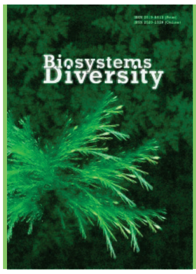

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Application of remote sensing data for monitoring eutrophication of floodplain water bodies

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The aim of this article was to investigate the influence of structural features of the floodplain water network on the spatial and temporal dynamics of chlorophyll-*a* concentration as an indicator of eutrophication. The research was conducted in the waters of the "Dnipro-Orilskiy" Nature Reserve. The geographic information base with polygonal objects which represented water bodies of the reserve was created on the basis of detailed geographical maps and the high resolution space images. The water bodies were characterized using such parameters as the distance of the water body centroid from the nearest shore of the Dnipro River, the area of the water body, the order of the water body and the connectivity of the water body. Chlorophyll-*a* concentration was estimated based on the surface algal bloom index. The information was obtained about 148 water bodies, 141 of which are water bodies in the floodplain of the Dnipro River. The area of floodplain water bodies within the reserve was 3.28 million m^2. The area of floodplain water bodies ranged from 300–232,500 m^2. Trophic State Index allows us to estimate the trophic level of Dnipro River waters as mesotrophic, water bodies of first and second order as eutrophic, and water bodies of third and fourth order as hypereutrophic. The dynamics of chlorophyll-*a* content in water followed the seasonal course of temperatures. The concentration was lowest in the cold period of the year and reached its maximum in the second half of summer. The autumn decrease occurred at the end of September. The seasonal course of air temperature was superimposed on the peculiarities of the temperature regime of a particular water body, which depended on its depth and flow rate. The time, water body area, distance from the Dnipro River channel, connectivity and order of water bodies were the statistically significant predictors of chlorophyll concentration in water and were able to explain 85% of the variation of this indicator. The increase in chlorophyll-a concentration with increasing order of a water body is due to a decrease in the intensity of water exchange and a decrease in the depth of water bodies of higher order. An increase in the order of a water body is accompanied by a branching network of water bodies, the ability of water bodies to clear sediments decreases. Sediment accumulation leads to a decrease in their depth. Warming of shallow ponds and accumulation of organic matter in them are factors of intensive growth of blue-green algae. The evacuation of surplus organic matter, which results from mass vegetation development with excessive nutrient inputs, is a key driver of the eutrophic regime of water bodies. The increasing importance of regulatory processes develops in agreement with an increase in chlorophyll-a concentration in a water body. The importance of the considered factors reaches the highest level in summer time, when simultaneous maximum warming of water bodies and minimum water level in them take place. Accordingly, the differences between deep and relatively cool water bodies and shallow water bodies that warm up quickly, which significantly stimulates the growth of organic mass, reach the greatest contrast. The spatial patterns of variation in chlorophyll-*a* concentration have a complex multiscale structure, indicating the multiple nature of the acting factors. The spatial variability was represented as a composition of broad-scale and medium-scale spatial processes. The broad-scale process is most dependent on connectivity, whereas for the medium-scale process the leading one is the effect of water body order.

Keywords: GIS-technology; nature conservation; nature reserve; water body connectivity; spatial pattern; spatial ecology.

Introduction

Water pollution affects human health and the environment (Haseena et al., 2017; Pinkina et al., 2022). Declining water quality has reduced the ecological integrity and economic value of freshwater ecosystems around the world (Boesch et al., 2001; Kennish, 2002; Craig, 2015; Cooke et al., 2016; Bogardi et al., 2020). An increase in the amount of organic waste in the water leads to the growth of microorganisms that can cause eutrophication (Yang et al., 2008). Eutrophication is a process in which the primary production in water is increased and photosynthetic microorganisms reproduce due to the availability of nitrogen and phosphorus in unbalanced proportions (Conley et al., 2009). These microorganisms inhabit the water surface and prevent sunlight from penetrating into the lower layers of the water column, causing an increase in biomass and a narrowing of microbial biodiversity, an unbalanced ecological niche, and increased mortality of aquatic animals due to anoxic episodes (Alarcon et al., 2018). One of the main reasons for water quality deterioration is the increased nutrient loading, which may directly or indirectly cause a number of environmental problems, including a decrease in the concentration of dissolved oxygen or hypoxia (Nixon, 1995; Cloern, 2001; Boesch, 2002; Miltner, 2018). Inland lakes are often heavily influenced by the environmental changes due to the growing impact of human activities (Wen Liu et al., 2020).

The Dniprovsko-Orilsky Nature Reserve is located in the center of industrial agglomeration in the zone of intensive industrial influence (Bondarev et al., 2022). The Dnipro-Zaporizhzhya-Kryvyi Rih triangle was recognized as a territory heavily affected by pollutants generated by many activities, including heavy industry, oil refining, metallurgy, petrochemistry, mining and energy (Vasenko, 1998). Much of the territory of the reserve is occupied by wetland habitats, which are formed in the floodplain of the Dnipro River (Ponomarenko et al., 2021). Despite the proximity of industrial centers and high level of impact of agroindustrial complexes, the Reserve's territory performs an important environmental function and is an oasis of land and water biota biodiversity. The protected area regime creates conditions for the restoration of animal and plant populations and their dispersal into the surrounding ecosystems. The biodiversity of the Reserve is a factor of maintaining the functional resilience of ecosystems both within the Reserve and in its immediate proximity (Solonenko et al., 2021). Deterioration of water quality, which manifests itself in increased nutrient concentrations and turbidity, a decrease in dissolved oxygen, is harmful to the survival, growth and reproduction of freshwater animals (Pérez-Quintero, 2013). Eutrophication and associated pollution are significant negative factors affecting habitat quality.

In the floodplain of the reserve there is a large variety of lakes, which are connected to each other and to the channel of the Dnipro River by many channels, forming a dense network of reservoirs. A floodplain lake is any inland body of water whose basin arose as a result of river processes, and the limnological functioning of which is caused by irregular but periodic limnophases and potamophases (Dawidek & Ferencz, 2012). The level of connectivity of water bodies varies greatly and depends on many factors. The hydrological connectivity of floodplain water bodies determines the natural flow regime, affects the spatial and temporal heterogeneity of habitats, regulates species turnover, and is a factor in aquatic biodiversity dynamics. Increased connectivity and diversity of water body types in degraded floodplains increases biodiversity and promotes functional and ecological restoration of the river landscape (Gallardo et al., 2008). The connectivity of water bodies provides migration opportunities for plant and animal populations and is a condition of species turnover. Also connectivity provides exchange of water masses and migration of nutrients and toxicants in the hydrological network. The functioning of flooded lakes depends on the state when water from the river flows into the lake (potamophase) and the state when the water remains in the river bed, providing stability to the lake (limnophase) (Napiórkowski & Napiórkowska, 2017). The duration of the potamophase determines the chemical characteristics of floodplain lake water (Ferencz et al., 2020). The productive potential of water bodies and water exchange creates a specific ecological regime and living conditions for biota (Zymaroieva et al., 2021). The system of lakes can be a concentrator of toxic substances and excessive nutrients and thus can act as an ecosystem filter that purifies water in the Dnipro River basin. Shifting the equilibrium in the opposite direction can change the flow of substances and floodplain lakes can become a source of secondary pollution and eutrophication.

The functioning of lakes takes place in the extremely dynamic environment of a large river floodplain. The regular flooding was a natural stage in the dynamics of floodplain ecosystems. However, the regulation of the river flow as a result of the creation of a cascade of reservoirs has reduced the frequency and intensity of flood events. The construction of dams may lead to changes in the water flow regime and nutrient cycling due to impediment to the flux of basic nutrients, including carbon, phosphorus, nitrogen and silicon, through river networks (Ingole & An, 2016; Maavara et al., 2020). The regular restoration of the channels between the lakes has slowed down considerably and the previously existing connections have disappeared. The reduced intensity of floods has led to the accumulation of substances in the floodplain, changes in the relief and hydrological regime. Obviously, this process has not reached its equilibrium state and the trend of changes in the hydrological regime will continue. These processes occur against the background of another phenomenon – global climate change (Zhukov et al., 2021). The climatic changes affect the seasonal course of temperatures, there is an increase in the average annual temperature and changes in the amount and rhythm of precipitation (Koshelev et al., 2021; Makaida et al., 2021). Undoubtedly, such climatic changes affect the state of river flow and functioning of floodplain ecosystems.

The global climatic changes and constantly increasing anthropogenic pressure significantly change the conditions of functioning of the already dynamic landscape system (Avtaeva et al., 2021). The understanding of the processes that occur in such a dynamic system under conditions of a significant variability of ecological regimes requires the application of new approaches, which would make it possible to obtain information on ecosystem processes in a significant spatial range, taking into account the temporal dynamics. Significant efforts by the international community may lead to a reduction in eutrophication, but the role of this factor will remain important for decades to come (Strokal & Kroeze, 2013). The monitoring of water quality and eutrophication in real time is essential for making adequate management decisions and conserving biodiversity (Lai et al., 2021; Mirzoeva & Zhukov, 2021). Earth remote sensing data provide sufficient opportunities for solving such problems.

