since 1961

Baltica

BALTICA Volume 36 Number 1 June 2023: 13–29
https://doi.org/10.5200/baltica.2023.1.2

Methodology for assessing the geoecological state of landscape-lake systems and their cartographic modelling (case study of Lake Bile, Rivne Nature Reserve, Ukraine)

Vitalii Martyniuk*, Vasyl Korbutiak, Ihor Hopchak, Ivan Kovalchuk, Ivan Zubkovych

Martyniuk, V., Korbutiak, V., Hopchak, I., Kovalchuk, I., Zubkovych, I. 2023. Methodology for assessing the geoecological state of landscape-lake systems and their cartographic modelling (based on the case study of Lake Bile, Rivne Nature Reserve, Ukraine). *Baltica*, *36 (1)*, 13–29. Vilnius. ISSN 1648-858X
Manuscript submitted 1 September 2022 / Accepted 24 February 2023 / Available online 2 May 2023

Abstract. The reassessment of the geoecological state of landscape-lake systems (LLS) and their cartographic modelling employing the methodology of landscape limnology has been conducted. The purpose of this study was to characterize the essence of the applied methodology and to evaluate the geoecological state of LLS based on the case study of the Lake Bile basin, Rivne Natural Reserve, Ukraine and to develop cartographic models of the aquatic complex and its catchment as an information basis for the integrated management of water and land resources of LLS and sustainable nature management. The results obtained from the field instrumental research conducted within the Bile Lake basin were used for substantiating the use of laboratory methods and QGIS software, for producing the catchment land use map and assessing the geoecological state of the basin, for developing the bathymetric model of the reservoir and determining hydrological and hydrochemical parameters, for analyzing the lithological composition of the rocks of the exploratory well, elucidation of the genesis of the reservoir, for the first-time production of landscape maps of the natural-aquatic complex and water catchment, and for establishing landscape-metric characteristics of the lake-basin system. The degree of the anthropogenic load on landscape complexes in the 100-meter zone around the lake was assessed. The performed research showed that the conceptual foundations of landscape limnology, as a modern transdisciplinary scientific direction, are an innovative and effective tool for assessing the geoecological state of LLS, and scientifically supporting the integrated management of its water resources and sustainable nature management.

Keywords: *landscape limnology; lake basin; lake genesis; bathymetric map; hydrochemical state of the lake; natural aquatic complex; geoecological assessment; landscape maps*

Vitalii Martyniuk (vitalii.martyniuk@rshu.edu.ua), http://orcid.org/0000-0002-8654-3510,*
Rivne State University of Humanities, Department of Ecology, Geography and Tourism, Rivne, Ukraine;

Vasyl Korbutiak (v.m.korbutiak@nuwm.edu.ua), https://orcid.org/0000-0002-8273-2306,
National University of Water and Environmental Engineering, Department of Land Management, Cadastre, Land Monitoring and Geoinformatics, Rivne, Ukraine;

Ihor Hopchak (i.v.hopchak@nuwm.edu.ua), https://orcid.org/0000-0003-4774-5504,
State Agency of Water Resources of Ukraine, Kyiv, Ukraine;

Ivan Kovalchuk (kovalchukip@ukr.net), https://orcid.org/0000-0002-2164-1259,
National University of Life and Environmental Sciences of Ukraine, Department of Geodesy and Cartography, Kyiv, Ukraine;

Ivan Zubkovych (zubkovych11@ukr.net), https://orcid.org/0000-0002-0641-2204,
Nobel National Nature Park, Nobel, Ukraine

**Corresponding author*

INTRODUCTION

Among the objects of the nature reserve fund (NRF), lakes stand out as being of particular interest to the scientific community and ordinary citizens as consumers of ecosystem services (Schallenberg *et al.* 2013; Xu *et al.* 2018; Sterner *et al.* 2020). From a paleo-geographical point of view, lakes are a kind of "window" through which the climate of past eras can be studied, and landscapes as a whole can be reconstructed. Lakes regulate the hydrological regime of the landscape, affect the mineralization of natural waters, level microclimatic changes in arid natural complexes; they accumulate fresh water and create special conditions for the life of aquatic organisms. Resort zones, tourist and recreational facilities, commercial fishing farms, ecological and national parks, nature reserves, etc. are established near lakes.

The Volyn Polissia physical-geographical region includes a number of nature reserves (Rivne, Cheremske), national parks (Shatsk, Prypiat-Stokhid, Nobel, Radzivil Pushcha, Tsuman Pushcha), regional landscape parks and lower-level NRF facilities with dozens of lakes within their territories. Such objects are inventoried, their monitoring observations are conducted in individual reservoirs, and their ecological passports are developed in accordance with the Chronicles of Nature, which are kept by research sectors of nature reserves and national parks.

Rivne Nature Reserve was established in 1999. Now, the total area of the reserve is 42,288.7 hectares (Decree dated August 14, 2014 N 264… 2015). Its territory includes four areas, namely Lake Bile, Perebrody, Syra Pohonia and Somyne. In the diverse reserve landscape, a number of lakes (Somyne, Krysyne, Bile) and wetland complexes stand out.

It should be noted that some territories of Rivne Nature Reserve are included in the Ramsar sites list, i.e.: UA-1402: Perebrody Peatlands (12,718 ha), UA-2274: Syra Pogonia Bog (9.926 ha), UA-2275: Somyne Swamps (10.852 ha), UA-2281: Lake Bile and Koza Berezyna Mire (8,036.5 ha), (Wetlands… 2022).

This research considers lakes not just as objects of hydrography or hydrology, but as complex natural formations with their own genesis, evolutionary development, functioning and subsequent ecosystem transformation. Integrative studies at the junction of landscape science, landscape ecology (Forman, Godron 1986; Richling, Solon 1998; Turner *et al.* 2001; Miller *et al.* 2002; Hrodzynskyi, Savytska 2008; Chmielewski 2012; Hrodzynskyi 2014; Hess, Tasa 2017; Gergel, Turner 2017) and limnology (Imberger, Patterson 1990; Wetzel, Likens 1991; Horne, Goldman 1994; Wetzel 2001; Choiński 2007; Kumar 2005; Il'in 2008a, b; Sethi, Kulkarni 2011; Cole, Weihe 2015; Oakenfold 2017; Evans III 2021) are considered to be landscape limnology studies. Today, they show sufficient theoretical and methodological potential for development and application in geoecology and sustainable nature management.

In landscape science (Herenchuk et al. 1975), a lake is considered to be a complex aquatic tract (aqua-tract), a component of the morphological structure of the landscape. It should be noted that this view mainly applies to small lakes with different types of bottom sediments, in which the lake basin "cuts through" various geological rocks of both Quaternary and pre-Quaternary origin. To emphasize the geocomplex approach to the lakes, landscape scientists suggested using the term natural aquatic complex. Back in the 1960s, the concept of the natural aquatic complex (NAC) was substantiated by N. Solntsev for the units of physical-geographical zoning of the ocean, as analogues of land landscapes, which gave impetus to the development of the conceptual foundations of inland NACs (rivers, lakes, reservoirs, etc.) studies (Martyniuk 2008).

In the 1990s, based on the complex field studies of the Volyn Polissia region, we justified the use of landscape method for lake research (Martyniuk 1998) and developed the landscape-limnological model of the lake-basin system (Martyniuk 1999).

The morphological structure of the lake NAC depends on peculiarities of the lake basin genesis, its geomorphological structure, elevation levels of the adjacent landscapes' relief, sedimentation processes in the reservoir, etc. Considering the lake basin from the landscape positions, it is possible to distinguish the morphological units of the NAC of a lower rank – aquatic sub-tracts (aqua-sub-tracts).

Such aquatic sub-tracts consist of littoral, sublittoral, profundal zones, which are distinguished by lithological-geomorphological factors, and the pelagic ones, which are distinguished by the thermal heterogeneity of the water bodies of the reservoir. The upper level of the lake NAC is occupied by aquatic facies (aqua-facies), which are structural components of the aquatic sub-tract. They are distinguished by the micro-relief of the lake basin, the physical and geochemical processes that develop in the lake, the composition and size of bottom sediments, the species diversity of plant communities (surface and underwater), the peculiarities of the temperature regime in the warm season of the year (Kovalchuk, Martyniuk 2015; Martyniuk 2015).

The development of landscape limnology studies in the USA is driven by research contributions of Webster *et al.* (1996), Soranno *et al.* (1999), Martin, Soranno (2006), Soranno *et al.* (2009, 2010), Fergus *et al.* (2017), etc. The main methodological structure employed by American landscape limnologists is the triadic concept of the lake freshwater ecosystem functioning, the ecosystem of the catchment area and the anthropogenic factor, i.e. economic activity. Each of the components of such a structure has a set of natural (precipitation, drain flow, groundwater feeding the lake; glaciation history during the Quaternary, geological rocks, configuration and relief, catchment area soils) and anthropogenic (national environmental policy, land use, road infrastructure, ecosystem value, etc.) elements that are hierarchically organized and interact in different spatial dimensions – from regional to local. According to this concept, the landscape-limnological study of the ecosystem is aimed at learning the peculiarities of the chemical, physical and biological state of the lake as a local level object of such a structure (Soranno *et al.* 2010).

Limnological studies of recent years reflect only certain aspects of the complex landscape and limnological approach to the study of lakes. They are related to: 1) zonal regulation of the protection areas of the Olsztyn Lake basin, taking into account the slope coefficients of the relief (Hakuć-Błażowska, Cymerman 2011); 2) restoration of lake shores based on landscape ecology (Boromisza *et al.* 2014); 3) assessments of the ecological consequences of hydromorphological loads on European lakes (Poikane *et al.* 2020) and assessments of the ecological state of lakes in natural parks whose watersheds are located at different geomorphological levels (Paszteleniec, Kutyła 2015); 4) changes in water resources under the influence of natural and anthropogenic factors (Choiński *et al.* 2016); 5) natural and anthropogenic conditions of fluctuating lake water levels (Nowak, Ptak 2019); 6) assessments of anthropogenic pollution of lakes based on the content of heavy metals in bottom sediments (Ignatavičius *et al.* 2022); 7) correlations between water quality in reservoirs and land use within the watershed basin (Dumitran *et al.* 2020; Česonienė *et al.* 2021); 8) monitoring of the lake water quality according to the data of RSE (Ciężkowski *et al.* 2022; Fesiuk *et al.* 2022). Such a variety of approaches is natural since the development of landscape science and limnology is based on different fundamental concepts. At the same time, most of the above-mentioned publications are united by a common problem, i.e., the study of the geoecological conditions of the reservoirs themselves, or their catchments, or the correlation between the quality of water masses and the nature management implemented in their basins.

In landscape science, the mapping of natural territorial complexes is well-developed (Miller *et al.* 2002), while in limnology, in our opinion, the attention paid to the mapping of lake NACs, except for the bathymetric one, is insufficient. A strong point of limnology is the synthesis of ecosystem processes occurring in the reservoir with the further justification of the aquatic ecosystem "health condition". It is obvious that the principle of the complementarity of sciences has a potential for the fruitful development of landscape limnology in the transdisciplinary direction.

