulic, water management, and water objects that have been damaged or subjected to negative anthropogenic impacts during hostilities. The tasks set are not trivial, but the use of modern remote sensing and geographic information technologies (GIT) helps to systematically obtain and interpret data on photometric parameters of individual water bodies and catchment areas in a wide spectral range with the necessary resolution and frequency of information updating, and to assess their sanitary and biological characteristics. C.B. Pande *et al*. (2024) considered that remote sensing provides opportunities for obtaining valuable information about various objects, enabling monitoring of the surface and the dynamics of ongoing processes, and is widely used around the world. In India, remote sensing is used to assess the soil cover in winter and to detect changes in the impact on evapotranspiration parameters. In the United States, remote sensing is used to assess high-resolution forest cover in an ecologically diverse landscape (Zurqani, 2024). Flood mapping in Pakistan is carried out using remote sensing and geographic information systems (GIS) (Ghouri *et al*., 2023). In the Kashmir Himalayas, the dynamics of wetlands are being assessed based on satellite Earth observation data (Alam *et al*., 2023). The use of remote sensing is associated not only with uninhabited areas, but also with inhabited ones, as it is also used to map and monitor cities (Kumar *et al*., 2023).

Ecological restoration is key to counteracting anthropogenic biodiversity degradation and reducing disaster risk. However, there is limited knowledge of the barriers that prevent wider adoption of restoration practices, despite the high-level political priority to halt biodiversity loss. Ecologists are looking for opportunities to turn restoration projects into long-term hypothesis-driven ecological restoration experiments, and for funding, time, and institutional support to do so. R.E. Young *et al*. (2023) identified eight principles for ecological restoration: involving stakeholders; applying different types of knowledge; obtaining information from relevant reference ecosystems, considering environmental changes; sustaining ecosystem restoration processes; evaluating against clear goals and objectives using measurable indicators; aiming for the highest degree of restoration; obtaining cumulative value when applied at large scales; and application of continuous restoration activities. The environment that has been restored after considerable human impacts on the river environment may have a higher or lower ecological value compared to the original state. However, in the context of an anthropocentric assessment, such restored environments are certainly much more valuable today than they were before the restoration programme. Ecological restoration is used to restore areas around the world. In China, W. Hong *et al*. (2024) used indices of damage to the green space ecosystem and its ability to recover to build a discrimination matrix for an ecological recovery model under 12 different scenarios. T. Alamenciak *et al*. (2023) described that forest, peatland, grassland, and lake ecosystems are being restored through ecological restoration in Canada. The practice of ecological restoration, as a deliberate activity that initiates or accelerates the restoration of an ecosystem (which has been degraded, damaged, or destroyed), factoring in its integrity and stability, includes a wide range of projects. These include erosion control, reforestation using local plant genetic resources, removal of introduced species and weeds, revegetation, reclamation of disturbed lands, river revitalisation, reintroduction of native species, and improvement of habitat and habitat quality for target species (Restoration Ecology, n.d.). The territory can be restored using various methods, including ecological restoration, reclamation, and bioremediation. P. Li *et al*. (2022) note that technologies related to ecological river restoration are essential for improving river habitat and biodiversity, as well as for restoring river ecosystem functions. Revegetation is used to artificially restore soil fertility and vegetation cover after anthropogenic disturbance of nature. The treatment of water, soil, and atmosphere using the metabolic potential of biological objects (plants, fungi, insects, worms, bacteria) or their enzymes is possible using a set of methods referred to as bioremediation.

The purpose of this study was to investigate the territory of the Kakhovka Reservoir using remote sensing and to propose a method of restoring the Velykyi Luh on the territory of the Kakhovka Reservoir.

Objectives: to study the territory of the Velykyi Luh in the historical aspect; to analyse the dewatered territory of the Kakhovka Reservoir using remote sensing; to investigate and compare the territory of the Kakhovka Reservoir during the 19th-21st centuries in the EO Browser software using the normalised differential water index, normalised differential vegetation index, normalised differential humidity index; based on the analysis, to propose optimal biotopes for the restoration of the historical territory by means of ecological restoration.