Disconnection of rivers and floodplain lakes and eutrophication negatively affect the diversity of freshwater mollusk communities (Jiang et al., 2022). Hydrological connectivity of floodplain bodies of water is important for maintaining the diversity of hydrobionts (Rumm et al., 2018; Jiang et al., 2022). The eutrophication of fresh water and the proliferation of aerobic algae are closely related to the concentration of chlorophyll-*a* in the water (García Nieto et al., 2019; Zhukov & Arabadzhy-Tipenko, 2021). Chlorophyll-*a* concentration showed a strong positive correlation with inorganic suspended matter concentration, indicating a positive effect of resuspension on the phytoplankton biomass in floodplain lakes. The turbidity of floodplain lakes is determined more by the processes occurring in the lakes than by the dynamics of the river (Roozen et al., 2003). The concentration of chlorophyll-*a* can be used as an index for monitoring algae abundance by remote sensing because it has active optical properties in the visible and near-infrared regions of the electromagnetic spectrum (Dörnhöfer et al., 2018).

The aim of this article was to investigate the influence of structural features of the floodplain water network on the spatial and temporal dynamics of chlorophyll-*a* concentration as an indicator of eutrophication.

Materials and methods

Study area. The research was conducted in the waters of the "Dnipro-Orilskiy" Nature Reserve. The "Dnipro-Orilskiy" Nature Reserve was created in 1990. The area is 3,766 hectares, of which the water bodies are 203 hectares (Bondarev et al., 2022). Intensive changes in the relief on the territory of the "Dnipro-Orilskiy" Nature Reserve occurred after the construction of the Dnipro Hydroelectric Station dam in 1932. The water level here was raised by 1.5–2.0 m, which corresponds to the average level of 49.7 m above sea level. During the Second World War, the dam was destroyed in 1941, which returned the water level to its previous state. After the dam was restored in 1950, the water level was restored, and after the start of the second Dnipro Hydroelectric Station block in 1960s and the construction of Dniprodzerzhinsk (Kamianske) Hydroelectric Power Plant, the water level was raised to 51.4 m above sea level. Thus, after the construction of the Dnipro reservoirs cascade, the total Dnipro level rise in the "Dnipro-Orilskiy" Nature Reserve area, as compared to the natural one, was 3.0–3.5 m, which led to the inundation of part of the floodplain, changes in the configuration of banks and the area of water bodies. The studied water bodies are the Dnipro River bed and floodplain water system.

The mouth of the Oril River. The estuary section of the Oril River was artificially created in the early 1960s, by diverting the natural channel of the Orel River into the Dnipro (Zaporozhye) reservoir. This need arose during the large-scale hydro construction and creation of a cascade of reservoirs on the Dnipro River. The main purpose of this activity was to preserve the ways of natural spawning migration and sustainable fish reproduction in the water area of the upper section of the Dnipro (Zaporozhye) reservoir. For the most part, this artificial canal was laid along the remnants of the Prototch River system, which had a narrow strip of water flowing in the opposite direction along the Dnipro River from Obukhovka village. The functioning of the hydrological regime of the reservoir largely depends on the daily regulation of water level in the reservoir. This is especially true in the summer period, when almost daily the reverse direction of the flow is observed. In the spring period (especially in multiyear years), the natural flow of the Oril is expressed to a much greater extent, and the impact of the reservoir is reduced. The site is characterized by a limited area of coastal biotopes, which is explained by its artificial origin. The water reservoir is in close contact with the water area of the Obukhovskaya floodplain. The greatest distance from the Dnipro River bed is about 2 km. The total length of the site within the Reserve does not exceed 5 km. On the left bank of the Oril the village Obukhovka is located and a significant number of recreation centers, which considerably increases the anthropogenic load on the water area of this area. Maximum depths reach 8–10 m (exactly near the inflow point). In higher water areas the depth does not exceed 4 meters.

Water reservoirs of the Mykolaevka Ledge System. The system of floodplain ponds is located in the narrowest part of the floodplain terrace. The ponds extend as a narrow strip along the channel of the Dnipro. The maximum distance of water bodies from the Dnipro River bed within the Reserve is about 300–1000 meters. The water bodies are characterized by a significant level of flow and water level differences during the day, which depends on the conditions of the reservoir operation. Some of the water bodies, which are connected with separate streams with the specified area, are outside the Reserve. The area of shallow water areas (littoral zone) is minimal due to steep banks, which are typical for the water bodies of this area. Maximum depths are 5–6 meters. In recent years, the water bodies in the central part of this section began to be actively silted and overlapped by sandy sediments due to accumulation of excessive bottom deposits due to disturbance of the reservoir water regime.

Water bodies of the Obukhiv Floodplain System. Most of them are weakly flowing, shallow water bodies, which are the remnants of the lower part of the channel of the Dnipro River, which connected the Dnipro with the floodplain system of the Oril River. They were flooded as a result of the reservoir formation. They function under the significant influence of the reservoir water regime. They are characterized by significant sedimentation (in some areas, silt thickness reaches 0.6–1.0 m) and overgrowth of water macrophytes. They are connected to the Dnipro River and the mouth of the Oril River by narrow channels. The largest distance to the Dnipro River within this section is about 2 km.

Water area of the Dnipro River channel part. It includes a part of the upper section of the Dnipro (Zaporizhzhya) Reservoir, where the river regime is partly preserved, along the left bank between the islands Krachinyi and Kamyanyi. It is characterized by a significant level of flow and movement of sand masses, which is associated with active channel processes in this part of the reservoir. Depths fluctuate between 2–7 meters.

Water bodies of the Taromske Ledge System. The system of floodplain ponds, located in the low part of the floodplain terrace. All lakes are separated from the Dnipro River bed by a sand wall. The lakes are connected to each other and to the channel of the Dnipro by numerous waterways. Most of the lakes have a significant littoral zone, which is actively overgrown with water macrophytes. Depths fluctuate between 1–10 meters. Water is exchanged through the operation of the reservoir and spring floods. The maximum distance of individual ponds from the Dnipro River bed is about two kilometers. Currently, due to the unbalanced functioning of the reservoir, water bodies of this area are actively swamped and silted. In some areas the thickness of silt sediments reaches 0.3–0.7 meters.

Parameters of the water bodies. The geographic information base with polygonal objects which represented water bodies of the reserve was created on the basis of detailed geographical maps and the high resolution space images. The water bodies were characterized using such parameters as the distance of the water body centroid from the nearest shore of the Dnipro River, the area of the water body, the order of the water body and the connectivity of the water body. The order of the body of water was represented by five gradations: the river channel and artificial canal, as well as the bay of the river, the water bodies that directly flow into water bodies of zero order, the bodies of water that flow directly into bodies of water of the first order, all other bodies of water have a connection with other bodies of water, the isolated bodies of water. The connectivity of the body of water was represented by seven gradations: 0 an isolated body of water, 1 a body of water connected to another one via a narrow stream, 2 a narrow channel, 3 a body of water connected to another one via a narrow channel, 4 a body of water connected to other bodies of water through two narrow channels, 5 a body of water connected to another one via a middle or large channel, 6 the running channels of rivers or artificial canals.

Remote sensing data. Earth remote sensing data was downloaded from the USGS Earth Explorer website (https://earthexplorer.usgs.gov) for Sentinel-2 MSI. Satellite images with cloud cover of less than 10% were used for analysis. If the cloud cover was more than 10%, but did not cover the reserve area, the image was used for analysis. Images on the following dates were used for the analysis: 15.02.2021, 01.04.2021, 11.04.2021, 01.05.2021, 15.06.2021, 30.06.2021, 15.07.2021, 20.07.2021, 09.08.2021, 19.08.2021, 24.08.2021, 29.08.2021, 08.09.2021, 13.09.2021, 07.11.2021, 20.02.2022, 22.03.2022, 06.05.2022, 11.05.2022, 31.05.2022.

Chlorophyll-*a* concentration was estimated based on the surface algal bloom index (SABI) (Alawadi, 2010):

$$SABI = (b8a - b4)/(b2 + b3),$$

where b8a is the Sentinel-2 MSI near infra-red band (wavelength = 0.86–0.88 μm), b4 is the red band (wavelength = 0.65–0.68μm), b2 is the blue band (wavelength = 0.46–0.52 μm), b3 is the green band (wavelength = 0.54–0.58 μm).

The cartographic location of water bodies and their real boundaries may not coincide at different time periods due to the significant dynamism of aquatic ecosystems in the river floodplain. Therefore, SABI was estimated only in pixels where the water surface was identified using the Normalized Difference Water Index (NDWI) (McFeeters, 1996):

$$NDWI = (b3 - b11)/(b3 + b11),$$

where b3 is the Sentinel-2 MSI green band (wavelength = 0.54–0.58 μm), b11 is the short-wave infrared 1 band (wavelength = 1.57–1.66 μm).

The concentration of chlorophyll-*a* (μg/L) was estimated by the formula (Lai et al., 2021):

$$Chl\text{-}a = 14.29 \times SABI + 5.94.$$

The Trophic State Index was calculated based on chlorophyll-*a* concentration data:

$$TSI = 30.6 + 9.81 * \ln(Chl\text{-}a),$$

where TSI is Trophic State Index, Chl-a is the concentration of chlorophyll-*a* in water (μg/L).