The purpose of the study was to characterize the essence of the applied methodology and to assess the geoecological state of the landscape-lake system (LLS) (based on the case study of the basin of Lake Bile, Rivne Natural Reserve, Ukraine) and to create cartographic models of the aquatic complex and its catchment as an information basis for the integrated management of water and land resources of the LLS and sustainable nature management.

STUDY AREA AND SITE DESCRIPTION

This lake is part of the Biloozersskyi massif of Rivne Nature Reserve (Ukraine) and is situated in the Nyzhnostyrskyi district of the Volyn Polissia region (Fig. 1).

The basin of Lake Bile belongs to the landscape of upland interfluves of water-glacial sands with a close occurrence of chalky marls. In 1984, the lake became part of Lake Bile landscape reserve of national importance and in 1999 – part of Rivne Nature Reserve (Hryshchenko 2008). The Lake Bile reserve territory together with the lake itself is an important structural node of the eco-network of Central-Eastern Europe, the formation of which is a priority direction of the Pan-European strategy for the protection of biotic and landscape diversity. Human economic activity, primarily, the drainage reclamation conducted in the 1960s and 1980s, and the recreational development (the rehabilitation and health complexes) of the territory, have led to the balance disturbance in Lake Bile basin landscape complexes. The lake is situated in the 30-km zone of the Rivne NPP, and the landscapes of the catchment area suffered from the technogenic effects of the accident at this NPP (Chumak *et al.* 1992).

Being highly vulnerable to climate changes, lakes react to them by disrupting functional relationships both in reservoirs themselves and within their catchment areas (Woolway *et al.* 2020).

The analysis of average monthly temperatures (2010–2019) in January and July at the Varash weather station, which is located 18 km southeast of Lake Bile, showed that the average January temperature during this period was -3.73 ºC, and the average July temperature was +20.56 ºC. During the ten-year period, the average annual temperature at the weather station was 9.20 ºC (Fig. 2). The last 7 years in the Volyn Polissia area were quite dry.

A series of glaciations in the Quaternary period had a noticeable influence on the development of the landscape in the region, and hence the genesis of Lake Bile. During the glaciation, the lowlands of the Volyn Polissia region were a periglacial zone of glacial meltwater accumulation in the form of large lake basins and streams that deposited a mass of sandy material. Under the influence of melting glacial waters, swamp-lake natural complexes were formed in low-lying areas. The erosive and hydrodynamic activity of the glacier, primarily of the Dnieper glacier (290–240 thousand years), significantly transformed the relief

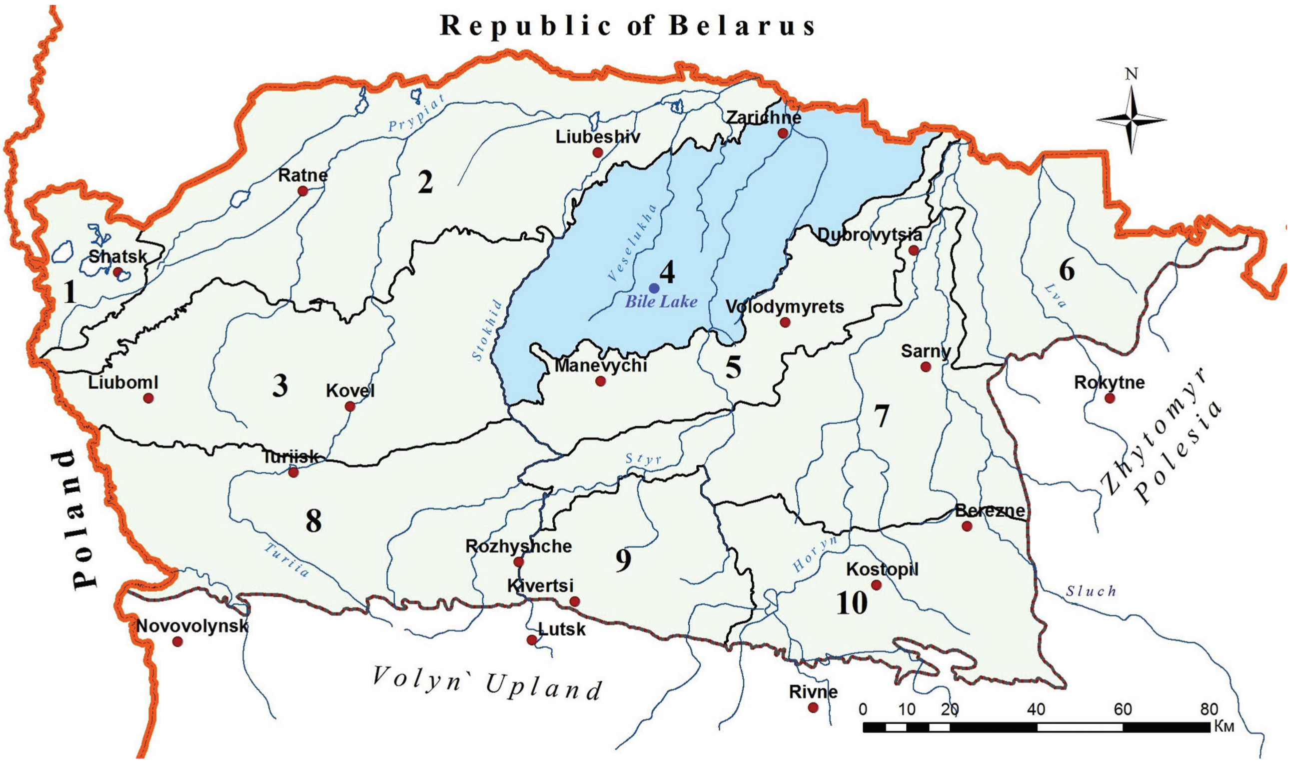


Fig. 1 Localization of Lake Bile basin in the scheme of physical and geographical zoning of Volyn Polissia. *Physiographic regions:* 1 – Shatsk, 2 – Upper-Prypiat, 3 – Liuboml-Kovel, 4 – Lower-Styr, 5 – Manevychi-Volodymyrets, 6 – Lva-Horyn, 7 – Kolky-Sarny, 8 – Turiisk-Rozhyshche, 9 – Kivertsi-Tsuman, 10 – Kostopil-Berezne

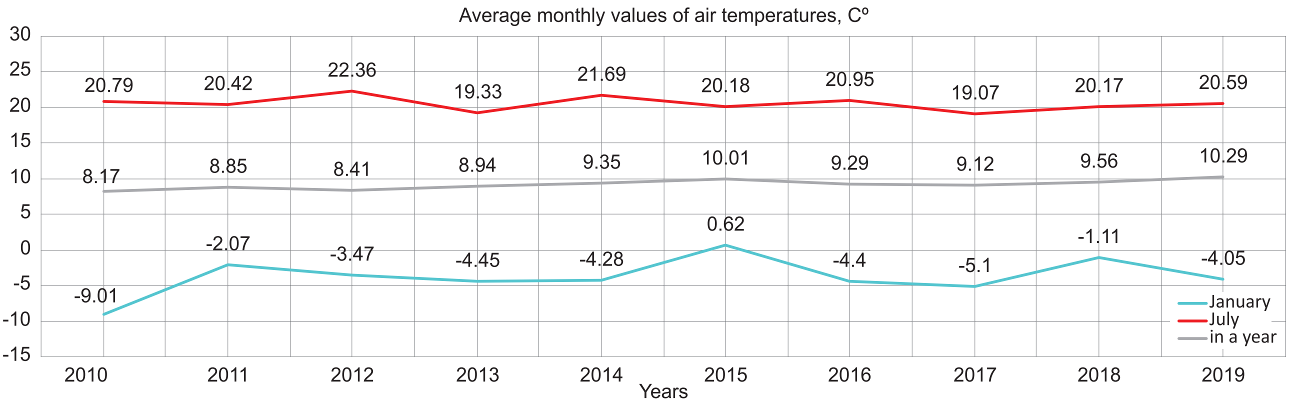


Fig. 2 Dynamics of average monthly and average annual temperatures recorded at the Varash weather station (based on the materials of the automatic weather station NAWS-301 ACKPC of the Rivne nuclear power plant)

of the sedimentary cover, which lifted the Upper Cretaceous deposits close to the daytime surface in some areas. All further development of landscapes took place under the influence of excessive wetting of the territory. A ridge-hilly relief was formed on the raised sand massifs before they were covered by vegetation. An important feature of the landscapes of the Volyn Polissia region is their insufficient drainage, which contributes to the wide spread of swamps, primarily, the lowland ones (Zubkovych, Martyniuk 2020). Such a general overview of the formation of landscapes allows assessing the paleo-geographic conditions in which the erosion-hydrographic network and lake basins of the Volyn Polissia region were formed.

RESEARCH METHODOLOGY AND METHODS

The methodological base of this study consists of the basin approach in geography (Horton 1945; Kovalchuk, Pavlovska 2008; Samoilenko, Ivanok 2015; Kashiwaya 2017; Kovalchuk, Kovalchuk 2018; Kovalchuk et al. 2020; Shit *et al.* 2022) and the concept of "lake-catchment area" in limnology (Oldfield 1977). The study is based on the materials of the field landscape limnology research performed within the Lake Bile basin in 2019–2021. The following methods were employed in this study: the method of «key areas» of landscape science (Herenchuk *et al.* 1975), soil profiling at reference points within the catchment area (Lyko *et al.* 2019), general limnology methods (Imberger, Patterson 1990; Cole, Weihe 2015; Oakenfold 2017; Evans III 2021), and methods of landscape and geographical mapping (Miller *et al.* 2002). Bathymetric surveying of lakes is one of the most time-consuming and mandatory components of landscape and limnological studies. This fact is also confirmed by other scientists' (Giuliani *et al.* 2019; Paul *et al.* 2019; Muhtadi *et al.* 2020; Chormanski *et al.* 2021; Simpson *et al.* 2021; Hamilton *et al.* 2022; Yang *et al.* 2022) studies related to the bathymetric survey of different water bodies in terms of depth, area and natural-geographical location. In August 2020, high-precision echo sounding with the geodetic surveying of the water section was carried out on Lake Bile. We used a *Hummingbird 597ci HD* sounder, which was fixed on the transom of a 2-seater boat with an electric drive. The development of the bathymetric model of Lake Bile involved the correction of echograms aimed to specify and correct the depth values in the areas where the bottom was covered with algae and silted with fine fractions. Interpolation between track points was performed using the *TIN* method. The obtained bathymetric model served as the basis for assessing the hydrological parameters of the reservoir, which is a prerequisite for the analysis of the lake basin genesis and the subsequent development of the landscape map of the lake's NAC.