Materials and Methods

The study of the historic territory of Velykyi Luh was carried out in two stages between June and December 2023. The first stage analysed the territory of the Velykyi Luh from the end of the 19th century to 2024 on the territory of the Kakhovka Reservoir from a historical perspective. The second stage was a comparison of the dynamics of the restoration of the Velykyi Luh area using a map and 21st-century satellite images. Access was gained to the state of the vegetation on the territory of the Velykyi Luh of the Kakhovka Reservoir. To determine the relationship between plant growth rates and their moisture availability, the regularity between the normalised differential vegetation index (NDVI) and the normalised differential moisture index (NDMI) in the territory of the Velykyi Luh was analysed. The normalised differential water index (NDWI) (1) was used to analyse the dynamics of the water surface from 1990 to 2010. The normalised differential water index is the most appropriate index for mapping water bodies. Water bodies have a value greater than 0.5. Vegetation is characterised by lower values. Artificial objects have positive values from 0 to 0.2 (NDWI..., n.d.).

$$\mathrm{NDWI} = \frac{B03 - B08}{B03 + B08}, \tag{1}$$

where *B03* – Band 3 – Green – 560 nm; *B08* – Band 8 – Near infrared (NIR) – 842 nm (Table 1).

Table 1. Specification of spectral bands for the Sentinel-2 satellite

Band	Central wavelength, nm
1	443
2	490
3	560
4	665
5	705
6	740
7	783
8	842
9	865
10	1380
11	1610
12	2190

EO Browser software with access to Sentinel-2 and Landsat 4-5 TM satellites was used to determine NDVI, NDMI, and NDWI. Archival images and data from 2020-2023 were analysed. Satellite images were selected with 0% cloud coveradge. The authors received and analysed 6 data each from the NDVI and NDMI indices. EO Browser software was used for digital map processing. NDVI was calculated using formula (2) and can range from -1 to 1, where negative values indicate water:

$$\mathrm{NDVI} = \frac{B08 - B04}{B08 + B04}, \tag{2}$$

where *B08* – Band 8 – Near-infrared (NIR) – 842 nm; *B04* – Band 4 – Red – 665 nm (Table 1).

The range of NDVI values is from -1 to 1. Negative NDVI values (values approaching -1) indicate approaching water. Values close to zero (from -0.1 to 0.1) indicate a location on exposed rocks, sand, or snow. Low positive values are typical for shrubs and grasslands (approximately 0.2-0.4), while high values are typical for temperate forest vegetation (values close to 1). The index was calculated according to the emission or reflection from the red channel of about 0.66 µm and the near-infrared channel of about 0.86 µm (Gao, 1996).

NDMI is a normalised difference moisture index with near-infrared (NIR) and short-wave infrared (SWIR) bands for displaying moisture. NDMI was used to monitor changes in leaf water content. The SWIR bands depend on changes in the water content of the vegetation and the structure of the spongy mesophyll of the plant canopy. The water content does not affect the NIR but depends on the internal structure of the leaves and the dry matter content of the leaves. The NDMI was calculated and is found according to the formula (3) and can vary from -1 to 1. Negative values may indicate a water stress.

$$\mathrm{NDMI} = \frac{B08 - B11}{B08 + B11}, \tag{3}$$

where *B08* – Band 8 – Near-infrared (NIR) – 842 nm; *B11* – Band 11 – Shortwave Infrared (SWIR) – 1610 nm (Table 1).

The normalised differential moisture index (NDMI) is used to determine the moisture content of vegetation and monitor drought (NDMI..., n.d.). The range of NDMI values is from -1 to 1. Negative NDMI values (values close to -1) correspond to open ground. Values close to zero (-0.2-0.4) indicate water stress. High positive values correspond to a high vegetation cover that is not under water stress (approximately 0.4-1). Based on the data obtained, biotopes were selected for the ecological restoration of the historical area of Velykyi Luh on the territory of the Kakhovka Reservoir. The study was conducted following the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992).

Results and Discussion

Velykyi Luh is the historical name of the area, a giant river floodplain (over 400 km^2) that existed on the left bank of the Dnipro River, between the Dnipro and the left tributary of the Konka River and stretched in a wide strip along the right bank from the mouth of the Serednia Khortytsia River. The entire area belonged to the Zaporizhzhian Sich and is therefore a crucial historical monument of the Ukraine (Fig. 1) (Solodko *et al.*, 2024).