The trophic status of water bodies was assessed according to the Carlson scale: ultra-oligotrophic (TSI = 0–20), oligotrophic (TSI = >20–40), mesotrophic (TSI = >40–50), eutrophic (TSI = >50–60), hypereutrophic (TSI = >60–70) (Carlson, 1977).

Data analysis. The geographic information database was created in ArcGIS 10.8. Descriptive statistics, GLM analysis, components of variation and correlation coefficients with significance level estimates were calculated using Software package Statistica 10.0. Constrained redundancy analysis (RDA) to extract the major patterns of variation (Legendre & Birks, 2012; Ter Braak & Šmilauer, 2015) was calculated by means of the package ade4 (Dray & Dufour, 2007). For a language and environment for statistical computing R. The partitioning of the data matrix variation with respect to the explanatory tables of ecological properties was performed with the help of the package vegan. The comparison of ordinal solutions was performed using the Procrustes analysis procedure (Peres-Neto & Jackson, 2001).

Results

The information was obtained about 148 water bodies, 141 of which are water bodies in the floodplain of the Dnipro River (Table 1).

Table 1
Correlation of hydrological connectivity and order of water bodies (the number of water bodies of the respective types)

Connectivity of the body of water*	Order of the water body**					Total
	0	1	2	3	4	
0	–	–	–	–	42	42
1	–	–	–	29	–	29
2	–	–		16	–	16
3	–	2	17	8	–	27
4	–	14		3	–	17
5	3	4	1	1	1	10
6	7	–	–	–	–	7
Total	10	20	18	57	43	148

Note: * – 0 denotes an isolated body of water; 1 denotes a body of water connected to another one via a thin stream; 2 is a thin channel; 3 denotes a body of water connected to another one via a thin channel; 4 denotes a body of water connected to other bodies of water through two thin channels; 5 denotes a body of water connected to another one via a middle or large channel; 6 denotes the running channels of rivers or artificial canals; ** – 0 denotes the river channel and artificial canal, as well as the bay of the river; 1 denotes the water bodies that directly flow into water bodies of zero order; 2 denotes the bodies of water that flow directly into bodies of water of the first order; 3 denotes all other bodies of water that have a connection with other bodies of water; 4 denotes the isolated bodies of water.

The area of floodplain reservoirs within the reserve was 3.28 million m^2. The area of floodplain water bodies ranged from 300–232,500 m^2. The distribution of water body area values was log-normal (Fig. 1). The centroids of the water bodies were distanced from the Dnipro River channel in the range of 29–2943 m. The distribution of distances was a mixture of three normal distributions, indicating the location of water bodies in the riverbed floodplain (distance 255 ± 184 m), central floodplain (1022 ± 437 m), and near-terraced floodplain (distance 2841 ± 65 m). Water bodies in the central floodplain were the most typical, accounting for 67.3% of the total number of water bodies. Water bodies of riverbed floodplain were represented by a much smaller number (29.9%). The number of water bodies in the near-terraced floodplain was the least (2.7%).

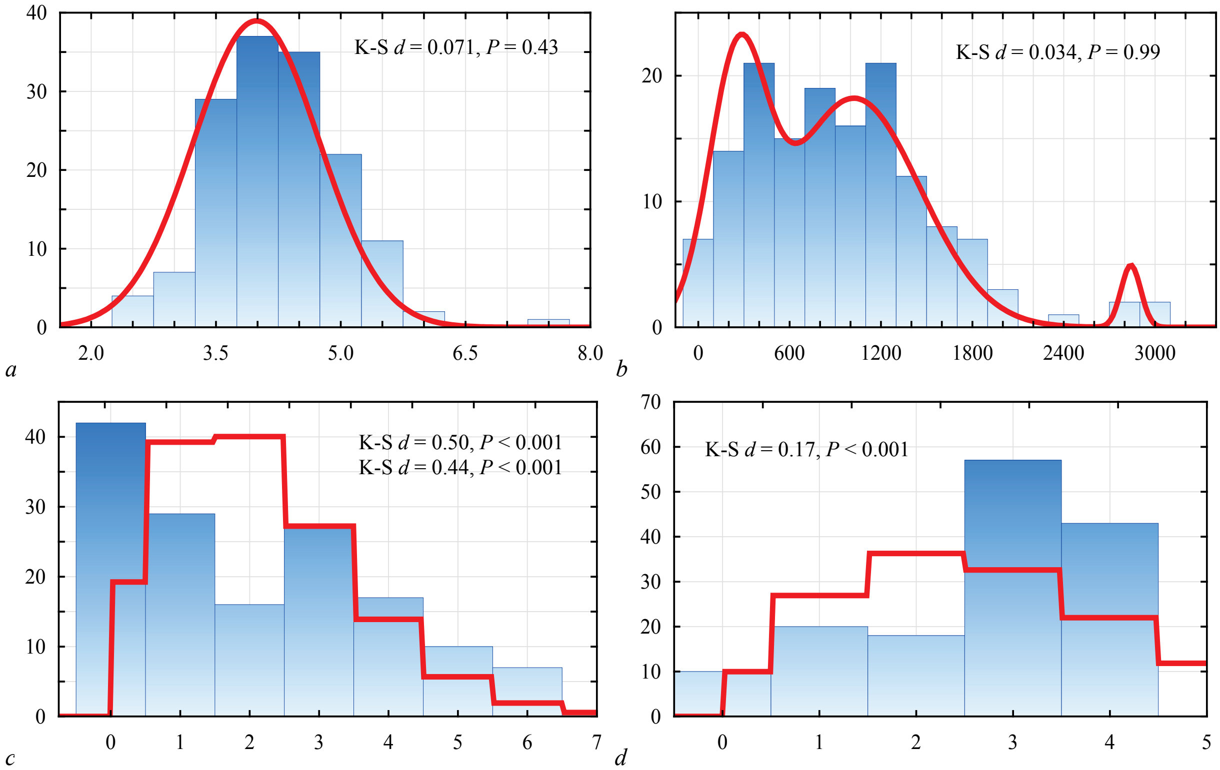

Fig. 1. Histograms of morphometric distributions of floodplain lakes: *a* – water body area distribution (m^2, logarithmic scale), red line is normal law approximation, *b* – the distance from Dnipro River channel to water body centroid, the red line is the approximation of mixture of three Gaussian laws, the first distribution is 29. 9% of the total sample, 255 ± 184 m (mean ± dispersion), the second distribution is 67.3% of the total sample, 1022 ± 437 m, the third distribution is 2.7% of the total sample, 2841 ± 65 m, *c* – reservoir connectivity: mixture of the two Poisson distributions, for connectivity 0, 1, and 2 $\lambda = 0.70$, for connectivity 3, 4, 5, and 6 $\lambda = 3.95$, *d* – reservoir order: Poisson distribution, $\lambda = 2.70$; connectivity: 0 denotes an isolated body of water; 1 denotes a body of water connected to another one via a thin stream; 2 is a thin channel; 3 denotes a body of water connected to another one via a thin channel; 4 denotes a body of water connected to other bodies of water through two thin channels; 5 denotes a body of water connected to another one via a middle or large channel; 6 denotes running channels of rivers or artificial canals; orders: 0 denotes the river channel and artificial canal, as well as the bay of the river; 1 denotes water bodies that directly flow into water bodies of zero order; 2 denotes bodies of water that flow directly into bodies of water of the first order; 3 denotes all other bodies of water that have a connection with other bodies of water; 4 denotes isolated bodies of water

The water bodies of the reserve form a range from running rivers and canals to isolated lakes according to connectivity index (Fig. 2). The distribution of the number of water bodies in terms of connectivity and order is bimodal. The isolated reservoirs were the most numerous (30.4% of the total number), but their average area was the smallest (4393 ± 649 m^2). The connectivity of water bodies and their area were positively correlated (Spearman correlation coefficient 0.89, $P < 0.001$). From the riverbed, water bodies form a sequence of connected water bodies (Fig. 3). Some of them lose their connection with others and become isolated. As the order of water bodies increases, their area decreases (Spearman correlation coefficient –0.80, $P < 0.001$).