Analyses of soil samples collected from the catchment, bottom sediments, and lake water were performed in certified laboratories (hydro-chemical analyses of water were performed in the respective laboratories of the National University of Water and Environmental Engineering (Rivne), and geochemical analyses of soils and bottom sediments – in the respective laboratories of the Rivne Branch of the State Institution «Soils Protection Institute of Ukraine»). The data on pre-Quaternary rocks within the catchment area and adjacent parts of the lake basin were taken from the materials of the Rivne Geological Exploration Expedition (Rivne GEE).

Indicators of diversity and complexity of landscape structures reveal an important aspect of the cartographic model of the lake-basin system (LBS). Although the arsenal of landscape indicators is quite large (Hrodzynskyi 2014), only those that are the most informative in assessing the complexity of the morphological structure of landscape complexes (territorial and aquatic) of LBS were selected and used in our study. They are as follows:

The average area of the contour (or landscape selection), S_0:

$$S_0 = S/n \tag{1}$$

where S_0 is the area of the studied territory (lake basin, aquasub-region, aquafacies or geotope), n is the number of landscape contours within the studied territory.

The index of fragmentation of landscape contours ($I_{f.s.}$) is calculated as the ratio of the number of landscape contours (n) to the area (S) of the object under study:

$$I_{f.s.} = n/S \tag{2}$$

This index shows the number of landscape contours within the LBS (the number of water bodies, aquafacies within the NAC or other morphological units of the catchment).

The index of landscape complexity ($I_{l.c.}$) is defined as the ratio of the number of landscape contours (n) to the average area (S_0) of the morphological units of the lake basin system:

$$I_{l.c.} = n/S_0 \tag{3}$$

The index of landscape fragmentation ($I_{l.f.}$) reflects the ratio of the average area of landscape allocations (S_0) to the area of the species (S) of the NAC or territorial catchment complexes (Domaranskyi 2006):

$$I_{l.f.} = 1 – S_0/S \tag{4}$$

Graphic materials were made using QGIS and ReefMaster Software. The quantitative assessment of the diversity and complexity of LLS structures was made using QGIS analysis tools. Such quantitative indicators of the LLS landscape structure are essential for conducting monitoring observations and making comparisons between the landscape structure and diversity of other LLS of Volyn Polissia.

RESULTS

Based on the field research materials and using 1:10000 topographic maps and the digital relief model (based on SRTM data), which was developed applying QGIS software (Fig. 3a), we defined the surface catchment area of Lake Bile that makes 9.17 km^2.

The northern, western and eastern boundaries of the catchment area clearly coincide with the orographic barriers around the lake, represented by sandbanks and dunes. In the southern part, a stream from a small lowland swamp drains water into the lake. The length of the water divide line in the catchment area is 14.9 km. The assessment of the catchment area land structure showed that 50.0% of it is occupied by the lake, 0.11% – by melioration canals, 0.72% – by paved roads, 0.4% – by open sands, 5.77% – by wetlands and meadows, 0.69% – by residential lands, and 42.3% – by forests (Fig. 3b). In accordance with the methodology (Martyniuk *et al.* 2020), the ratio of the anthropogenically transformed lands (ATL) to the ecologically stabilizing lands (ESL) is ATL – 1.53%/ ESL – 98.47%. Accordingly, the coefficient of eco-

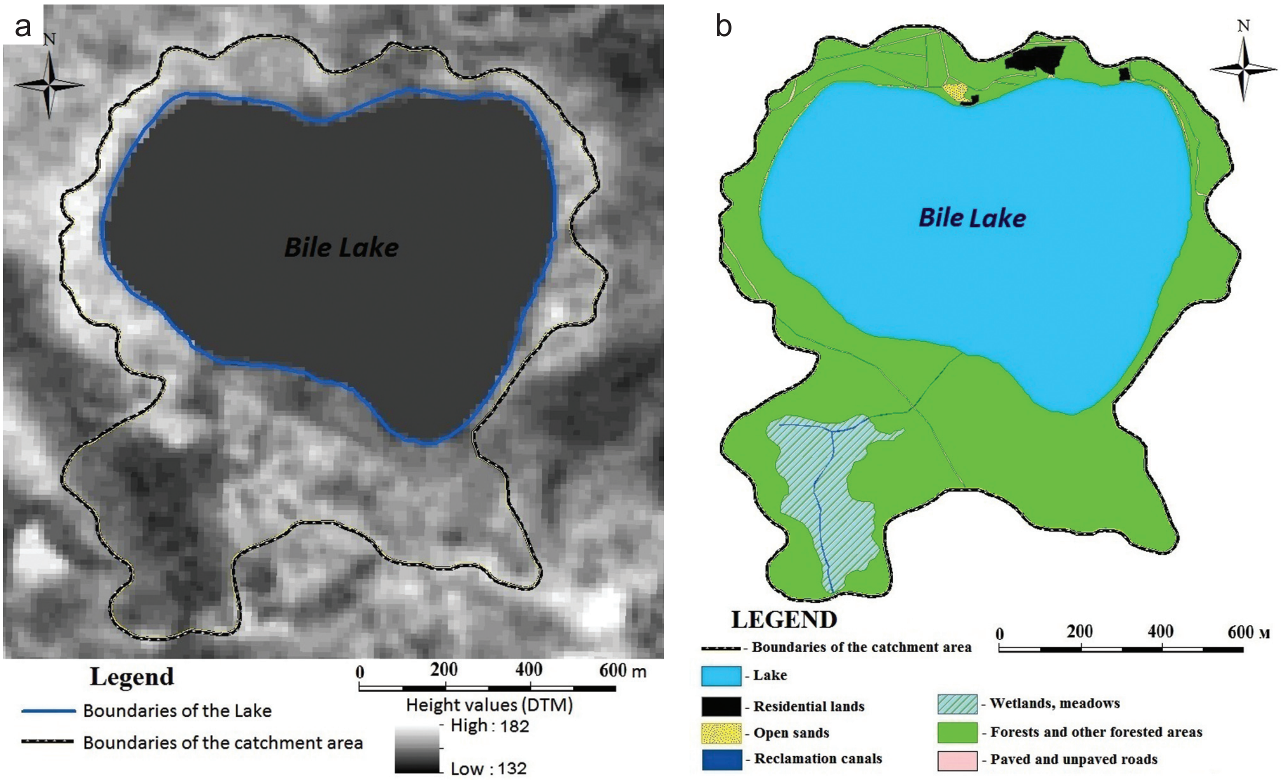


Fig. 3. Land structure model of the Lake Bile basin

nomic development K_{ED} of the catchment area can be defined as the ratio of the area of the anthropogenically transformed lands (S_{ATL}) to the area of the ecologically stabilizing lands (S_{ESL}):

$$K_{ED} = \frac{S\,\mathrm{ATL}}{S\,\mathrm{ESL}} = \frac{13.982 \text{ ha}}{902.675 \text{ ha}} = 0.015 \quad (5)$$

The geo-ecological state of the catchment area according to the structure of land use has benchmark indicators, and the level of economic development of the catchment area is very low.

The landscape structure of the Lake Bile catchment area is represented by 10 natural-territorial complexes (NTC), including the complex aquatic tract of the lake (Fig. 4). The hierarchy of the NTCs in the legend is presented from the "oldest" to the "youngest" according to the age of the tracts.

The largest part of the catchment area is occupied by the NTCs of undulating interfluve sections, which are anthropogenically modified by recreational complexes and equipped beaches (24.82%). According to the frequency of occurrence with nine local areas, the NTCs of gently slanting (6–10º) watershed slopes are distinguished, their area is 15.69%. A total of 27 tracts were identified, the average area of NTC being 33.95 ha.

The assessment indicators of NTCs in the Lake Bile catchment area are given in detail in Table 1. The most vulnerable to climatic changes and to eco-

Table 1 Estimates of natural territorial and aquatic complexes of the Lake Bile watershed

Index of tracts, *n*	Area of the geocomplex type, ha	Share of the type area of the total area	Number of type outlines	Share of the total area	Average area of the type, ha
1	8.380	0.91	2	7.41	4.190
2	143.808	15.69	9	33.33	15.979
3	9.440	1.03	6	22.22	1.573
4	220.243	24.03	1	3.70	220.243
4a	7.249	0.79	3	11.11	2,416
5	2,720	0,30	2	7.41	1.36
6	37.807	4.12	1	3.70	37.807
7	26.373	2.88	1	3,70	26.373
8	1.895	0.21	1	3.70	1.895
9	458.743	50.05	1	3.70	458.743
Total	**916.657**	**100.0**	27	**100.0**	**33.950**

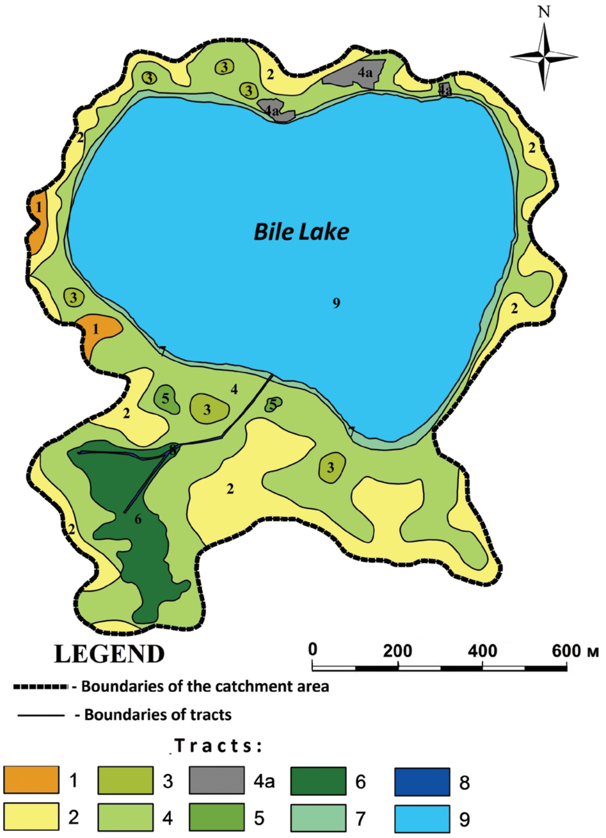


Fig. 4 Landscape structure of the Lake Bile catchment. **1.** High-rising ridges and uplands with abrupt (10–15º) slopes covered with oak-pine and pine-shrub-lichen forests on sod-hidden-podzolic and sod-light-podzolic sandy slightly gravelly soils. **2.** Declivious (6–10º) slopes adjacent to watershed, covered by birch-pine and oak-pine blackberry-green moss forests on sod-podzolic sandy and sandy loam slightly gravelly soils. **3.** Low hills with slanting (3–6º) slopes, covered by birch-oak-pine black and green moss forests on sod-light podzolic, sometimes clayey, sandy and sandy loam soils. **4.** Undulated parts of the interfluve, covered by birch-pine black and green moss forests on sod-light podzolic clayey and sod-clayey sandy and sandy loam soils. **4a.** Undulated parts of the interfluve, anthropogenically modified by recreational complexes and equipped beaches. **5.** Small local closed depressions, covered by *Eriophorum-Sphagnum* and shrub-motley grass – green moss communities, sometimes with coppices of *Bétula nána* and *Salix* on meadow swamp and marshy thin soils. **6.** Marshed depressions, covered by *Eriophorum-Carex-Sphagnum* communities with rarefied forests of *Alnus* and *Pinus* L. on marshy medium-thick and thick soils, partially drained. **7.** The lake terrace with low sandy ramparts, covered with birch-pine-alder small forests and bog-heather and sedge-herb-sedge communities on meadow poorly developed silty sandy and sandy loam and meadow-swamp soils. **8.** Straightened channels of small watercourses. **9.** An oval-shaped lake basin of the karst genesis covered by sapropels with various types of underwater and surface macrophytes on water-glacial sands, underlain by upper cretaceous rocks