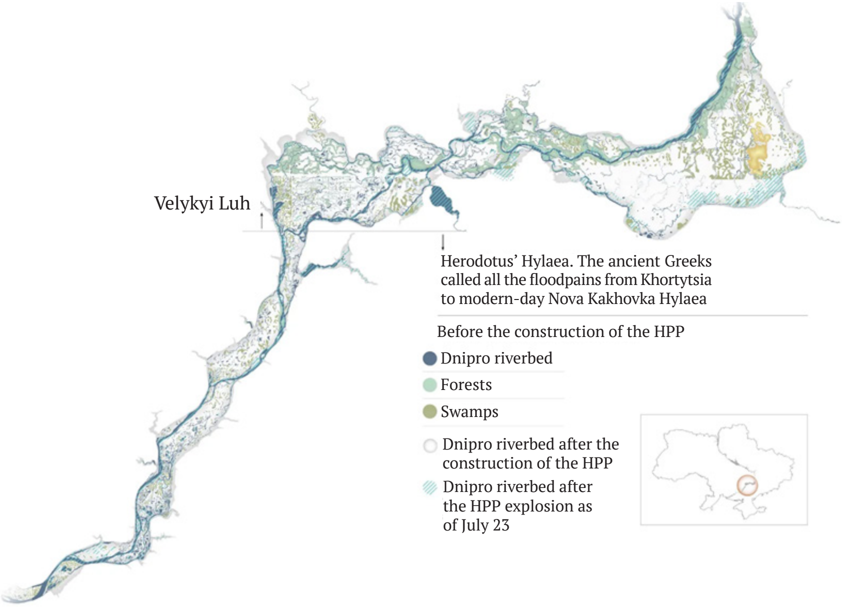

Figure 1. Velykyi Luh

Source: P. Solodko *et al.* (2024)

Velykyi Luh was flooded by the waters of the Kakhovka Reservoir (Fig. 2a) in 1955-1957, except for some areas. The reservoir was 230 km long and had an average width of 9.4 km (maximum width of 24 km). The area was 2,155 km^2 and the volume of water was 18.2 km^3. The coastline was 896 km long. As a result of the reservoir creation, about 90 villages and the historical monument of Ukraine, Velykyi Luh, where rare plants grew, were flooded (Fig. 2b). Even after the flooding of the Velykyi Luh, unique vegetation was preserved among the remains of the floodplains, including relict, endemic, and rare plant groups: *Salvinia natans* L., *Trapa natans* L., *Nymphoides peltata* (S.G. Gmel.) O. Kuntze), *Aldrovanda vesiculosa* L., *Nymphaea alba* L., *Nuphar lutea* L., *Sagittaria sagittifolia* L., *Glyceria arundinacea* Kunth, *Ceratophyllum tanaiticum* Sapjegin and *Ceratophyllum submersum* L. On the islands and elevations of the left-bank sandy terrace (arena) of the Velykyi Luh, thickets of the endemic *Betula borysthenica* Klokov have been preserved. These phytocoenosis are listed in the Green Book of the Ukraine (Veliky Luh..., 2023).

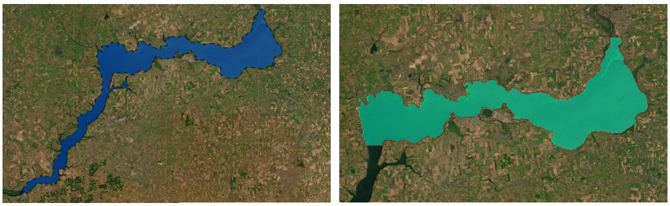
a) b)

Figure 2. Satellite images of the Kakhovka Reservoir and Velykyi Luh

Note: a) territory of the Kakhovka reservoir; b) territory of the Velykyi Luh

Source: ArcGIS Online internet service and Maxar satellite

A comparable trend was observed in Australia in the second half of the 19th century, when thousands of dams were built, including 446 large dams (crest height >10 m). Flow regulation has altered the hydrology of major rivers and is recognised as a major cause of declining conditions in many Australian river and floodplain ecosystems (Arthington & Pusey, 2003). Prior to the flooding of the Velykyi Luh area, the floodplains were inundated with water from early spring to early summer. In April, during the floods, the floodplains were almost a continuous expanse of water. The maximum water level occurred in late April and early May, and the minimum was in September and October (Petrochenko, 2009). Having investigated the dynamics of the water surface of the Kakhovka Reservoir from 1990 to 2010 using the normalised differential water index (NDWI), it was found that it stayed unchanged (Fig. 3).


a) b) c)

Figure 3. Satellite images of water surface dynamics from 1990 to 2010

Note: a) 1990; b) 2000; c) 2010

Source: EO Browser software, Landsat 4-5 TM L1 satellite, NDWI script

On 6 June 2023, as a result of the full-scale invasion, Russian troops blew up the dam of the Kakhovka hydroelectric power station, which led to the reservoir being dewatering. The water rapidly began to recede, which led to the release of the Velykyi Luh to the surface (Fig. 4).


a) b) c)

Figure 4. Dynamics of Kakhovka Reservoir dewatering and riverbed restoration (June-November 2023)

Note: a) 5 June; b) 20 June; c) 7 November

Source: EO Browser software, Sentinel-2 L2A satellite

The changes in the territory of the Velykyi Luh disturbed by anthropogenic impact, which arose as a result of the dewatering of the Kakhovka Reservoir, were analysed using the NDVI and NDMI indices in the EO Browser software. The normalised differential vegetation index (NDVI) is a simple but effective indicator for quantifying green biomass (NDVI..., n.d.). It is an indicator of vegetation health based on how plants reflect waves of light of a certain length.