The Trophic State Index allows us to estimate the trophic level of Dnipro River waters as mesotrophic, water bodies of first and second order as eutrophic, and water bodies of third and fourth order as hypereutrophic. The chlorophyll-*a* content was lowest in winter time (Table 2). In the second half of spring, a sharp increase in its concentration began, reaching its plateau by the end of June. Further until the end of September, the chlorophyll-*a* concentration was at the plateau, showing some fluctuations over time. From the end of September there was a decrease in chlorophyll-*a* concentration in the water bodies. The time, water body area, distance from the Dnipro River channel, connectivity and order of water bodies were the statistically significant predictors of chlorophyll-*a* concentration in water and were able to explain 85% of the variation of this indicator (Table 3). A local maximum of chlorophyll-*a* concentration was observed for reservoirs with a connectivity index of 1 (Fig. 4). With the further increase in connectivity, the concentration of chlorophyll-*a* in the water bodies decreased. As the order of water bodies increased, the concentration of chlorophyll-*a* increased, but a local maximum was observed for the water bodies of first order. The chlorophyll-*a* concentration decreased with increasing distance of the water body centroid from the Dnipro River channel (beta regression coefficient was –0.035 ± 0.0074, $P < 0.001$). The chlorophyll-*a* content was lower in water bodies of larger area (beta regression coefficient was –0.22 ± 0.011, $P < 0.001$). The connectivity of water bodies had a greater effect on chlorophyll-a concentration than the order of water bodies (Fig. 5). The significance of the predictors considered to explain variation in chlorophyll-a content varied over time. The predictors had the highest importance in summer time and the lowest in winter time.

The spatial variables described 41.1% of the variation in chlorophyll-*a* concentration ($F = 3.49$, $P < 0.001$). The pure spatial effect without accounting for environmental factors described 25.5% of the variation ($F = 7.47$, $P < 0.001$). The forward selection procedure allowed us to identify the most significant spatial predictors, which were variables 1, 2, 3, 4, 5, 7, 8 (the broad-scale component of the spatial trend) and 12, 13, 14, 17 (the medium-scale component of the spatial trend). The selected spatial variables were able to describe 39.3% of the variation in chlorophyll-*a* concentration ($F = 7.34$, $P < 0.001$). The fine-scale components of the spatial trend (spatial variables with an ordinal number greater than 17) were not statistically significant predictors of the spatial trend. The broad-scale spatial component described 22.8% of the variation in chlorophyll-*a* concentration (F = 7.21, P < 0.001, Fig. 6). The area, connectivity, and order of the water body, and distance from the Dnipro River channel were able to describe 65.1% of the variation in the broad-scale spatial component (F = 69.72, P < 0.001). The area of the water body (beta regression coefficient 0.62 ± 0.074, t = 8.3, P < 0.001) and connectivity of the water body (beta regression coefficient 0.30 ± 0.13, t = 2.30, P = 0.025) were statistically significant predictors of the broad-scale component of spatial variation. The medium-scale component described 11.2% of the variation in chlorophyll-*a* concentration (F = 4.78, P < 0.001). This pattern can be described by a single statistically significant canonical axis (F = 47.18, P < 0.001). The area, connectivity and order of the water body, and distance from the Dnipro River channel were able to describe 68.3% of the variation in the medium-scale spatial component (F = 80.12, P < 0.001). All of these predictors were statistically significant.

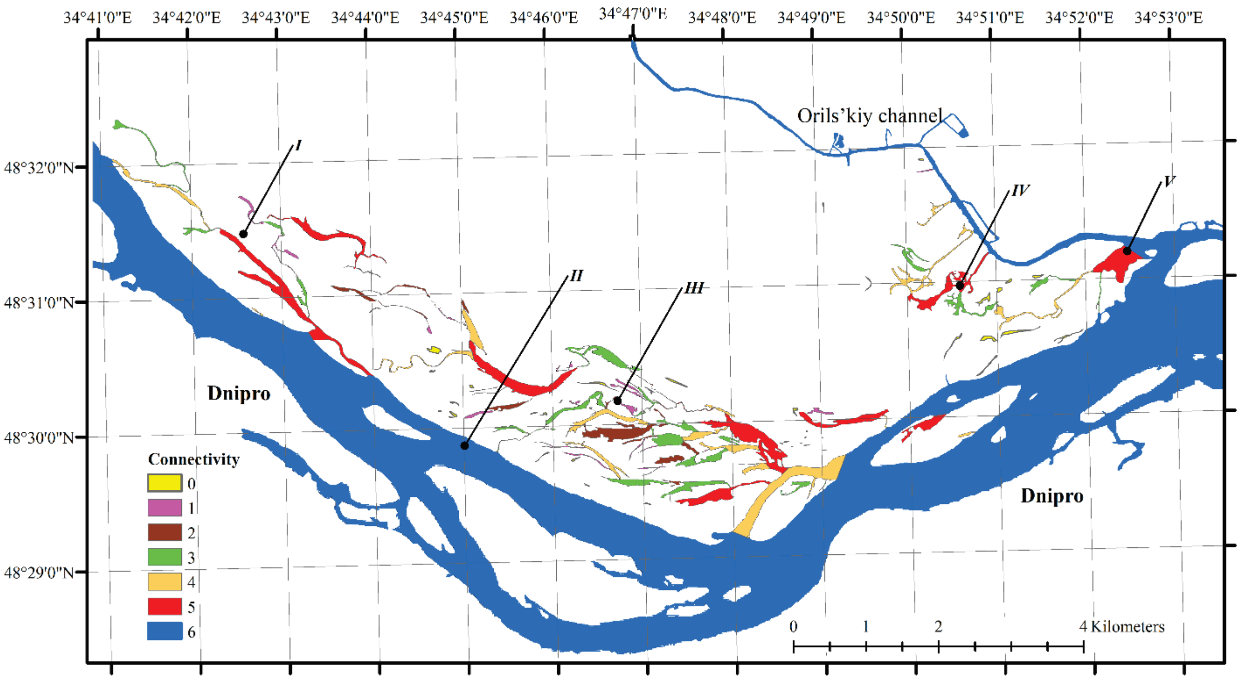

Fig. 2. Spatial distribution of water bodies and their connectivity: 0 denotes an isolated body of water; 1 denotes a body of water connected to another one via a thin stream; 2 is a thin channel; 3 denotes a body of water connected to another one via a thin channel; 4 denotes a body of water connected to other bodies of water through two thin channels; 5 denotes a body of water connected to another one via a middle or large channel; 6 denotes running channels of rivers or artificial canals; I – is the Mykolaevka ledge system; II is the Dnipro River channel part; III is the Taromske ledge system; IV is the Obukhiv floodplain system; V is the mouth of the Oril River

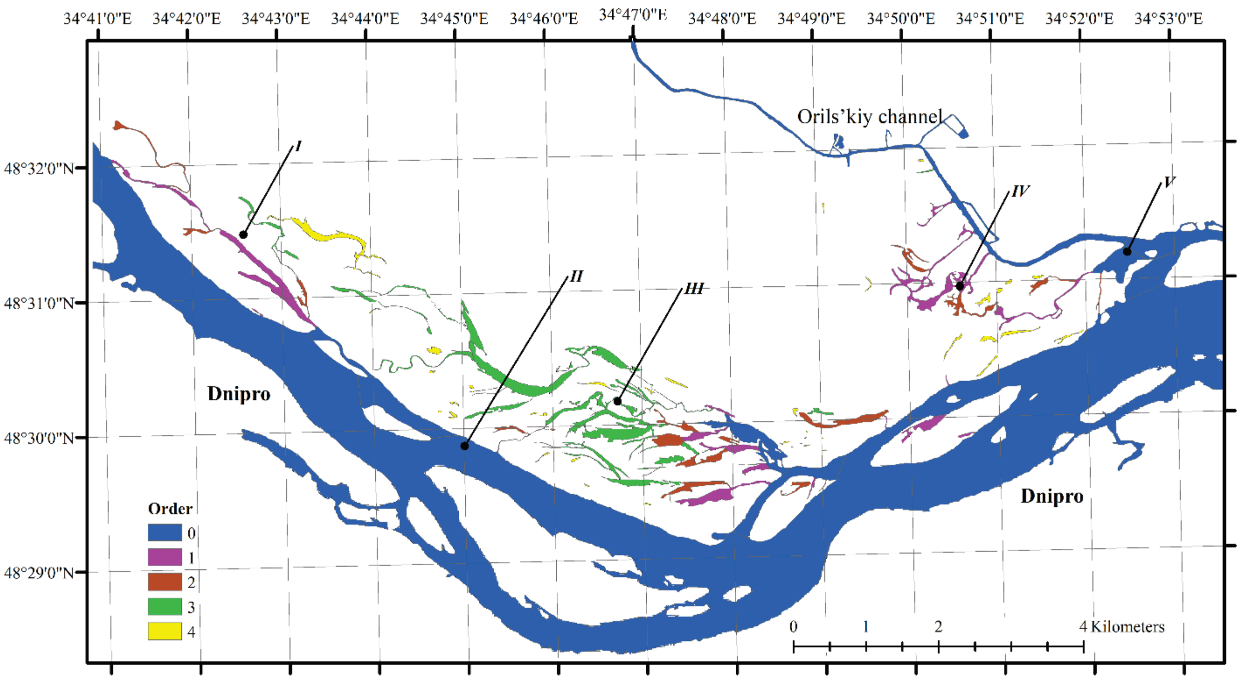

Fig. 3. Spatial location of water body orders: 0 denotes the river channel and artificial canal, as well as the bay of the river; 1 denotes water bodies that directly flow into water bodies of zero order; 2 denotes bodies of water that flow directly into bodies of water of the first order; 3 denotes all other bodies of water that have a connection with other bodies of water; 4 denotes isolated bodies of water; I – the Mykolaevka Ledge System; II – the Dnipro River channel part; III – the Taromske Ledge System; IV – the Obukhiv Floodplain System; V – the mouth of the Oril River

The predictors considered together were able to explain 88.7% of the variation in chlorophyll-*a* concentration (Fig. 7). They had both a net effect and an effect that was due to the interaction of the predictors with each other. The pure spatial component of chlorophyll-*a* variation embraced 18.9 % of variation in this index. The interaction of spatial patterns and water body area accounted for 3.0% of the variation. The relationship of spatial variables and connectivity covered 5.1% of the variation. The relationships were also of higher order. The pure influence of water body area described 7.4% of variation in chlorophyll-*a* concentration, and the pure influence of connectivity described 5.0% of variation. However, their relationship was able to explain 15.6% of the variation. The pure influence of water body order described 1.1% of the variation, whereas the relationship with connectivity described 19.4% of the variation in chlorophyll-*a* concentration.