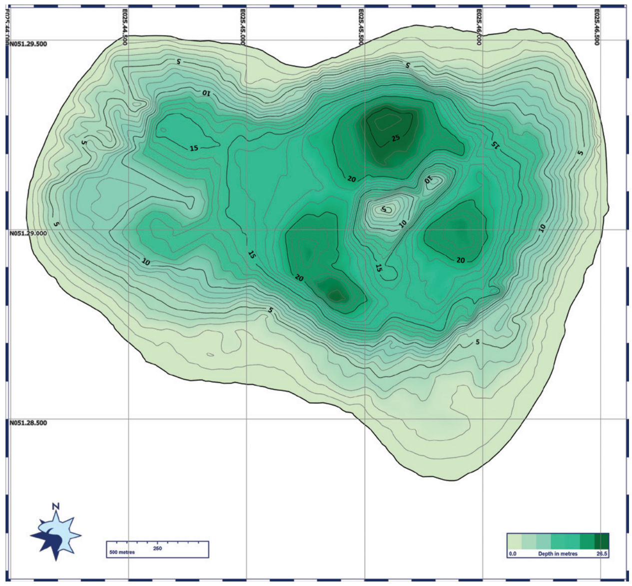


Fig. 5 Bathymetric map of Lake Bile

nomic activity are the NTCs, marked with indexes 5–8; in particular, local closed depressions, waterlogged complexes, lake terraces, stream beds. At the same time, the above-mentioned NTCs (*n* 5–6, 8) are important stabilizers of the hydrological regime in the catchment area.

According to the digital mapping data, the area of the water mirror is 458.7 hectares. The length of the lake is 2.862 km, the maximum width is 2.234 km, and the average width is 1.6 km. The length of the coastline is 8.431 km. According to the geodetic survey data, the water's edge mark is 157.64 m above the sea level (according to Baltic Height System), which is 1.14 m higher than the water's edge mark on topographic maps. Echo sounding data showed that the maximum depth of the lake is 26.8 m, the average depth being 9.37 m. The volume of water is 42932.9 thousand m^3. The generated bathymetric model of the lake basin with the isobaths interval of 1.0 m is shown in Fig. 5.

This model shows that the south-eastern part of the basin is the deepest. The lake has three karst sinkholes with depths of more than 20.0 m. The geographic coordinates of the maximum depth (26.8 m) of the lake, which was recorded during the bathymetric survey, are N 51º29′285″ E 25º45′595″. Among deep karst depressions, there is a raised relief with two small elevations. The calculated hydrographic coefficients (indentation of the coastline, lake length, capacity, openness, depth) and indicators of the "lake-catchment area" system, which complement the morphological and morphometric parameters of the reservoir, are presented in Table 2.

The genesis of the reservoir is an important issue in landscape limnology analysis. The geological ex-

Table 2 Morphometric and hydrological characteristics of Lake Bile

*F, km^2	$H_{abs.}$, m	$h_{mid.}$, m	$h_{max.}$, m	L, km	$W_{max.}$, km	$W_{mid.}$, km	l, km	$C_{t.}$	$C_{len.}$
4.58	157.64	9.37	26.8	2.862	2.234	1.600	8.431	1.112	1.789
$C_{cap.}$	$C_{op.}$	$C_{dep.}$	$V_{lake,}$ thousand m^3	A	ΔS, km^2	$W_{influx.}$**, thousand m^3	$a_{wat.}$	$\Delta_{awat.}$, mm	$A_{layer.}$ mm
0.350	0.489	0.056	42932.9	0.620	1.616	1003.5	0.023	42.784	5801

*Area (F); absolute height of the water level ($H_{abs.}$); maximum ($h_{max.}$) and average depth ($h_{mid.}$); length (L); maximum ($W_{max.}$) and average ($W_{mid.}$) width; length of the shoreline (l); coefficients of: shoreline unevenness ($C_{t.}$); lake lengthening ($C_{len.}$); capacity ($C_{cap.}$); openness ($C_{op.}$); depth ($C_{dep.}$); lake volume (V_{lake}); area index *(A)*; specific catchment (ΔS); volume of inflow water from the catchment (W_{influx}); conditional water exchange ($a_{wat.}$); specific water exchange ($\Delta a_{wat.}$); water storage level on the catchment surface (A_{layer}). **The average annual runoff module, $dm^3/s*km^2$ – 4.3.

ploration well drilled 0.9 km northeast of Lake Bile made it possible to determine the lithological composition of rocks of the Anthropocene and pre-Quaternary deposits (Fig. 6).

Grey, sandy soils with plant root remnants dominate the 0–0.3 m depth interval. Light grey, fluvio-glacial, fine- and medium-grained sands with a yellowish tint and with the inclusion of quartz gravel grains prevail in the depth interval of 0.3–5.0 m. The depth interval from 5.0 to 14.0 m, is dominated by glacio-lacustrine grey loamy sands with a large number of shell fragments of freshwater fauna. Some sections of the core (up to a depth of 8.0 m) contain seeds of marsh flora. In the 8.0-12.0 m depth interval, the colour of loamy sands changes from dark grey to greenish, and there are no fragments of shells and seeds found therein. The horizon of the core at a depth of 12.0–14.0 m is represented by brownish-grey loamy sands with a lot of humus. The core in the depth interval 14.0–15.5 m is composed of moraine loamy sands, with lenses of multi-grained sand cemented with marly material; there are fragments of flint (3.0–5.0 cm in diameter). Grey, dense marls with a cracked structure are dominant in the depth interval 15.5–60.6 m.

Undoubtedly, the area of the underground basin, with which the feeding of the lake is associated, is much larger than the surface catchment area. The difference between the absolute mark of the exploration well 2196 and the water's edge of Lake Bile is 1.06 m. It means that from the absolute mark of 141.08 m (or 16.56 m from the water's edge mark), the Upper Cretaceous sediments of the Turonian layer lie in the lake basin. Thus, the feeding of the lake relates to the artesian waters of the Upper Cretaceous horizon. A dense distribution of the considerably sized (4–14 cm) flint fragments washed out from the Upper Cretaceous horizon is observed in the littoral zone of the lake, especially in the north-eastern part of the reservoir (Fig. 7).

Bottom sediments of Lake Bile are represented by sands and loamy sands, sandy-muddy, organic-clayey sapropel deposits. The geochemical analyses of the bottom sediment samples (0–0.3 m) collected from the south-eastern part of the lake littoral zone showed that the content of nitrogen (N) in percentage on dry matter

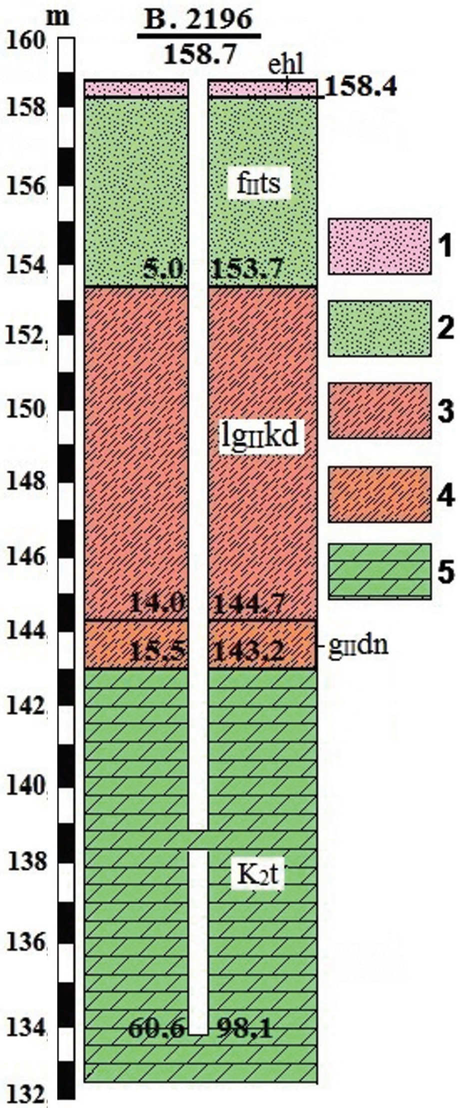


Fig. 6 Geological well 2196 (H – 158.7), 0.9 km northeast of Lake Bile (based on the materials of the Rivne Geological Survey Expedition). 1 – **ehl –** Holocene climatolite. The soil is grey, sandy, with plant root remains; 2 – $\mathbf{f_{II}ts}$ – Tiasmynskyi climatolite. Fine- and medium-grained fluvio-glacial sands with inclusions of quartz gravel grains; 3 – $\mathbf{lg_{II}kd}$ – Kaidatskyi climatolite. Dark grey limno-glacial loamy sands with fragments of shells and whole shells of freshwater fauna; 4 – $\mathbf{g_{II}dn}$ – Dniprovskyi climatolite. Glacial moraine loamy sands with lenses of fine-grained sand cemented by marly material; 5 – $\mathbf{K_2t}$ – Upper Cretaceous of the Turonian stage. Marl is grey, dense, cracked

Fig. 7 Fragments of siliceous rocks in the littoral zone of Lake Bile (photo by V. Martyniuk)

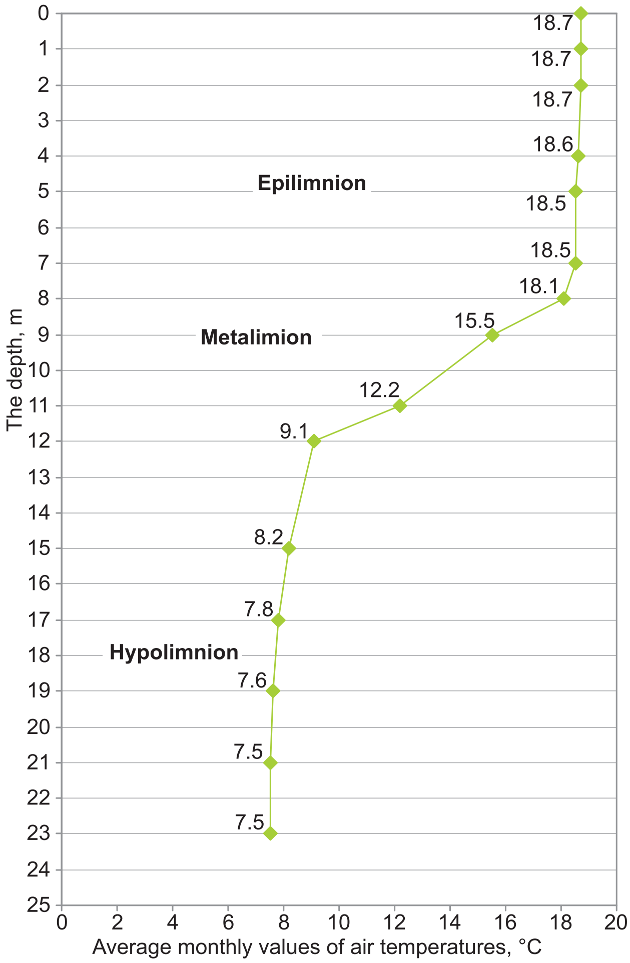


Fig. 8 Distribution of water temperature across depth in Lake Bile (07/08/2019)

basis is 0.49%, and 0.41% in natural matter. The mass fraction of total phosphorus (P_2O_5) in natural matter is 0.22%, and in dry matter – 0.26%. The content of total potassium (K_2O) in a dry matter sample is 0.45% with the same content of K_2O in natural matter.