Having analysed the satellite images of Figures 5a, 5b, 5c (NDVI) and Figures 5d, 5e, 5f (NDMI) for 2020, a trend was found that as of 10 June, the vegetation condition was characterised by optimal indicators (NDVI within 0.6-1 and NDMI within 0.4-1) and did not indicate the presence of water stress (Fig. 5d). As of 5 July, this indicator was deteriorating (Fig. 5e), with NDVI ranging within 0.3-1 and NDMI – within -0.2-0.4.) On 28 October, the vegetation condition went from optimal to standard (NDVI within 0.2-1 and NDMI within -1-0.4), while the area around the Kakhovka Reservoir began to show signs of water stress (Fig. 5f).

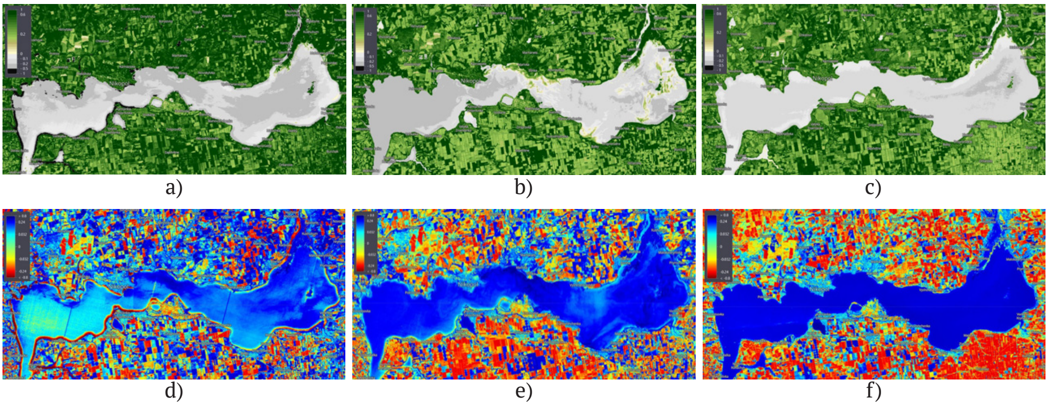
a) b) c)
d) e) f)

Figure 5. Quantification of green biomass and determination of the moisture content of vegetation in the Kakhovka Reservoir as of 2020.

Note: a) 2020-06-10 NDVI; b) 2020-07-05 NDVI; c) 2020-10-28 NDVI; d) 2020-06-10 NDMI; e) 2020-07-05 NDMI; f) 2020-10-28 NDMI

Source: EO Browser software, Sentinel-2 L2A satellite

Having analysed the satellite images in Figures 6a, 6b, 6c (NDVI) and Figures 6d, 6e, 6f (NDMI) for 2023 and compared them with analogous images of 2020 (Fig. 5a, 5b, 5c – NDVI and Fig. 5d, 5e, 5f – NDMI), the previously identified trend was recorded. There is also a difference in the 2023 indicators for June 5 (Fig. 6d, NDVI 0.8-1, NDMI 0.7-1) and November 7 (Fig. 6f, NDVI 0-0. 5, NDMI -1--0.5) compared to the 2020 indicators for 10 June (Fig. 5d, NDVI 0.6-1, NDMI 0.4-1) and 28 October (Fig. 5f, NDVI 0.2-1, NDMI -1-0.4). As of 5 June 2023 (Fig. 6d, NDMI 0.7-1), the moisture content of vegetation was significantly higher compared to 10 June 2020 (Fig. 5d, NDMI 0.4-1). However, by 7 November, the situation had changed dramatically (Fig. 6f, NDMI -1--0.5), and if by 19 August 2023 (Fig. 6e, NDVI 0.6-1, NDMI 0-0.4) the NDVI indicators were better compared to the relative humidity indicators by 5 July 2020 (Fig. 5e, NDVI 0.3-1, NDMI -0.2-0.4), the indicators for 7 November 2023 (Fig. 6f, NDVI 0-0.5, NDMI -1--0.5) were characterised by a small amount of biomass and critically lower moisture content in the vegetation around the Kakhovka Reservoir than on 28 October 2020 (Fig. 5f, NDVI 0.4-1, NDMI -1-0.4).