Table 2
Descriptive statistics of chlorophyll-*a* content estimation (μg/L)

Date	x ± SE	Minimum	Maximum	RDA1sp scores
15.02.2021	6.18 ± 0.06	5.03	8.17	0.27
01.04.2021	8.00 ± 0.06	6.20	9.70	0.14
11.04.2021	7.88 ± 0.13	4.35	11.26	0.78
01.05.2021	9.71 ± 0.19	4.48	15.53	1.15
15.06.2021	19.70 ± 0.45	6.15	31.14	3.19
30.06.2021	20.43 ± 0.54	6.09	32.00	3.87
15.07.2021	23.87 ± 0.53	6.53	34.77	3.90
20.07.2021	21.48 ± 0.44	6.92	30.21	3.32
09.08.2021	19.89 ± 0.37	7.13	28.92	2.57
19.08.2021	19.09 ± 0.36	6.99	26.18	2.80
24.08.2021	21.54 ± 0.46	5.96	30.41	3.49
29.08.2021	19.69 ± 0.37	6.66	27.13	2.68
08.09.2021	21.31 ± 0.48	6.11	30.89	3.61
13.09.2021	19.15 ± 0.40	6.46	26.70	3.04
07.11.2021	8.55 ± 0.12	4.37	11.67	0.79
20.02.2022	6.21 ± 0.04	5.10	7.45	0.23
22.03.2022	6.75 ± 0.06	4.20	8.31	0.41
06.05.2022	8.61 ± 0.14	5.51	12.42	0.80
11.05.2022	9.00 ± 0.13	5.28	13.07	0.71
31.05.2022	11.14 ± 0.19	6.15	16.35	1.26

The canonical redundancy analysis with spatial variables as predictors allowed us to reveal the spatial trend of variation in chlorophyll-*a* concentration. The canonical redundancy analysis can be extended with other factors as a conditional variable, yielding solutions whose differences can be detected by Procrustes analysis. The shift detected by Procrustes analysis is due to the effect of the factor that is treated as the conditional variable (Fig. 8). The ordinal shifts identified can also be mapped in geographic space (Fig. 9). The role of water body area as a factor affecting chlorophyll-*a* concentration was greatest in the Taromske and the Mykolaevka ledge system. The role of connectivity was greatest with the approach to the Dnipro River channel. The role of the order of the water body was uniform over the territory of the water body system.

Table 3
GLM estimation of the effect of water body area, distance from the Dnipro River channel, date, connectivity and order of the water body on chlorophyll-a concentration ($R_{adj}^2 = 0.85$, $F = 589.3$, $P < 0.001$)

Effect	Sum of squares	Degrees of freedom	Mean sum of squares	F	P
Intercept	18137	1	18137	2363	<0.001
Area (log-trasformed)	3157	1	3157	411	<0.001
Distance	175	1	175	22.9	<0.001
Data	120650	20	6033	786	<0.001
Connectivity	1183	6	197	25.7	<0.001
Order	108	4	27.0	3.5	<0.001
Error	23600	3075	7.7	–	–

Discussion

The modern relief of the Dnipro River floodplain within the reserve is very mosaic. The following geomorphological elements are distinguished in the river floodplain: riverbed, central and near-terrace floodplains (Dedova & Burul, 2021). The Dnipro floodplain is formed by the furcation type (Gritsan et al., 2019), with meandering almost not developed. The genetic zones of the modern floodplain, formed due to the furcation of the channel, are superimposed on the zones associated with the degree of distance from the main channel. The distance from the channel is a marker of decaying intensity of alluvial sedimentation. The Dnipro River floodplain relief is a system of segments, within each of which the riverbed, central and near-terrace geomorphological elements are formed. The Dnipro Reservoir has the greatest influence on the hydrological and hydrographic features of the floodplain and channel parts of the reserve. The reservoir was created as a result of the construction of the Dnipro Hydroelectric Power Plant in 1932. The normal elevation of the reservoir is 51.4 m. The width of the reservoir in the area of the reserve is about 1 km. The maximum depth reaches 8.0 m. The Kamianske Water Reservoir whose dam is situated 12 km from the western border of the reserve, has a significant influence on the hydrological regime of the territory of the reserve. During activation of the spillways the water level in the Dnipro River in the area of the reserve can rise by up to 1 m above the normal level, although these discharges usually occur only during floods and floods, mainly in spring. As a result of creation of the cascade of reservoirs, there has been a radical change in the hydrological regime of the Dnipro, which has led to significant changes in its hydrochemical, biological and sanitary regimes. The gas regime, the regime and composition of biogenic and organic substances, major ions have changed. Changes in chemical and physical properties of water have also affected to a certain extent the living organisms living in this part of the reservoir. The average long-term amplitude of water level fluctuations in the reservoir is about 2.5 m (Zhukov et al., 2019; Bondarev et al., 2022).

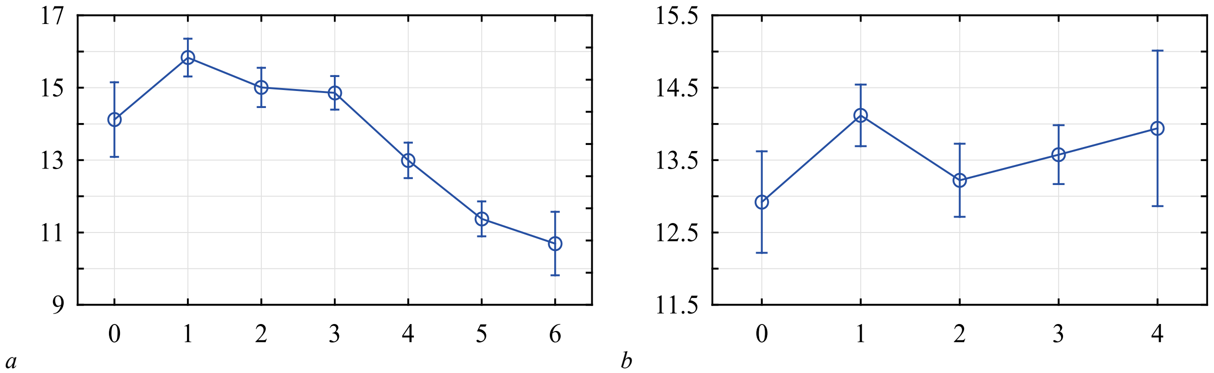

Fig. 4. Estimation of variation in chlorophyll-*a* concentration as a function of connectivity (*a*) and order (*b*) of water bodies by GLM-analysis with water body area and distance from the Dnipro River as covariates: the ordinate axis is the chlorophyll-*a* concentration (μg/L, mean and 95% confidence interval); connectivity: 0 denotes an isolated body of water; 1 denotes a body of water connected to another one via a thin stream; 2 is a thin channel; 3 denotes a body of water connected to another one via a thin channel; 4 denotes a body of water connected to other bodies of water through two thin channels; 5 denotes a body of water connected to another one via a middle or large channel; 6 denotes the running channels of rivers or artificial canals; orders: 0 denotes the river channel and artificial canal, as well as the bay of the river; 1 denotes the water bodies that directly flow into water bodies of zero order; 2 denotes the bodies of water that flow directly into bodies of water of the first order; 3 denotes all other bodies of water that have a connection with other bodies of water; 4 denotes the isolated bodies of water