The temperature regime of the lake is heterogeneous, especially in the warm season of the year (April 15 – October 15); sometimes this chronological range can shift depending on the timing (early or (late) of spring and autumn. It is during this period that thermal stratification is clearly evident in the lakes of the Polissia region (Martyniuk *et al.* 2018). During the exploration of the lake, the thermocline phenomenon was discovered at a depth of 8.0–12.0 m (Fig. 8). In this depth interval, the water temperature sharply changes from 18.1 ºC to 9.1 ºC. Thus, the epilimnion zone of the lake stretches up to the depth of 8.0 m, the metalimnion zone ranges from the depth of 8.0 to that of 12.0 m, and the hypolimnion zone from the depth of 12.0 m to that of 26.8 m.

The hydro-chemical composition of Lake Bile water by salt content does not exceed the maximum permissible concentrations set out for water bodies used for cultural, everyday use and recreational purposes (MPCcerp) and for fishing purposes (MPCfp). The quality of surface water according to salt content is assigned to the 1st category (class I). A significant deterioration of water quality was determined by tropho-saprobiological indicators, i.e., a 0.9-fold exceedance of the MPCcerp was recorded by the BOD_5 indicator, and the exceedance of the MPCfp by the same indicator was found to be 1.9-fold. Accordingly, by BOD_5, water quality belongs to the 5th category (class III). According to COD (Mn), the MPCcerp was found to be exceeded 5.1 times, and MPCfp – 3.4 times; water quality being assigned to the 7th category (class V). According to the nitrate nitrogen content, the lake water belongs to the 7th category (class V), according to the content of ammonium nitrogen – to the 4th category and class III, and according to the phosphate content – to the 3rd category and class II (Table 3).

In the MPCfp block of toxic action indicators, there is an excess of copper by 9.0 times, zinc – by 4.0 times, and according to the quality of surface water, the obtained indicators are assigned to the 1st category (class I). The combined ecological assessment of hydro-chemical indicators of surface water quality of Lake Bile is $I_e = 1.96$, which corresponds to the 2nd category of water class II.

The final document based on the analysis of geo-components of the lake is a landscape map of Lake Bile NAC (Fig. 9). Considering the lake as a complex aquatic tract, the study has identified three aquatic sub-tracts: littoral-sublittoral, profundal and pelagic.

I. Littoral-sublittoral aquatic sub-tract on alluvial sand with various types of surface and submerged macrophytes.

Aqua-facies: **1.1.** Shallow-water, abrasion-accumulative sandy, water-lily-sedge-reed associations with a homogeneous temperature mode.

Table 3 Hydrochemical indices of Lake Bile (as of 09/09/2021)

Serial No	Index	Unit of measurement	*MPC_{cerp}	**MPC_{fp}	Measurement results	***Quality categories and water classes	
					Lake Bile	Category	Class
A. Indicator of salt composition							
1	Mineralization (dry residue)	mg/dm³	≤1000	<300	113.0	**1**	**I**
2	Chloride ions	mg/dm³	350	300	5.65	**1**	**I**
3	Sulphates	mg/dm³	500	100	11.0	**1**	**I**
Integral index by salt block I_1 = 1.0						**1**	**I**
B. Tropho-saprobiological indicators							
4	pH	pH units	6.5–8.5	6.5–8.5	6.65	**3**	**II**
5	Ammonium nitrogen	mg*N*/dm³	0.5	0.5	0.31	**4**	**III**
6	Nitrite nitrogen	mg*N*/dm³	3.3	0.08	0.0	**1**	**I**
7	Nitrate nitrogen	mg*N*/dm³	45	40	3.6	**7**	**V**
8	Phosphorus phosphates	mg*P*/dm³	3.5	2.14	0.05	**3**	**II**
9	Biological oxygen consumption, BOC_5	mgO_2/dm^3	≤ 6 (t = 20)	≤ 3.0	5.6	**5**	**III**
10	Chemical oxygen consumption (Mn)	mgO_2/dm^3	≥ 4	≥ 6	20.3	**7**	**V**
11	Suspended substance	mg/dm³	0.75 + backg round (30)	15	< 5.0	**1**	**I**
12	Calcium	mg/dm³	–	180.0	20.0	–	–
13	Magnesium	mg/dm³	50.0	40.0	24.3		
14	Hydrocarbons	mg/dm³			73.2	–	–
15	Rigidity is general	mmol/dm³	7	7	3.0	–	–
16	Alkalinity is general	mmol/dm³	–	–	1.2	–	–
17	Color	degrees	80	20	40.0	–	–
Integral index by tropho-saprobiological block I_2 = 3.88						**4**	**III**
C. Specific indicators of toxic impact							
18	Copper	mg/dm³	1.0	0.001–0.01	0.09	**1**	**I**
19	Zinc	mg/dm³	1.0	0.01	0.04	**1**	**I**
20	Iron	mg/dm³	0.33	0.1	0.06	**1**	**I**
21	Mangan	mg/dm³	0.1	0.01	0.001	**1**	**I**
Integral index by block of indicators of toxic action I_3 = 1.0						**1**	I
Combined ecological assessment of hydrochemical indicators I_e = 1.96						2	II

Maximum permissible concentrations (MPC) were calculated according to: *Khilchevskyi, Grebin 2022; **Khilchevskyi 2022. Categories and classes of water quality were calculated according to: ***Romanenko *et al.* 1998.

1.2. Sublittoral, abrasion-accumulative, sandy sedge-cane associations with a homogeneous temperature mode.

II. Profundal aquatic sub-tract on sapropels formed on alluvial sand.

Aqua-facies: **2.1.** Profundal, transient depositions of sandy-sapropel (0–2.0 m) with sedge-cane associations with a non-stable temperature mode in the summer period.

2.2. Profundal, transient depositions of sandy sapropels on organic-clayey sapropels (1.0–2.0 m) interspersed with sedge-cane associations with a non-stable temperature mode in the summer period.

2.3. Profundal, depositions of organic-clayey sapropel with lenses of carbon sapropels (2.0–5.0 m), individual floating seaweeds and a nonstable temperature mode in the summer period.

2.4. Profundal, transient depositions of organic clay-sapropel (1.0–2.0 m) on the uphill slope of the hollow basin with individual floating seaweeds and a non-stable temperature mode in the summer period.

III. Pelagial, accumulative aquatic sub-tract of the hollow depths with the deposition of sapropel on alluvial sands underlain by chalk sediments.

Aqua-facies: **3.1.** Pelagial epilimnion up to about 8.0 m deep with a homogeneous temperature mode in the summer period and with the whole layer being illuminated.

3.2. Pelagial metalimnion up to 8.0–12.0 m deep with a sharp temperature jump.

3.3. Pelagial gipolimnion up to 12.0–26.8 m deep with low temperature (7.5–7.6ºC), low illumination and hydrodynamical stability.

Table 4 The complexity of NAC territorial structure of Lake Bile

NAC type		Area of NAC type, ha		% of the type area of the total area		No. of units of facies within NAC	% of total number	Mean area of the subtract (ha)	*The index of the fractionality of landscape contours	*Index of landscape complexity	*The index of landscape fragmentation
Subtract	Aqua-facies	Subtract	Aqua-facies	Subtract	Aqua-facies						
I		169.073		36.89		3	30.00	56.358	0.018	0.053	0.667
	1.1		16.441		3.59						
	1.2		152.633		33.30						
II		253.833		55.38		4	40.00	63.458	0.016	0.063	0.750
	2.1		83.820		18.29						
	2.2		73.638		16.07						
	2.3		85.048		18.55						
	2.4		11.326		2.47						
III		35.451		7.73	7.73	3	30.00	11.817	0.085	0.254	0.667
Total		**458.358**	**458.358**	**100.0**	**100.0**	**10**	**100.0**	**45.836**	**0.022**	**0.218**	**0.900**

*Indices and coefficients were calculated according to the formulas proposed by A. Domaranskyi (2006).

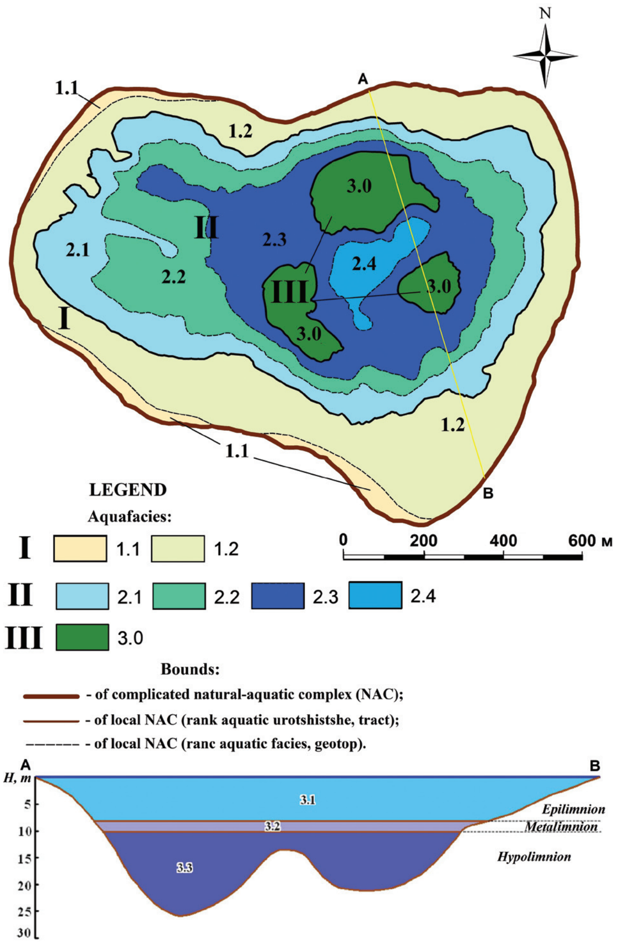


Fig. 9 Landscape structure of the natural-aquatic complex of Lake Bile. AB – profile line across the lake; *H*, m is the depth of the water layer

The littoral-sublittoral aquatic sub-tract (36.89% of the total area) includes two types of aqua-facies with three contours. These are parts of the NAC with depths reaching up to 5.0 meters. The profundal aquatic sub-tract is the largest in terms of area (55.38%). It occupies the central part of the lake basin and has four types of aqua-facies and the same number of landscape features. The pelagic aquatic sub-tract (7.37% of the area) has three types of aquafacies. The distinction of this aquatic sub-tract is based on the deep thermal stratification of the NAC. Profile A–B shows epilimnion (up to 8.0 m), metalimnion (8.0–12.0 m) and hypolimnion (12.0–26.8 m) aqua-facies. These areas of the lake NAC correspond to bed depressions, namely karst sinkholes. The territorial dissection of the lake NAC is presented in Table 4. There are 10 landscape contours in the NAC, the average area is 45.836 ha, the fragmentation index is 0.022, the complexity coefficient is 0.218, and the landscape fragmentation coefficient is 0.9.