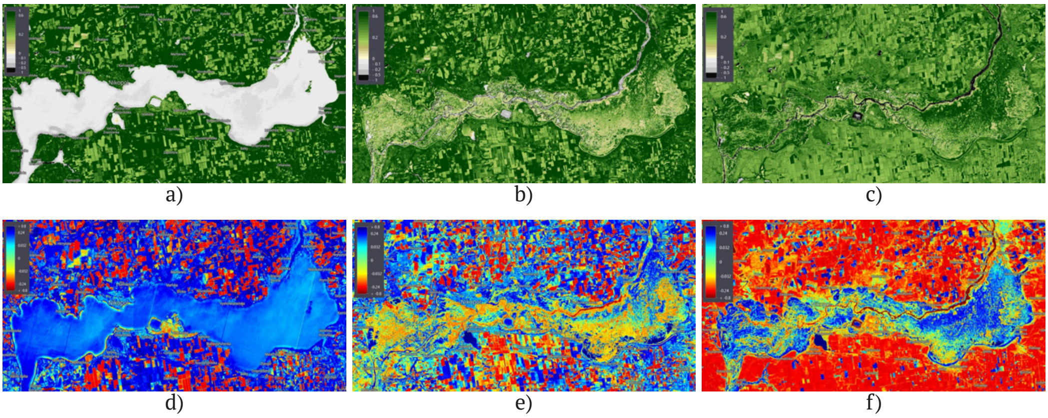

Figure 6. Quantification of green biomass and determination of the moisture content of vegetation on the territory of the Kakhovka Reservoir as of 2023

Note: a) 2023-06-05 NDVI; b) 2023-08-19 NDVI; c) 2023-11-07 NDVI; d) 2023-06-05 NDMI; e) 2023-08-19 NDMI; f) 2023-11-07 NDMI

Source: EO Browser software, Sentinel-2 L2A satellite

The method of ecological restoration is the most suitable for the restoration of historic areas. This method has a wide range of applications and is supported by accumulated experience in the environmental field. Ecological restoration should also factor in the spread of exotic plant species that can colonise a natural area. The spread of exotic populations can occur in the early stages of invasion in large natural areas that are not strictly monitored (D'Antonio & Meyerson, 2002). Invasive plants pose a considerable threat to biodiversity, ecosystem management, agriculture and forestry, etc.

Based on the analysis conducted (Fig. 5-6), it was found that the Kakhovka Reservoir contributed to the relative stability of the water balance for vegetation. After the explosion of the Kakhovka Hydroelectric Power Plant, the gradual dehydration of the reservoir led to a stressful condition of the plants, which increased over the course of six months. However, there have also been positive changes, and the water balance is now optimal as a result of natural vegetation regeneration. Thus, the vegetation that appears on the territory of the reservoir is not subject to water stress (NDMI approximately 0.4-1) and contributes to the formation of the necessary moisture. As a result, ecological restoration and biotopes restoration will contribute to the formation of the necessary water balance in this area. When carrying out ecological restoration, it is necessary to factor in the impact of exotic species that may complicate the restoration process. At the same time, there may be circumstances where their removal may have unintended negative consequences or their use for restoration is desirable (D'Antonio & Meyerson, 2002). To achieve a sustainable outcome in restoring former coastal environments, a balance must be struck between ecological and human objectives (Chenoweth, 2006).

The area of the Velykyi Luh study area was measured (Fig. 7), which is 1,615.8 km^2, and the dynamics of biomass increase during August-November 2023 was calculated (Table 2).

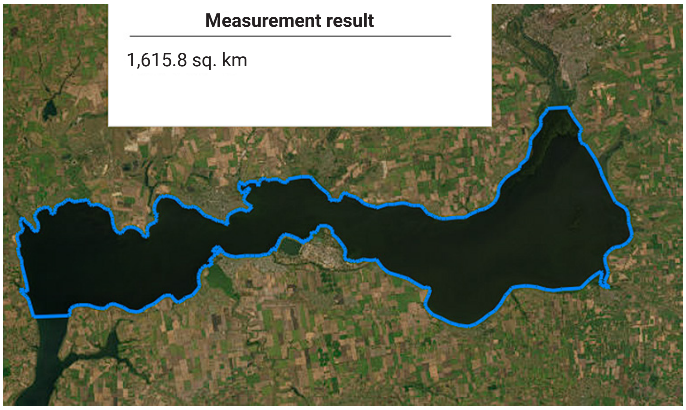

Figure 7. The area of the Velykyi Luh study area

Source: Arc GIS online service, Maxar satellite

Table 2. Biomass area and its increase on the territory of the Kakhovka Reservoir

Date	Biomass area, km^2	Increase in biomass area, km^2	Biomass area of the total area under study, %
19 August	≈311.48	–	19.27
8 September	≈570.22	258.74	35.29
7 November	≈737.61	167.39	45.65

Source: developed by the authors of this study

After the Kakhovka HPP was blown up and the territory of the Kakhovka Reservoir was drained, vegetation (biomass) was rapidly restored (Figs. 8a, 8b, 8c). From 19 August to 7 November 2023, the biomass area increased by 237% (Table 2). This shows the favourable conditions for further restoration of the historical part of Velykyi Luh through ecological restoration. As of 25 November 2023, willow stands formed on the territory of the dewatered Kakhovka Reservoir (Belousova, 2023). This indicates the beginning of the formation of full-fledged floodplain willow and poplar stands, which were common in this area before the 1950s when the reservoir was created. In general, the main woody plants that grew on the territory of the Velykyi Luh are considered *Quercus* L., *Pyrus communis* L., *Salix* L., *Populus nigra* L., *Malus sylvestris* Mill. (Kashchenko, 1917).