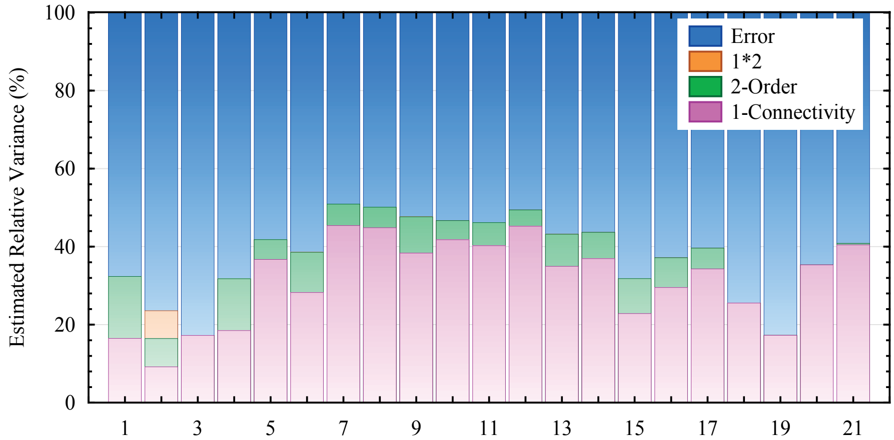

Fig. 5. Components of variation in chlorophyll-*a* concentration: the ordinate axis is the estimated relative variation in chlorophyll-*a* concentration, and the abscissa axis is the dates: 1 – 15.02.2021, 2 – 01.04.2021, 3 – 11.04.2021, 4 – 01.05.2021, 5 – 15.06.2021, 6 – 30.06.2021, 7 – 15.07.2021, 8 – 20.07.2021, 9 – 09.08.2021, 10 – 19.08.2021, 11 – 24.08.2021, 12 – 29.08.2021, 13 – 08.09.2021, 14 – 13.09.2021, 15 – 07.11.2021, 16 – 20.02.2022, 17 – 22.03.2022, 18 – 06.05.2022, 19 – 11.05.2022, 20 – 31.05.2022

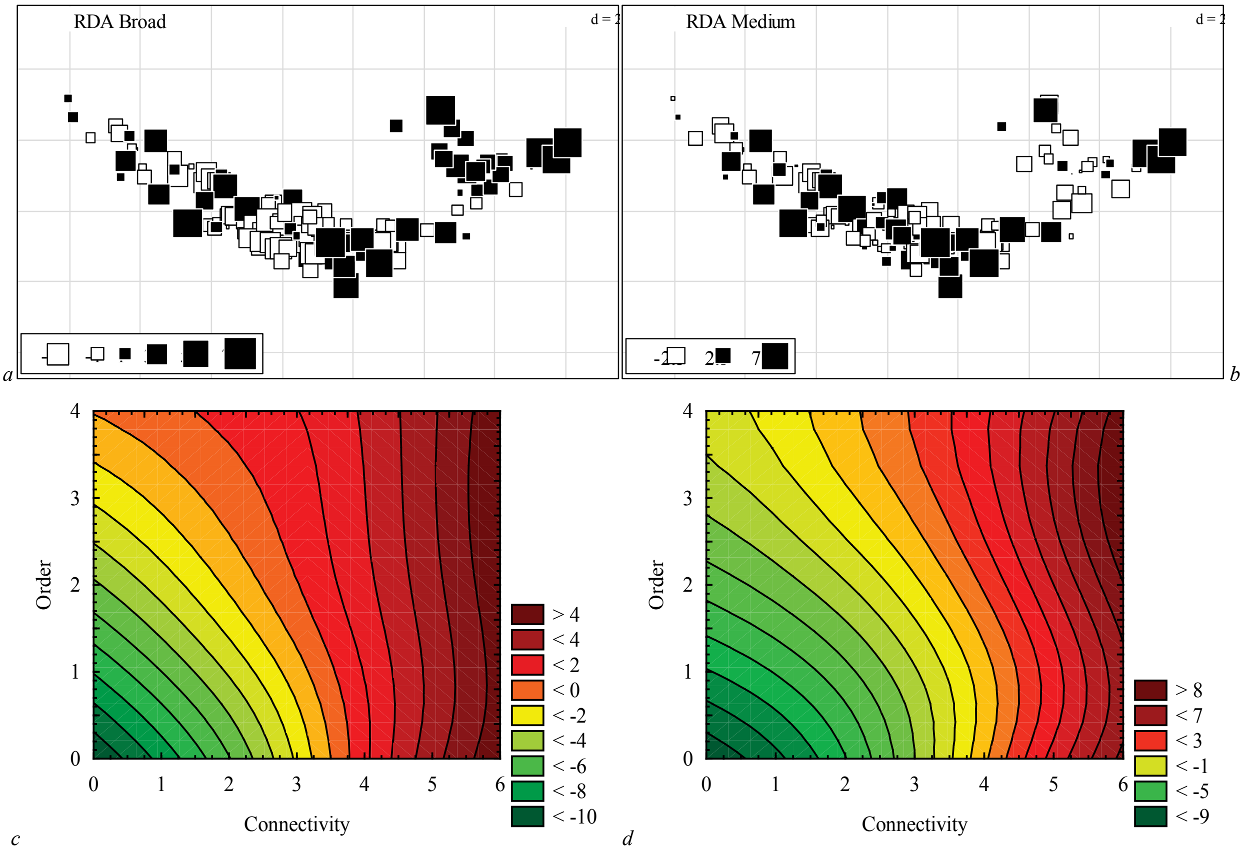

Fig. 6. Variation in chlorophyll-*a* concentration: *a* – broad-scale spatial pattern; *b* – medium-scale spatial pattern; *c* – broad-scale pattern in the space of connectivity and order of floodplain water bodies; *d* – medium-scale pattern in the space of connectivity and order of floodplain water bodies; connectivity: 0 denotes an isolated body of water; 1 denotes a body of water connected to another one via a thin stream; 2 is a thin channel; 3 denotes a body of water connected to another one via a thin channel; 4 denotes a body of water connected to other bodies of water through two thin channels; 5 denotes a body of water connected to another one via a middle or large channel; 6 denotes the running channels of rivers or artificial canals; orders: 0 denotes the river channel and artificial canal, as well as the bay of the river; 1 denotes the water bodies that directly flow into water bodies of zero order; 2 denotes the bodies of water that flow directly into bodies of water of the first order; 3 denotes all other bodies of water that have a connection with other bodies of water; 4 denotes the isolated bodies of water

Basic morphometric (depth, volume) and hydrologic (inflows, surface and land use in the watershed) characteristics determine the vulnerability of a lake to eutrophication (Vinçon-Leite & Casenave, 2019). The floodplain of the Dnipro River within the reserve is formed by the furcation type and is a periodic flooded area, which is penetrated by a system of water bodies stretched in a general direction along the riverbed of the Dnipro. These water bodies are interconnected, forming a dense network of interacting water bodies. The main sources of water in these water bodies are the Dnipro River and groundwater runoff from the second terrace in the Dnipro River floodplain, which is above the floodplain. The floodplain as a dynamic system functions under conditions of constant spring floods. The extreme floods may be a sufficiently strong stressor for the transition from a turbid to a clear floodplain lake state. Cyclic transitions between alternative stable states in floodplain ecosystems can probably be expected as a consequence of climate change-induced extreme hydrological events (Mihaljević et al., 2010). Floodplain lakes are sensitive to nutrient enrichment and the effects of climate change. During floods, pollutants accumulated in floodplain lake water and sediments can enter the river. Thus, the protective role of floodplain lakes as "buffer zones of river pollution" will be negated, as they can become a major diffuse source of pollution and pose a threat to the river (Norris, 1993). Lakes with dropping water levels in summer are less turbid due to a lower concentration of inorganic suspended solids (Roozen et al., 2003). The floodplain water bodies play an important role in the retention and conversion of nitrogen and phosphorus compounds. The seasonal fluctuations in river water levels lead to periodic connection and disconnection of the river channel and floodplain water bodies, thereby causing the exchange of chemically different water sources. The sediments of the floodplain water bodies become a nitrogen and phosphorus sink for the river, contributing to improved river water quality (Weigelhofer et al., 2015).

The creation of a cascade of reservoirs on the bed of the Dnipro River led to a significant reduction of floods and, thus, to a decrease in the difference in water levels in the river during the year. As a consequence, the intensity of the flooding regime of the river has also decreased. Old floodplain lakes are more turbid than young ones and this is mainly due to an increase in phytoplankton (Roozen et al., 2003). However, there is a constant seasonal and daily level difference in the Dnipro River. The natural rhythm of water level in the river is superimposed on the artificial regulation of the level at the dams. These water level fluctuations are the reason for the constant water exchange in the floodplain water bodies. An increase in water level in the Dnipro River causes water to flow into the floodplain water bodies, while a decrease, on the contrary, leads to an outflow of water from the floodplain water bodies into the river. It is natural that the intensity of water exchange depends on the distance from the water body to the river channel, on the order of the water body and the level of its connectivity with other water bodies. Obviously, it is the water flowing from the Dnipro River into the floodplain water bodies that is the source of biogenic elements and a factor in the growth of eutrophication.