DISCUSSION

The methodological approach employed in this research rests on a number of debatable provisions, which, although seem to have been resolved long ago, still demand attention, namely: Should a lake be treated as an "aquatic ecosystem", as an "aquatic complex", or as an "aquatic geo-system?". All of them are definitely correct. In limnological works (Horne, Goldman 1994; Wetzel 2001), which develop the works by A. Thienemann (1926) and E. Naumann (1929) using the ecosystem approach (or monocentric approach according to M. Hrodzynskyi 2014) to the analysis of limnological processes in water bodies, the term "aquatic ecosystem" prevails. In studies on geographic limnology (Il'in 2008 a, b) conducted in post-Soviet countries, the term NAC (or hydro-system, aqua-geo-system, limno-geo-system) is mainly used to emphasize the systemic or complex nature of the research object.

The concept of NAC emphasizes the lithogenic factor (genesis, lithology of bottom sediments, geomorphology of the lake basin, etc.), other factors being considered derivative. In the concept of an aqua-geo-system and its application to a lake, all geo-components are viewed as equal; such a geosystem is polycentric. It is obvious that the integration of methodological concepts formed by different geographic-limnological and biological-limnological schools allows developing unified (or non-contradictory) approaches and their application in the scientific field of landscape limnology.

The genesis of lakes in the Volyn Polissia region, including Lake Bile, remains a problematic and debatable issue, which is due to the lack of studies on the stratigraphy of lake basin sediments, radiocarbon dating, spore-pollen analysis, tectonic features and lineament structure of the region. Genesis of lakes in the Volyn Polissia region is partly considered in works by I. Zalessky (1999), L. Bezusko (Bezusko *et al.* 2001), R. Dobrowolski (Dobrowolski *et al.* 2001). In our study, attention is focused only on the dominant geological-geomorphogenic process, in particular, on the denudation-karst process, which most actively manifested itself in the lake basin formation. The authors are convinced that the formation of the Lake Bile basin could not have taken place without the influence of all geological-tectonic, geomorphological and climatic factors of the physical-geographic region of Volyn Polissia. It is the landscape-geographical approach (Miller *et al.* 2002) that allows a comprehensive study of the genesis of the lake, which is inextricably linked with the paleo-geographical development of the landscape as a regional unit of physical-geographical zoning.

The formation of the chemical composition of Lake Bile proceeds under the influence of natural and anthropogenic factors, namely: the ingress of pollutants with precipitation into the water area, the ingress of various chemical elements and compounds with surface water from the catchment area, the dissolution of minerals and rocks in the lake basin, the vital activity of water organisms, recreational activities, etc. The hydrological regime of the reservoir, which depends on seasonal factors as well as on weather and climatic conditions, plays the main role in determining the hydro-chemical composition of the NAC.

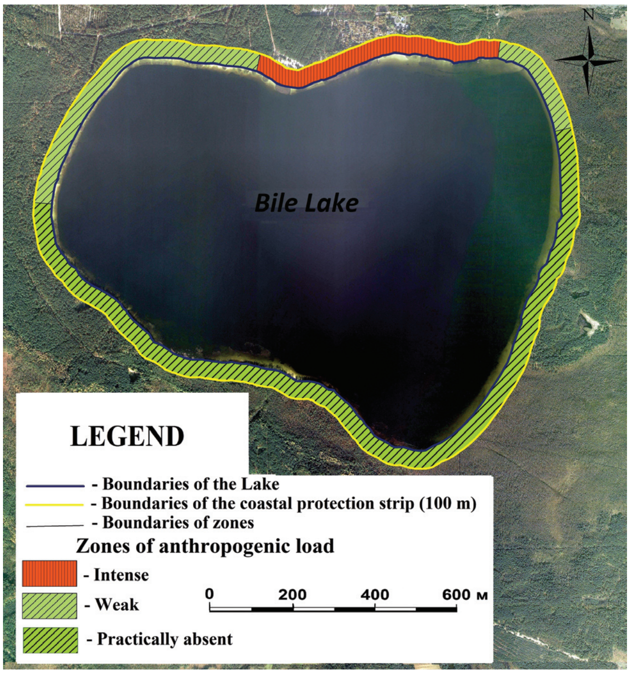
The research into the hydro-chemical condition of Lake Bile water in 2020 revealed a 2.1-fold non-compliance with standards for the block of tropho-saprobiological indicators of the MPCcerp BOD_5 and a 4.2-fold non-compliance with standards for the indicators of MPCfp. According to the nitrite nitrogen content, the lake water belonged to the 5th category (class III), according to the phosphate content – to the 4th category (class III), and according to COD (Mn) – to the 6th category (class IV). In the MPCcerp block of toxic action indicators, an excess for total iron was found to be 2.6-fold, and of the MPCfp – 8.5-fold, but according to its qualitative composition, the water was classified as belonging to the 1st category and class I (Gopchak, Yakovyshyna 2020). Increased concentrations of heavy metals in Lake Bile water in 2000–2009 were discovered by Klymenko and Petruk (2011). According to the calculations made by these authors, the quality of water by the content of iron was classified as belonging to the 4th category, by the content of zinc – to the 5th category, by that of copper – to the 4th category, and by the content of manganese – to the 4th category.

It is known that Polissia landscapes are characterized by high concentrations of total iron, both in watercourses and reservoirs with slow water exchange. The natural causes of the entry of iron compounds into water bodies include the transformation of primary minerals into secondary at reduced water pH indicators, which causes the release of ferrous compounds, as well as the leaching of Fe from iron-magnesium nodules, which are contained in the illuvial horizon of sod-podzolic soils of Polissia landscapes (Sukhodolska 2017) during the weathering processes of sedimentary rocks. In addition, Fe compounds can enter reservoirs with drainage waters of reclamation systems, etc.

Arrival of other elements and compounds of heavy metals into Lake Bile is due to the operation of internal combustion engines of water scooters (motorcycles) and the use of small rescue boats. The operation of the Rivne NPP, which is located within a 30-km wide zone around the lake, exerts a significant technogenic load on the reservoir.

A rather debatable problem that led to a conflict between the departments of nature use (nature reserves, recreation, forestry) and nature protection was the allocation of a recreational area around the lake with a length of 4.5 km, width of 0.05 km and a total area of 22 hectares, as well as 22 hectares of water area, in the protected zone of the lake (Voloshynova *et al.* 2007). In this regard, the NTCs around the lake are subject to a noticeable anthropogenic load, especially during the high season (May–September). During our research, a 100-meter area around Lake Bile was divided into zones and the degree of anthropogenic load in three sectors was determined (Fig. 10).

The zone of intensive anthropogenic load accounts for 16.33%, that of weak load – for 26.89%, and the anthropogenic load is practically absent in 56.78% of the area. The northern sector of the coastal zone is undergoing the greatest anthropogenic transformations, primarily recreational.



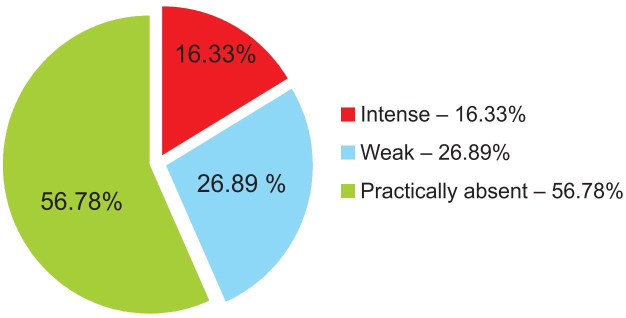


Fig. 10 Zoning of the 100-meter water protection zone around Lake Bile

CONCLUSIONS

The present study has proved that our conceptual principles of modern transdisciplinarity in landscape limnology, which is based on the comprehensive analysis of the ecological state of landscape-lake system (LLS) geocomponents, are both theoretically and practically innovative and effective in solving problems of sustainable nature management. Local LLSs are convenient operational units that can be easily integrated into the management system of water and land resources applying the basin principle of nature management and using modern GIS.

The developed series of cartographic models reflects the current geoecological state of the Lake Bile LLS. They are important when evaluating the geoecological parameters of the whole LLS and its individual elements, and in revealing its functional features. These models act as an information and analytical basis for planning measures to optimize nature use and protect water resources from pollution and their quality impairment. Maps of the spatial and typological structure of the land areas within the lake basin, the bathymetric map, the landscape structure of the catchment and the aquatic complex are especially important in this respect:

1. Using the land use map, the degree of the economic development of the catchment area was assessed as very low. In the future, it is necessary to monitor spatial changes in the state of the catchment land and dynamics of the recreational area around the lake, which will affect the degree of LLS anthropogenization.

2. The bathymetric model created by us reveals the morphological structure of the lake basin relief and, in combination with other factors, serves as the basis for determining the genesis of the reservoir. Lake Bile can act as a representative NAC when analysing the genesis and evolutionary development of natural water bodies in the Nyzhnostyrskyi physical-geographical district of Volyn Polissia. The bathymetry of the lake is the basis for creating a landscape map or its variant, a recreational map (for the needs of swimming, diving, recreational fishing, boating, etc.) of the NAC of the lake.

3. The maps of the landscape and morphological structure of the catchment and the lake itself are important documents for evaluating geotopes according to the degree of evolutionary development and environmental protection functions: a) environment-forming; b) environment stabilizers; c) environmental protection; d) environmental regulators. Landscape metric characteristics make it possible to establish the degree of diversity, complexity, fragmentation of LLS, which are important when comparing it with other LLS of this region.