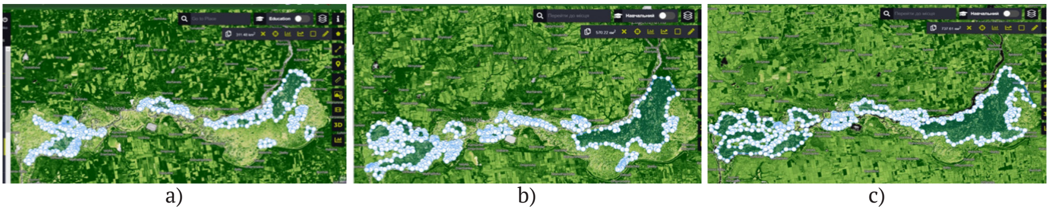
a) b) c)

Figure 8. Dynamics of biomass area growth in the Kakhovka Reservoir

Note: a) 2023-08-19; b) 2023-09-08; c) 2023-11-07

Source: EO Browser software, Sentinel-2 L2A satellite

Based on the study conducted, it was found that the restoration of the historical territory of the dewatered Kakhovka Reservoir, namely the Velykyi Luh, is possible through ecological restoration. This involves the creation of three main biotopes on the reservoir territory, namely Pannonian and Pontic sandy steppes, mesophyllic permanent grasslands of the plains, and floodplain forests. The first biotope is the Pannonian and Pontic sandy steppes (Kuzemko, 2022), which should be created in the eastern, southern, and central parts of the reservoir, as it is mainly formed on less developed soils, while the central, southern, and eastern parts of the reservoir are predominantly sandy plains. It includes the following vascular plants: *Secale sylvestre, Carex colchica, Festuca beckeri, Stipa borysthenica, Thymus pallasianus, Tragopogon borystenicus, Astragalus varius, Achillea micrantha, Agropyron dasyanthum, Jacobaea borysthenica, Dianthus platyodon, Agropyron lavrenkoanum, Koeleria glauca aggr, Asperula graveolens, Centaurea arenaria aggr, Euphorbia seguieriana, Erysimum montanum, Anchusa gmelinii, Jurinea longifolia, Chondrilla juncea, Minuartia viscosa, Artemisia campestris aggr*. Bryophytes: *Ceratodon purpureus, Polytrichum piliferun, Syntrichia ruralis*. Rare species: *Agropyron dasyanthum, A. cimmericum, Allium savranicum, Alyssum savranicum, Carex liparocarpos, Centaurea appendicata, C. breviceps, C. donetzica, C. konkae, C. margaritacea*. The second proposed biotope is mesophyllic permanent grassland of the plains, which is mainly grassland for grazing (Kuzemko, 2022) in the northern and north-eastern parts of the reservoir, which will provide favourable conditions for livestock. It includes the following vascular plants: *Achillea millefolium aggr, Trifolium pratense, Lotus corniculatus, Trifolium repens, Schedonorus pratensis, Galium verum, Prunella vulgaris, Convolvulus arvensis, Centaurea jacea subsp. jacea, Scorzoneroides autumnalis, Carex praecox, Ranunculus acris aggr., Potentilla argentea, Medicago lupulina, Agrostis capillaris*. Bryophytes: *Thuidium delicatulum, Atrichum undulatum, Brachythecium rutabulum*. Rare species: *Anacamptis coriophora, Carex secalina, Fritillaria meleagroides, Gladiolus tenuis*. The following may also grow: *Quercus*, *Populus nigra, Malus sylvestris*, *Pyrus communis, Betula borysthenica*. The third biotope is floodplain forests, which develop on river sediments within the floodplain in the western and eastern parts of the reservoir, where the highest concentration of rivers is found. Floodplain forests can be represented by the following woody and herbaceous plants: *Quercus*, *Pyrus communis*, *Salix, Populus nigra, Malus sylvestris, Betula* *borysthenica*. *Rorippa brachycarpa, Vicia hirsuta, Carex melanostachya, Elatine alsinastrum, Vicia villosa, Allium regelianum, Dianthus guttatus, Phalacrachena inuloides, Crepis ramosissima, Damasonium alisma, Achillea micranthoides, Linaria biebersteinii, Gratiola officinalis, Butomus umbellatus,* including rare plants: *Salvinia natans*, *Trapa natans*, *Nymphoides peltata*, *Aldrovanda vesiculosa*, *Nymphaea alba*, *Nuphar lutea*, *Sagittaria sagittifolia*, *Glyceria arundinacea*, *Ceratophyllum tanaiticum, Ceratophyllum submersum* and bryophytes: *Sampylium stellatum, Calliergonella cuspidata, Plagiomnium medium, Drepanocladus aduncus, Fissidens adianthoides, Bryum pseudotriquatrum, Aulacomnium palustre, Thuidium philibertii,*