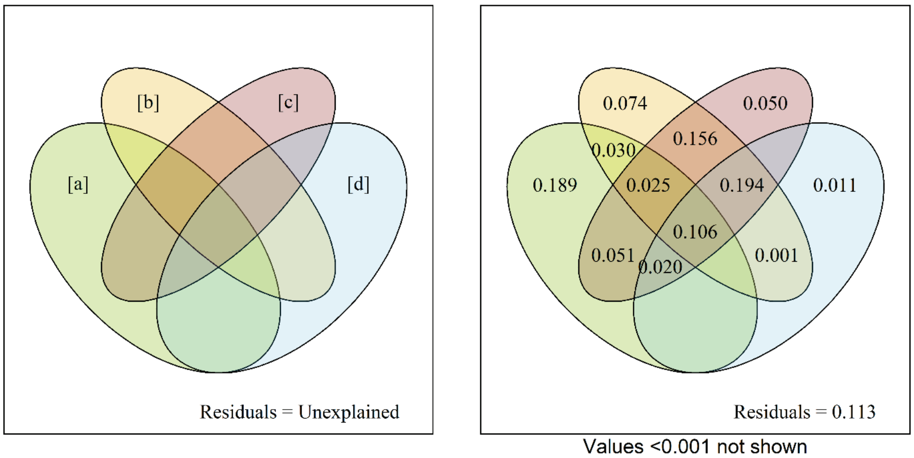

Fig. 7. Variation partitioning of chlorophyll-*a* a concentration under the influence of spatial variables (*a*), water body area (*b*), connectivity (*c*), and water body order (*d*)

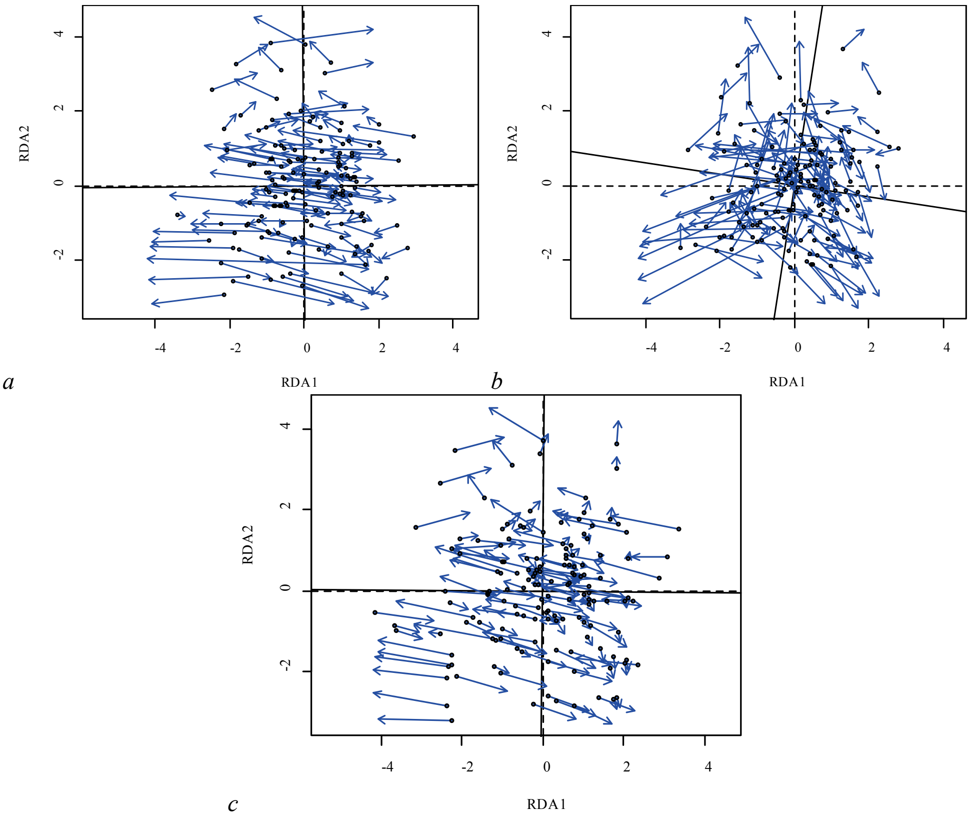

Fig. 8. Procrustes analysis of ordination solutions for the chlorophyll-*a* content variation matrix using area (*a*), connectivity (*b*), and order (*c*) of water bodies as conditional variables: the points are water bodies, the arrows denote directions of shift of ordinal solutions with spatial predictors and individual variables as conditional predictors

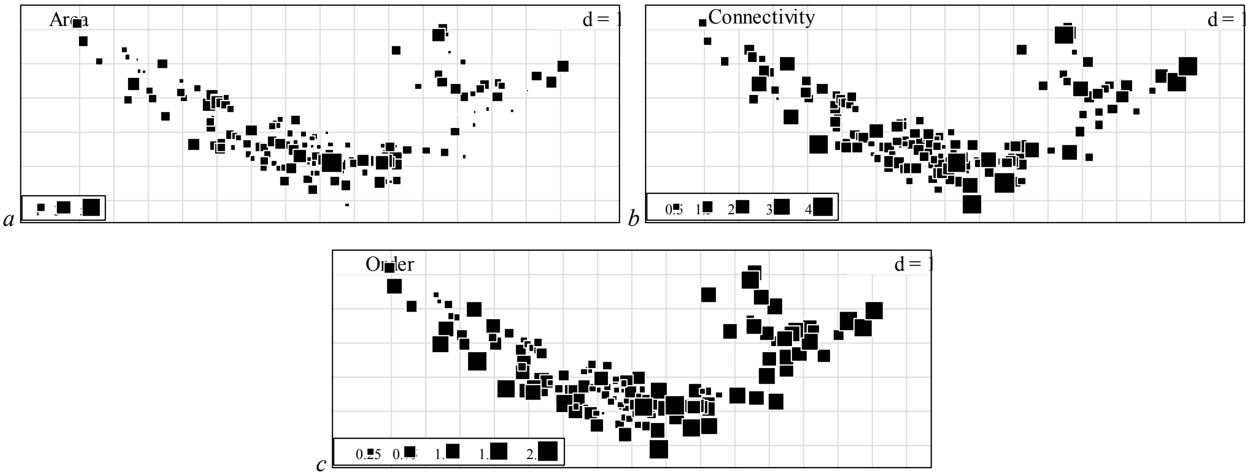

Fig. 9. Spatial variability of shifts of ordination solutions, which result from the use of area (*a*), connectivity (*b*) and order (*c*) of water bodies as conditional variables

Groundwater can also be a source of water flowing into floodplain water bodies. The groundwater is generated as a result of moisture condensation or precipitation filtration through a sand terrace that is located directly along the river floodplain (Zhukov et al., 2018). Groundwater has low salinity and is a factor that has the opposite effect of eutrophication. Groundwater is most important for water bodies in the near-terraced floodplain. Therefore, the distance from the channel of the Dnipro River is a marker of increasing efficiency of low-mineralized water inflow through groundwater runoff from the first terrace above the floodplain.

Water bodies can become disconnected and some of the floodplain water bodies are temporarily or permanently isolated (Kunakh et al., 2020, 2021; Teluk et al., 2020; Yorkina et al., 2021). After disconnection from neighbouring bodies of water, the water in the lake becomes slow-flowing or completely standing, resulting in the increased deposition of fine soil particles and an increase in the amount of silt and clay in the substrate. The simplification and degradation of the structure of aquatic macrophyte communities may result from the isolation of water bodies (Zhang et al., 2014). During floods, the connection between water bodies can be restored. Traditionally, all water bodies in the river floodplain are called lakes, although formally, only isolated water bodies are lakes.

A typology of water bodies has been proposed to describe hydrological connectivity. The five types of water bodies were distinguished. The possibility of water exchange through groundwater or surface water was considered as the classification criteria. However, this approach appeared to be extremely site-specific and complex field work is required to characterize a particular water body, which makes the classification procedure very difficult (Gallardo et al., 2008).

Basically, water bodies in the floodplain were represented by channels or bays of the Dnipro River. The connectivity as a categorical variable is a convenient tool for qualitative characterization of the potential level of water exchange in a particular water body. The categories of connectivity do not form an order and are in some sense independent values. The morphological categories themselves do not form order relations, but can only be used to distinguish natural objects from each other. Order forms the function of objects and in this respect, a connectivity can lead to differently directed results. An increase in connectivity can result in an increase in the potential for eutrophication if the source of water is predominantly a river channel. Alternatively, an increase in connectivity can lead to a decrease in eutrophication if the source of water in the water body is predominantly groundwater. Therefore, the procedure of comparing the level of connectivity is formal and we can only say that a given object differs or not from other objects by the criterion of connectivity.

The order of the water body is an indication of the position of the water body in the sequence from the river channel. Each link in this sequence leads to a decay of water level changes and to a decrease in the intensity of water exchange between neighboring water bodies. The anthropogenic component of water level change is high-frequency. Water level during water discharge at the dam can change significantly during the day and the direction of water flow in the floodplain reservoirs can also change. As the order of the reservoir increases, the rheophilic regime may change to limnophilic. Lake ecosystems are particularly sensitive to nutrient inputs from the watershed because of the thermal stratification of the water column during the period when the primary production is highest (spring and summer). The thermal stratification divides the water column into two layers: the upper layer, the warmer and more illuminated epilimnion, where primary production occurs, and the colder, deeper layer, the hypolimnion. Thermal stratification occurs in all lakes, but on different time scales. In shallow lakes, thermal stratification is unlikely to last longer than a few hours or days (Vinçon-Leite & Casenave, 2019). The area of the water body is proportional to the volume of water in it and, in some cases, to the depth of the water body. Water transparency is positively related to lake depth and the presence of vegetation (Roozen et al., 2003). Water bodies with high water flow have a U-shaped profile and high depths of water bodies, which can reach 4 meters. Ponds with low flow have a flat bottom and shallow depths of 0.5–1.0 meters. The small floodplain lakes are more sensitive to nutrient enrichment. Due to the higher ratio of sediment area to water volume compared to large lakes, the release of nutrients from sediments to water is more probable (Maberly et al., 2020). Water bodies with greater depths take much longer to warm up and have a thermocline, which prevents the mixing of the upper and lower layers of water Small bodies of water are more susceptible to climate change. An increase in average air temperature causes a direct increase in surface water temperature, intensification of evaporation and eutrophication processes, a decrease in oxygen content and an increase in the concentration of pollutants in water bodies (Biswas et al., 2018). The underwater light climate is strongly influenced by chlorophyll-a and to the greatest extent by the inorganic suspended matter. The dissolved organic carbon is less important (Roozen et al., 2003). Therefore, in deep transitional water bodies, eutrophic water can be transferred to the following water bodies in the chain, having much less impact on the enrichment of the aquatic ecosystem with nutrients than is the case with shallower and rapidly warming water bodies.