4. The zoning model of the 100-meter area around the lake showed that the level of anthropogenic load therein is permissible (43.22%). In the future, we recommend moving recreation facilities outside the northern sector of the catchment area and regulating the number of vacationers in this zone during the summer season.

Evaluation of the water body according to hydrochemical parameters showed that according to the block of indicators of salt composition, the quality of lake water is excellent; according to trophosaprobiological indicators, its quality is satisfactory, despite being already polluted, eutrophic; according to indicators of toxic action, the lake water is of excellent quality, water is very clean. An integral ecological assessment of the quality of surface waters of the lake allowed us to evaluate them as “good” according to the degree of quality, “clean” according to the degree of pollution, and “mesotrophic” according to the predominant type of trophicity.

We discovered that the landscape and the geographical organization of Lake Bile as a protected object caused a departmental conflict at the initial stage of nature management. The Ramsar lands "Bile Lake and Koza-Berezyna bog" represent a nature conservation area of the Rivne Nature Reserve, where the recreation and health centre of the Rivne NPP operates in the coastal zone of the northern sector of the lake's catchment area. Today, it is imperative to develop such a model of the landscape and basin management that would make the violation of the environmental protection regime through recreational activities impossible.

We suggest starting a landscape and limnological monitoring program of the basin system of Lake Bile and adjacent protected massifs using traditional and modern methods of remote sensing of the Earth; to expand the spectrum of geocomponents, primarily hydrobionts, that must be included into evaluative observations. Such recommendations are related to the annals program for reserves and the functioning of LLS in the 30-km impact zone of the nuclear power plant. The obtained results, i.e. the geoecological parameters of the LLS and several created maps, will serve as the basis for the development of the ecological passport of Lake Bile.

ACKNOWLEDGEMENTS

The authors express their gratitude to the employees of the Rivne Nature Reserve, in particular to Mykhailo Franchuk, PhD in Biology, and to Rostyslav Zhuravchak, the deputy director of the Rivne Nature Reserve at that time, for their help in conducting field research within the Lake Bile basin. The authors are sincerely grateful to three anonymous reviewers for their valuable comments and recommendations for improving the structure and content of the manuscript. We would like to thank Dr. Vaida Šeirienė (Nature Research Centre, Vilnius) for professional expertise and diligent work on reviewing the manuscript. We extend our sincere gratitude to Laima Monkienė for the text correction. Her attention to detail has undoubtedly improved the readability of the article.

REFERENCES

Bezusko, L.G., Bezusko, T.V., Kovaliukh, M.M. 2001. Paleobotanical and radiochronological studies of the sediments of Lake Bolotne (Ukraine, Volyn region). *Scientific notes of the National University of Kyiv-Mohyla Academy. Biology and ecology 19*, 43–50. Kyiv: KM Academy [In Ukrainian].

Boromisza, Z., Pádárné Török, É., Ács, T. 2014. Lakeshore-restoration-landscape ecology-land use: Assessment of shore sections, being suitable for restoration, by the example of Lake Velence (Hungary). *Carpathian Journal of Earth and Environmental Sciences 9 (1)*, 179–188.

Ciężkowski, W., Frąk, M., Kardel, I., Kościelny, M., Chormański, J. 2022. Long-term water quality monitoring using Sentinel-2 data, Głuszyńskie Lake case study. *Scientific Review Engineering and Environmental Sciences 31 (4)*, 283–293.

Chmielewski, T.J. 2012. *Systemy krajobrazowe: Struktura – Funkcjonowanie – Planowanie*. Warszawa: Wydawnictwo Naukowe PWN, 408 pp. [In Polish].

Choiński, A. 2007. *Physical limnology of Poland*. UAM Science Publishing, Poznań [In Polish].

Choiński, A., Ptak, M., Ławniczak, A.E. 2016. Changes in Water Resources of Polish Lakes as Influenced by Natural and Anthropogenic Factors. *Polish Journal of Environmental Studies 25 (5)*, 1883–1890.

Chormanski, J., Nowicka, B., Wieckowski, A., Ciupak, M., Jóźwiak, J., Figura, T. 2021. Coupling of Dual Channel Waveform ALS and Sonar for Investigation of Lake Bottoms and Shore Zones. *Remote Sensing 13 (9)*,1833. https://doi.org/10.3390/rs13091833

Chumak, V., Belousova, P., Babenko, V. 1992. Way to the trouble. Rivne NPP, 1982. *Ojkumena (Ukrainskyi Ecologichnyj visnyk) 4*, 33–41. Kyiv [In Ukrainian].

Cole, G.A., Weihe, P.E. 2015. *Textbook of Limnology*. Fifth Edition. Waveland Press Inc., Long Grove, Ilinois, 440 pp.

Česonienė, L., Šileikienė, D., Marozas, V., Čiteikė, L. 2021. Influence of Anthropogenic Loads on Surface Water Status: A Case Study in Lithuania. *Sustainability 13*, 4341. https://doi.org/10.3390/su13084341

Decree dated August 14, 2014 N 264 «On approval of the Regulation on the Rivne Nature Reserve in the new version», 2015. With changes and additions introduced by the decree of the Ministry of Ecology and Natural Resources of Ukraine dated October 22, 2015. No. 388. https://ips.ligazakon.net/document/view/fn006739?an=1&ed=2014_08_14 [In Ukranian].

Dobrowolski, R., Bałaga, K., Bogucki, A., Fedorowicz, S., Melke, J., Pazdur, A., Zubović, S. 2001. Chronostratigraphy of the Okunin and Czerepacha lake-mire geosystems (Volhynia Polesiye, NW Ukraine) during the Late Glacial and Holocene. *Geochronometria 20*, 107–115.

Domaranskyi, A.O. 2006. *Landscape diversity: essence, meaning, metrization, conservation*. Kirovograd. 146 pp. [In Ukrainian].

Dumitran, G.E., Vuta, L.I., Popa, B., Popa, F., 2020. Hydrological Variability Impact on Eutrophication in a Large Romanian Border Reservoir, Stanca-Costesti. *Water 12 (11)*, 3065. https://doi.org/10.3390/w12113065

Evans, W.L. III. 2021. *Lake Hydrology: An Introduction to Lake Mass Balance*. Baltimore, Maryland: Johns Hopkins University Press.

Fergus, C.E., Lapierre, J.F., Oliver, S.K., Skaff, N.K., Cheruvelil, K.S., Webster, K., Scott, C., Soranno, P. 2017. The freshwater landscape: Lake, wetland, and stream abundance and connectivity at macroscales. *Ecosphere 8 (8)*. e01911.10.1002/ecs2.1911

Fesiuk, V., Polianskyi, S., Kopytiuk, T. 2022. Methods and practical implementation of application of remote sensing for monitoring of eutrophication of reservoir (on the example of Turkish lake). *Scientific notes of Ternopil State Pedagogical University. Ser. Geography 1*, 159–166. Ternopil. https://doi.org/10.25128/2519-4577.22.1.20 [In Ukrainian].

Forman, R.T.T., Godron, M. 1986. *Landscape Ecology*. New York, J. Wiley, 619 pp.

Gergel, S.E., Turner, M.G. 2017. *Learning Landscape Ecology: A Practical Guide to Concepts and Techniques*. 2nd edition. Publisher: Springer, 350 pp.

Giuliani, C., Caronte-Veisz, A., Piccinno, M., Recanatesi, F. 2019. Estimating vulnerability of water body using Sentinel-2 images and environmental modelling: the study case of Bracciano Lake (Italy). *European Journal of Remote Sensing 52 (S4)*, 64–73.

Gopchak, I.V., Yakovyshyna, M.S. 2020. Influence of recreation load on the Bile Lake ecosystems in the Rivne nature reserve. *Bulletin of the National University of Water Management and Nature Management. Agricultural sciences*, *2 (90)*, 3–15. https://doi.org/10.31713/vs220201 [In Ukrainian].

Hakuć-Błażowska, A., Cymerman, R. 2011. Principles of Developing Limnological Restrictions in the Planning Process. *Polish Journal of Environmental Studies 20 (6)*, 1501–1511.

Hamilton, S.E., McGehee, D.D., Nyamweya, C. *et al.* 2022. High-resolution bathymetries and shorelines for the Great Lakes of the White Nile basin. *Scientific Data 9 (1)*, https://doi.org/10.1038/s41597-022-01742-3

Herenchuk, K.I., Rakovska, E.M., Topchiiev, O.G. 1975. *Field geographical researches*. Kyiv: High school, 248 pp. [In Ukrainian].

Hess, D., Tasa, D. 2017. *McKnight's Physical Geography: A Landscape Appreciation*. 12th edition. Publisher: Pearson. https://pubhtml5.com/ymwp/czse

Horne, A.J., Goldman, C.R. 1994. *Limnology*. New York: McGraw-Hill, 576 pp.

Horton, R.E. 1945. Erosional Development of Streams and Their Drainage Basins: Hydro-Physical Approach to Quantitative Morphology. *Geological Society of American Bulletin 56*, 275–370.

Hrodzynskyi, M.D. 2014. *Landscape ecology*: a textbook. Kyiv: Knowledge [In Ukrainian].

Hrodzynskyi, M.D., Savytska, O.V. 2008. *Landscape Science*. Kyiv: Kyiv University Publishing and Printing Center [In Ukrainian].

Hryshchenko, Yu.M. (ed.) 2008. *Nature Reserve Fund of the Rivne Region*. Rivne: Volynski oberehy, 216 pp. [In Ukrainian].

Ignatavičius, G., Satkunas, J., Grigiene, A., Nedveckyte, I., Hassan, H.R., Valskys, V. 2022. Heavy Metals in Sapropel of Lakes in Suburban Territories of Vilnius (Lithuania): Reflections of Paleoenvironmental Conditions and Anthropogenic Influence. *Minerals 12* (17). https://doi.org/10.3390/min12010017

Imberger, J., Patterson, J.C. 1990. Physical limnology. *Advances in Applied Mechanics 27*, 303–475.

Il'in, L.V. 2008a. *Limnocomplexes of Ukrainian Polesia*: *Monograph: In 2 t. T. 1: Spatial and geographical bases of research and regional patterns*. Lutsk: RVV "Vezha" VNU im. L. Ukrainka [In Ukrainian].

Il'in, L.V. 2008b. *Limnocomplexes of Ukrainian Polesia: Monograph: In 2 t. T. 2: Regional features and optimization*. Lutsk : RVV "Vezha" VNU im. L. Ukrainka [In Ukrainian].

Kashiwaya, K. 2017. Geomorphology of Lake-Catchment Systems: *A New Perspective from Limnogeomorphology*. https://doi.org/10.1007/978-981-10-5110-4

Khilchevskyi, V.K. 2022. *Hydrochemical Dictionary*. Kyiv: DIA. 208 pp. [In Ukrainian].

Khilchevskyi, V.K., Grebin, V.V. 2022. *Water objects of Ukraine and recreational assessment of water quality*: textbook. Kiev: DIA. 240 pp. [In Ukrainian].