Global warming, urbanisation, intensification of human activity (drainage reclamation, agricultural use, and chemicalisation of watershed soils, growth of settlement land, uncontrolled extraction of water from underground horizons, unauthorised amber mining, etc.) and great pressure on river ecosystems have led to ecosystem degradation, reduction of biotopes and biodiversity, and loss of their functions. P. Li *et al*. (2022) investigated the application of ecological restoration technologies aimed at improving biodiversity and river ecosystems, which is determined by the research and implementation of innovative approaches. These technologies include methods of restoring natural vegetation, regenerating water basins and managing anthropogenic impacts for the balanced functioning of river ecosystems. The study of this issue reveals the effectiveness and possibilities of using ecological technologies to improve the state of biodiversity and ecosystems in rivers. V.O. Martyniuk & O.V. Tomchenko (2021) considered the use of remote sensing tools in the study of lakes in the Polissia region, which opens the possibility of a detailed assessment of natural and anthropogenic transformations of these water systems. The analysis of satellite images allows identifying changes in the landscape, as well as the impact of anthropogenic activities on the hydrological and ecological aspects of the lake environment. This innovative approach allows effectively monitoring and responding to changes, contributing to the scientific understanding and effective management of the Polissia region’s natural resources.

J. Chenoweth (2006) reflected the establishment of sustainable goals for ecological restoration, using evidence from the restoration of river systems in Israel. The cited study defined concrete and sustainable goals for improving the river environment and developing strategies and technologies to achieve these goals. The implementation of sustainable goals for the restoration of river ecosystems in Israel contributes to improving the quality of natural resources and ensuring environmental sustainability. Y. Zhang *et al*. (2024) found that to combat environmental degradation and promote ecosystem resilience, China made considerable investments in ecological restoration of territories during 2009-2019. They noted that they have identified key aspects and technological tools that have helped to achieve positive results in the field of environmental restoration in this period. The study aims to identify and understand the factors that have determined the success of environmental measures in China and their contribution to the sustainability of natural systems. S. Poikane *et al*. (2024) noted that the most effective and widely used restoration measures target nutrient loading (both in the catchment and in the lake), while hydrological modifications and implementation of natural solutions are less commonly used. According to D. Galea & J.E. Major (2024) from Eastern Canada, ecological restoration is possible even on severely degraded sites in two years, provided the site preparation factor: growth and biomass using four early successional species (*Betula* *papyrifera* Marshall., *Betula populifolia* Marshall., *Alnus viridis* Vill. *subsp. crispa* Ait., *Alnus incana* L. *subsp. rugosa* Du Roi.) is used. The scale of ecosystem degradation is enormous: over 75% of the land has been severely altered by human activities, and one million species are threatened with extinction (Alamenciak *et al*., 2023). According to A. Tamura (2016), who investigated this phenomenon in the forests of eastern Japan, ecological restoration of old wet forests is possible due to seeds staying in the soil.

Ecosystem restoration is not just about protecting wildlife. Nature contributes to humanity's overall health and well-being and provides considerable social and economic benefits. But today we are losing nature at an unprecedented rate (Factsheet 2. Economic..., 2023). To determine the possibility of restoring the flooded historical area – the Velykyi Luh of the Kakhovka Reservoir, which has undergone changes due to anthropogenic impact, the authors conducted a spectral analysis of the territory of the Kakhovka Reservoir. F.H. Alexander *et al*. (2022) note that spectral analysis can be used to determine the characteristics of objects by their reflection or emission in different spectral ranges. The spectra of vegetation have two general forms: green and moist (photosynthetic) and dry non-photosynthetic. Green vegetation has an absorption of less than 1 μm due to chlorophyll. Those with a wavelength of more than 0.9 μm are dominated by liquid water. Dry vegetation shows an uptake dominated by callulose, as well as lignin and nitrogen. R.A. Ryerson & A.N. Rencz (1999) analysed the use of remote sensing in land management sciences, which is determined by its powerful potential for collecting information about the Earth. This method helps to obtain data from a large area, studying various aspects of geology, hydrology, and other branches of Earth science. The use of remote sensing in land management studies helps to analyse the dynamics of changes in natural processes and the interaction of various ecosystem components.