The role of secondary eutrophication should be considered in relation to the water body system. Most floodplain lakes have an intense resuspension of inorganic suspended matter. The wind resuspension is much less important than the resuspension by benthos fishes (Roozen et al., 2003). Undoubtedly, the source of eutrophication increase in floodplain reservoirs is nutrients dissolved in the water of the Dnipro River. However, our results indicate that the level of eutrophication in floodplain water bodies is higher than in the Dnipro River itself. The biogenic accumulation of nutrients leads to a concentration of eutrophication factors in floodplain ecosystems and an increase in their eutrophication. The nutrients accumulated in plant biomass and detritus can enter the water again in the process of organic matter degradation, which is the cause of secondary eutrophication. The incoming nutrients can be a factor in the rapid growth of lower algae, causing negative effects of eutrophication.

The distance from the river to the floodplain lakes is usually related to the frequency of hydrologic connectivity. The height of the river embankment also matters. The morphology of floodplain lake boundaries affects both flow and water turnover during floods. Dense thickets of emergent vegetation are a natural biological filter for water entering natural water lakes, causing a decrease in water velocity and simultaneous settling of suspended material. Sediment accumulation has increased due to the lack of intense erosional flooding over the past several decades, which reduces groundwater infiltration into natural lakes. The timing and duration of connection of a floodplain lake to the main river channel depends on river flow and other wetland characteristics (Gallardo et al., 2008). The differentiation of the floodplain into riverbed, central and near-terrace indicates the different intensity of deposition of disturbed soil particles during floods. Near the riverbed, the sediment is composed of coarse sand particles, and the size of the sediment particles decreases as one moves away from the riverbed. Smaller particles within soils increase the capillary rise of water and thus provide groundwater supply to water bodies. The sandy soils near the river channel have almost no groundwater supply, while the clay soils in the near-terraced floodplain create conditions for constant groundwater recharge of water bodies. The central floodplain occupies the largest area, so it is natural that the number of water bodies in it is the largest.

The dynamics of chlorophyll-*a* content in water followed the seasonal course of temperatures. The concentration was lowest in the cold period of the year and reached its maximum in the second half of summer. The autumn decrease occurred at the end of September. The seasonal course of air temperature was superimposed on the peculiarities of the temperature regime of a particular water body, which depended on its depth and flow rate. The depth of the Dnipro River is the greatest, so the water temperature in it was the lowest in summer. In shallow water bodies, water warmed up quickly and to relatively higher levels, which stimulates intensive development of algae in conditions of nutrient abundance. Water exchange with colder water bodies contributed to lower temperatures in floodplain water bodies. Thus, the role of the connectivity factor can be explained as a consequence of the ability of water exchange to influence the temperature regime of water bodies. Excluding isolated water bodies, the greater was the connectivity of the water body, the lower was the level of chlorophyll-*a* in it. Obviously, water exchange is both a source of nutrients and can be considered as a factor of eutrophication and a cause of decrease in relative temperature of a given water body. Isolated water bodies had predominantly ground nutrition, so they did not follow the general pattern established for open water bodies. The increase in chlorophyll-*a* concentration with increasing order of a water body can be explained by a decrease in the intensity of water exchange and a decrease in the depth of water bodies of higher order. An increase in the order of a water body is accompanied by a branching network of water bodies, the ability of water bodies to clear sediments decreases. Sediment accumulation leads to a decrease in their depth. Warming of shallow ponds and accumulation of organic matter in them are factors of intensive growth of blue-green algae.

Floodplain lakes accumulate N and P from the river, surface runoff, and primary production. Natural factors reflecting the buffering capacity of lakes for nutrient inputs may also play an important role in explaining eutrophication status (Wenzhi Liu et al., 2010). The connectivity and order of water bodies are of different importance for the dynamics of eutrophication, with connectivity playing a greater role. The connectivity indicates the possibility of water exchange between water bodies, while the order of the water body indicates the gradient of conditions as one moves away from the river channel in the sequence of water bodies. Thus, the evacuation of surplus organic matter, which results from mass vegetation development with excessive nutrient inputs, is a key driver of the eutrophic regime of water bodies. The increasing importance of regulatory processes enhances in agreement with an increase in chlorophyll-*a* concentration in a water body. The importance of the considered factors reaches the highest level in summer time, when simultaneous maximum warming of water bodies and minimum water level in them take place. Accordingly, the differences between deep and relatively cool water bodies and shallow water bodies that warm up quickly, which significantly stimulates the growth of organic mass, reach the greatest contrast.

The application of spatial predictors allows one to solve two problems. First of all, to evaluate the spatial structuring of the influence of the identified factors. The role of factors that are not measured in this study, but may influence the variation in chlorophyll-a concentration, can also be assessed. The spatial variables, connectivity and order of the water body, distance to the river, and area of the water body can explain 4.7 times more variation in chlorophyll-*a* concentration than the pure spatial component. Thus, the predictors considered are the leading ones for describing patterns of variability in chlorophyll-a concentration. Obviously, connectivity and order of water bodies are morphological markers of functional properties and regimes of water bodies and do not fully accurately describe them, so an additional part of the variability of the studied index can be distinguished as a pure spatial pattern. We should note that the connectivity and order of water bodies are also spatially structured predictors. This means that the functional content of these indicators is not spatially invariant, but varies in a regular way. The role of connectivity is especially high in the zone of contact of the system floodplain ponds with the river channel. This corresponds well to the concept that the connectivity of a water body is a marker of the ability of the water body to undergo purification from excessive amounts of synthesized organic matter. At the same time, in water bodies that are in contact with the river bed, there is an evacuation of organic matter, which is subsequently carried out with the flow of water in the Dnipro River. In other water bodies, their quantity is evened out between the neighbouring water bodies, and in this sense, the role of connectivity as a factor of variation of eutrophication is reduced. The spatial component of water body order factor variation is much more flattened. This pattern fits well with the notion that pond order is a marker of the introduction of water masses that are enriched with additional nutrients.

The role of water body area in varying chlorophyll-*a* concentrations is also demonstrated by the spatial pattern. Depth, volume, elevation, and mean annual precipitation are major predictors of eutrophication parameters for lakes (Wenzhi Liu et al., 2010). The area is an indicator that can be easily estimated using GIS-technologies. However, to describe the chlorophyll-*a* dynamics, the more detailed morphological description of water bodies, which includes the depth, profile shape, and shoreline shape of the water body, is important. However, even accurate acquisition of relevant information does not solve the problem of their formalization and quantification of their significance. The spatial predictors allow one to indirectly and accurately estimate the role of unaccounted spatial factors, which were not measured directly.

The spatial patterns of variation in chlorophyll-*a* concentration have a complex multiscale structure, indicating the multiple nature of the acting factors. The spatial variability was represented as a composition of broad-scale and medium-scale spatial processes. The broad-scale process is most dependent on connectivity, whereas for the medium-scale process the leading one is the effect of water body order.

Conclusion

The increase in chlorophyll-*a* concentration in water bodies of the Dnipro-Oril Nature Reserve begins in the second half of spring, reaching a plateau at the end of June. The decrease of chlorophyll-*a* concentration occurs from the second half of September. Chlorophyll-*a* concentration increases as the floodplain water bodies are removed from the Dnipro River channel and as the order of the water bodies increases. The connectivity and increased area of floodplain water bodies contribute to a decrease in the level of eutrophication. The spatial patterns of variation in chlorophyll-*a* concentration have a complex multiscale structure, indicating the multiple nature of the acting factors. The spatial variability was represented as a composition of broad-scale and medium-scale spatial processes. The broad-scale process is most dependent on connectivity, whereas for the medium-scale process the leading one is the effect of water body order. The complex nature of the factors that cause the dynamics of eutrophication in floodplain water bodies leads to the generation of a multiscale structure of spatial variation in chlorophyll-*a* concentration. The variability of chlorophyll-*a* is represented as a composition of a broad-scale and a medium-scale spatial component. The broad-scale component depends on connectivity of water bodies, and the medium-scale component depends on the order of water bodies.

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