Klymenko, O.M., Petruk, A.M. 2011. Ecological assessment of the water quality of Lake Bile of the Rivne region. *Bulletin of the National University of Water and Environmental Engineering. Agricultural sciences 2 (54)*, 103–111. Rivne [In Ukrainian].

Kovalchuk, A.I., Kovalchuk, I.P. 2018. *Atlas mapping of river basin systems*: *monograph*; *for sciences*. I.P. Kovalchuk (ed.). Lviv: Prostir-M, 348 pp. [In Ukrainian].

Kovalchuk, I.P., Martyniuk V.A. 2015. Methodology and experience of landscape-limnological research into lake-basin systems of Ukraine. *Geography and Natural Resources 36 (3)*, 305–312. https://doi.org/10.1134/S1875372815030117

Kovalchuk, I., Martyniuk, V., Šeirienė, V. 2020. The basin-landscape approach to the protection and condition optimization of the lakes of the national parks. *Visnyk of V.N. Karazin Kharkiv National University. Series* "*Geology. Geography. Ecology*" *53*, 239–254. Kharkiv.

Kovalchuk, I.P., Pavlovska, T.S. 2008. *River basin system of Horyn: structure, functioning, optimization: monograph*. Lutsk: RVV "Vezha" VNU im. L. Ukrainka, 244 pp. [In Ukrainian].

Kumar, A. 2005. *Fundamentals of Limnology*. APH Publishing, 243 pp.

Lyko, D.V., Martyniuk, V.O., Lyko, S.M., Portuhai, O.I., Zubkovych, I.V. 2019. *The method of soil-geochemical catenas in studies of watersheds of Volyn Polisia*. Monograph. Rivne: Publisher O. Zen, 140 pp. [In Ukrainian].

Martin, S.L., Soranno, P.A. 2006. Lake landscape position: Relationships to hydrologic connectivity and landscape features. *Limnology and Oceanography 51 (2)*, 801–814.

Martyniuk, V.O. 1998. The landscape method of study of lakes for the purposes of their rational use. *Scientific Bulletin of the Volyn State University. Geographical sciences series 5*, 49–51. Lutsk [In Ukrainian].

Martyniuk, V.O. 1999. Landscape-limnological analysis of the basin (lake) geosystem. *Scientific notes of Ternopil State Pedagogical University. Ser. geography 2*, 29–36. Ternopil [In Ukrainian].

Martyniuk, V.O. 2008. Landscape science direction in lake science. *Lakes and artificial reservoirs of Ukraine:*

current state and anthropogenic changes. Lutsk : RVV "Vezha" VNU im. L. Ukrainka, 230–234. [In Ukrainian].
Martyniuk, V. 2015. Constructive geographical model of the lake-basin specialized recreational system (on the example of the lake Ostrivske, Ukrainian Polesia). *Journal of Wetlands Biodiversity 5*, 115–126.
Martyniuk, V.O., Zubkovych, I.V., Andriichuk, S.V. 2018. The landscape-geographic modelling of thermal stratification of natural-aquatic complex of Lake Svitle (Volyn Polissia). *Scientific Bulletin of Kherson State University. Series: Geographical Sciences* 9, 131–139 [In Ukrainian].
Martyniuk, V., Zubkovych, I., Andriichuk, S. 2020. Methodical approaches to the evaluation of the geoecological state of the lake-basin system. *Slupskie prace geograficzne 17*, 89–110. Slupsk: Instytut Geografii Spoleczno-Ekonomicznej i Turystyki Akademii Pomorskiej w Slupsku. https://doi.org/10.34858/spg.17.2020.007
Miller, G.P., Petlin, V.M., Melnyk, A.V. 2002. *Landscape science: theory and practice*. Lviv [In Ukrainian].
Muhtadi, A., Leidonald, R., Rahmadya, A., Lukman. 2020. Bathymetry and morphometry of Siais Lake, South Tapanuli, North Sumatra Province, Indonesia. *Aquaculture, Aquarium, Conservation & Legislation – International Journal of the Bioflux Society 13 (5)*. http://www.bioflux.com.ro/home/volume-13-5-2020/
Naumann, E. 1929. The Scope and Chief Problems of Regional Limnology. *Hydrobiology 22 (1)*, 423–444.
Nowak, B.M., Ptak, M. 2019. Natural and anthropogenic conditions of water level fluctuations in lakes – Lake Powidzkie case study (Central–Western Poland). *Journal of Water and Land Development 40 (I–III)*, 13–25.
Oakenfold, S. (ed.) 2017. *Limnology and Freshwater Ecology*. Syrawood Publishing House, 241 pp.
Oldfield, F. 1977. Lakes and their drainage basins as units of sediment based ecological study. *Progress in Physical Geography 1*, 460–504.
Pasztaleniec, A., Kutyła, S. 2015. The Ecological Status of Lakes in National and Landscape Parks: Does the Location of a Lake and Its Catchment within a Protected Area Matter? *Polish Journal of Environmental Studies 24 (1)*, 227–240.
Paul, S., Oppelstrup, J., Thunvik, R., Magero, J.M., Ddumba Walakira, D., Cvetkovic, V. 2019. Bathymetry Development and Flow Analyses Using Two-Dimensional Numerical Modelling Approach for Lake Victoria. *Fluids 4 (4)*, 182. https://doi.org/10.3390/fluids4040182
Poikane, S., Zohary, T., Cantonati, M. 2020. Assessing the ecological effects of hydromorphological pressures on European lakes. *Inland Waters 10 (2)*, 241–255.
Richling, A., Solon, J. 1998. *Ekologia krajobrazu*. Warszawa: Wydawnictwo Naukowe PWN [In Polish].
Romanenko, V.D., Zhukynskyi, V.M., Oksiiuk, O.P., *et al*. 1998. *Methodology of ecological assessment of surface water quality by appropriate categories*. Kyiv: Symbol-T, 28 pp. [In Ukrainian].
Samoilenko, V.M., Ivanok, D.V. 2015. *Modelling of basin geosystems*. Monograph. K.: SE «Print Service», 208 pp. [In Ukranian].
Sethi, P., Kulkarni, V.S. 2011. *Environmental Limnology*. Alfa Publications.
Shit, P.K., Bera, B., Islam, A., Ghosh, S., Bhunia, G.S. (eds) 2022. *Drainage Basin Dynamics: An Introduction to Morphology, Landscape and Modelling (Geography of the Physical Environment).* Springer Cham, 568 pp.
Schallenberg, M., de Winton, M.D., Verburg, P., Kelly, D.J., Hamill, K.D., Hamilton, D.P. 2013. Ecosystem services of lakes. In: Dymond J.R. (ed.) *Ecosystem services in New Zealand – conditions and trends*. Manaaki Whenua Press, Lincoln, New Zealand, 203–225.
Simpson, C.E., Arp, C.D., Sheng, Y., Carroll, M.L., Jones, B.M., Smith, L.C. 2021. Landsat-derived bathymetry of lakes on the Arctic Coastal Plain of northern Alaska. *Earth System Science Data 13*, 1135–1150.
Soranno, P.A., Webster, K.E., Riera, J.L., Kratz, T.K., Baron, J.S., Bukaveckas, P.A., *et al*. 1999. Spatial variation among lakes within landscapes: ecological organization along lake chains. *Ecosystems 2*, 395–410.
Soranno, P.A., Webster, K.E., Cheruvelil, K.S., Bremigan, M.T. 2009. The lake landscape-context framework: linking aquatic connections, terrestrial features and human effects at multiple spatial scales. *Verh. Internat. Verein. Limnol. 30 (5)*, 695–700. https://doi.org/10.1080/03680770.2009.11902218
Soranno, P.A., Cheruvelil, K.S., Webster, K.E., Bremigan, M.T., Wagner, T., Stow, C.A. 2010. Using landscape limnology to classify freshwater ecosystems for multi-ecosystem management and conservation. *BioScience 60 (6)*, 440–454.
Sterner, R.W., Keeler, B., Polasky, S., Poudel, R., Rhude, K., Rogers, M. 2020. Ecosystem services of Earth's largest freshwater lakes. *Ecosystem Services 41*, 101046. https://doi.org/10.1016/j.ecoser.2019.101046
Sukhodolska, I.L. 2017. Seasonal variations in the level of heavy metals in the water of minor rivers. *Biosystems Diversity 25 (1)*, 3–8. https://doi.org/10.15421/011701 [In Ukranian].
Thienemann, A. 1926. *Das Leben im Süßwasser*. Breslau: Ferdinand Hirt, 108 pp. [In German].
Turner, M.G., Gardner, R.N., Oniel, R.V. 2001. *Landscape Ekologie in Theory and Practice: Patter and Process*. New York: Springer-Verlag, 482 pp.
Voloshynova, N.O., Bachuk, V.A., Hryshchenko, Yu.M. 2007. *Forest, marsh, lake reserve.* Rivne: Publishing House of JSC "Rivnenska Drukarnia" [In Ukrainian].
Webster, K.E., Kratz, T.K., Bowser, C.J., Magnuson, J.J., Rose, W.J. 1996. The influence of landscape position on lake chemical responses to drought in northern Wisconsin, USA. *Limnology and Oceanography 41*, 977–984.
Wetlands of the Rivne Nature Reserve. 2022. https://rivnenskyipz.blogspot.com/p/blog-page_93.html [In Ukrainian].

Wetzel, R.G. 2001. *Limnology: Lake and River Ecosystems*, 3rd ed. Academic Press, 1006 pp.

Wetzel, R.A., Likens, G.E. 1991. *Limnological analysis: monograph*. 2nd ed. New York: Springer, 429 pp.

Woolway, R.I., Kraemer, B.M., Lenters, J.D., *et al*. 2020. Global lake responses to climate change. *Nature Reviews Earth & Environment 1*, 388–403.

Xu, X., Jiang, B., Tan, Y., Costanza, R., Yang, G. 2018. Lake-wetland ecosystem services modelling and valuation: Progress, gaps and future directions. *Ecosystem Services 33*, 19–28.

Yang, H., Guo, H., Dai, W., Nie, B., Qiao, B., Zhu, L. 2022. Bathymetric mapping and estimation of water storage in a shallow lake using a remote sensing inversion method based on machine learning. *International Journal of Digital Earth 15 (1)*, 789–812.

Zalessky, I. 1999. Morfogenetyczne osobliwości rzeźby podłoza plejstocenu na Polesiu Wołyńskim. *Annales Universitatis Mariae Curie-Skłodowska 2*, 33–40. LIV, Lublin [In Polish].

Zubkovych, I.V., Martyniuk, V.O. 2020. The Peculiarities of the Landscape Structure of Volyn Polesia (Based on Results of Field Researches on Key Areas). *Scientific Notes of Sumy State Pedagogical University. Geographical Sciences 2 (1)*, 3–18. https://doi.org//10.5281/zenodo.3727228 [In Ukrainian].