The ecological restoration of the Kakhovka Reservoir to restore the Velykyi Luh is considered a vital step in preserving natural diversity and restoring lost ecosystems. This process involves not only the restoration of natural vegetation, but also active consideration of natural processes and the wetland environment. The spectral analysis and investigation of the territory's characteristics, carried out using modern methods, help to create scientifically based approaches to restoration, contributing to the sustainable development of the Velykyi Luh ecosystem at the Kakhovka Reservoir.

Conclusions

The destruction of the Kakhovka HPP is an environmental crime with grave consequences for the Ukraine. The territory of Velykyi Luh is an important historical monument of the Ukraine and needs to be restored. By analysing the water surface dynamics from 1990 to 2010 using the NDWI, it was found that for 30 years the water surface of the Kakhovka Reservoir stayed almost unchanged until the moment of the explosion. Using NDVI, NDMI, and NDWI together with satellite images in the EO Browser software, it was possible to determine the dynamics of the water surface and vegetation, considering the moisture availability in the reservoir area. By quantifying green biomass and determining the moisture content of the vegetation on the territory of the Kakhovka Reservoir, it was found that gradual dehydration led to a stressful state of plants around the reservoir, which only increased from 6 June to the end of 2023. The NDVI and NDMI indices are dynamic and demonstrate the consequences of the damaged area as a result of anthropogenic impact and its recovery. The green biomass, which has increased by 237% since the dewatering, contributes to the formation of the necessary water balance. Based on the analysis of historical sources, three biotopes (Pannonian and Pontic sandy steppes, mesophyllic permanent grasslands of the plains, and floodplain forests) were proposed to help restore the historical territory of the Velykyi Luh. It was found that based on the analysis of images and moisture indices, focusing on the state of vegetation and water resources, it is possible to effectively select biotopes for ecological restoration. Presently, nature is initiating its own process of regeneration of the Velykyi Luh, and without active human involvement, the restoration of this historic area is unlikely.

Future research may be aimed at continuing to monitor the dynamics of vegetation biomass growth after the ecological restoration of the dewatered part of the Kakhovka reservoir, as well as the dynamics of the restoration of the Velykyi Luh river network.

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Conflict of Interest

The authors of this study declare no conflict of interest.

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Відновлення Великого Лугу шляхом екологічної реставрації Каховського водосховища

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Анотація. Актуальність сучасної екологічної проблематики вимагає комплексних підходів до відновлення та збереження природних екосистем, зокрема через використання екологічної реставрації як інструменту для усунення наслідків антропогенних втручань. Мета дослідження – обстежити територію Каховського водосховища за допомогою дистанційного зондування Землі та запропонувати спосіб відновлення історичної території Каховського водосховища Великого Лугу. Застосовано методи досліджень: емпіричні, аналіз і систематизація, дистанційне зондування Землі, геоінформаційні системи. Дослідження складалося з двох основних етапів. Перший етап включав аналіз динаміки історичної території Великого Лугу, з кінця XIX століття до нині. Другий етап передбачав порівняння динаміки відновлення даної території, використовуючи картографічні дані XIX століття та супутникові знімки XXI століття. Застосування сучасних технологій, зокрема аналіз супутникових зображень деградованої території та трьох індексів програмного забезпечення EO Browser, таких як диференційований вегетаційний індекс, нормалізований диференційний індекс вологості, диференційний індекс води, дозволило отримати дані щодо стану рослинності та водних ресурсів на досліджуваній території. Аналіз закономірностей між цими показниками дозволив визначити тісну взаємодію між темпами зростання рослин та їх вологозабезпеченістю. Було виміряно приріст біомаси на території Каховського водосховища з моменту зневоднення до листопада 2023 року. Отримані результати вказують на можливість ефективного відновлення екосистеми Великого Лугу шляхом екологічної реставрації. Цей процес передбачає вибір оптимальних біотопів для відновлення історичної місцевості, що є важливим кроком у збереженні біорізноманіття та стабілізації природного середовища на території Каховського водосховища. Результати досліджень із застосування нового підходу до екологічної реставрації, що базується на високоточних технологіях та глибокому аналізі динаміки екосистем сприятимуть розвитку наукових підходів до відновлення природних ландшафтів і стануть важливим внеском у сучасну екологічну практику

Ключові слова: дистанційне зондування землі; рослинність; екологія; регенерація; історична місцевість