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A Cartographic Landscape Analysis of the Geo-Ecological Condition of the Natural Reserve Object—Lake Doshne (Volyn Polissya, Ukraine)

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Abstract: The cartographic landscape analysis of Lake Doshne employs geographic landscape methods, GIS cartographic modeling, and geo-ecological analysis. This study includes hydrochemical analysis of the lake's water mass, focusing on saline blocks, tropho-saprobiological indicators, and specific toxic action indicators. Three geological sections of anthropogenic and pre-Quaternary complexes, along with a geological–lithological transverse profile of the lake basin, were developed. Additionally, a geographical landscape model of the lake's natural aquatic complex was presented, distinguishing littoral–sublittoral and profundal aquatic sub-tracts and five types of aquafacies with landscape metric assessments. This approach enables a comprehensive analysis and the creation of cartographic models that can serve as a basis for lake cadastre and optimization of the ecological and landscape conditions in local territories.

Keywords: lake; lake basin system; geo-ecological approach; bottom sediments; geological–lithological section; landscape mapping; natural aquatic complex; aquafacies; cadastre

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Citation: Kirvel, I.; Martyniuk, V.; Kovalchuk, I.; Andronache, I.; Korbutiak, V.; Zubkovych, I. A Cartographic Landscape Analysis of the Geo-Ecological Condition of the Natural Reserve Object—Lake Doshne (Volyn Polissya, Ukraine). *Limnol. Rev.* **2024**, *24*, 385–405. https://doi.org/10.3390/limnolrev24030023

Academic Editors: Petre Brețcan, Gabriel-Ionut Plavan and Rita Linkevičienė

Received: 30 April 2024
Revised: 19 August 2024
Accepted: 13 September 2024
Published: 18 September 2024

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1. Introduction

The adoption of the European Landscape Convention [1] has created new opportunities for landscape studies of lakes and lake basin systems (LBSs), promoting their protection, management, and planning. This study examines the geo-ecological condition of Lake Doshne using cartographic landscape methods, providing models that can serve as a basis for a lake cadastre and for planning the spatial development of territorial communities. The growing interest in studying LBS from ecological landscape and geographical landscape perspectives underscores the importance of integrating these approaches into regional planning policies [2].

Despite the ambiguous interpretation of the term "landscape" [3–10], there is a growing interest in studying lakes and lake basin systems (LBSs) from landscape-ecological and geographical landscape perspectives [11–24]. Transdisciplinary landscape and limnological research aim to study not only specific lakes but also the processes occurring within their catchment areas. The health of lake ecosystems depends on the geo-ecological situation that has developed within the catchment area. The advantages of the landscape approach

to studying lakes extend beyond the geo-complex analysis of the condition and functioning of the "lake-catchment area" system. It also enables the creation of sectoral and integral cartographic models that reflect the parameters of the geo-ecological condition of the LBS and can serve as an informational basis for the LBS cadastre.

Lakes constitute a significant portion of the water bodies within the Nature Reserve Fund (NRF). They are integral to nature reserves and natural parks or serve as hydrological monuments of nature. In accordance with the provisions of the Law of Ukraine "On the Nature Reserve Fund of Ukraine" [25], the state cadastre of NRF territories and objects is maintained [26]. The state cadastre of NRF objects contains concise information in tabular form, including area, location, land users, and decisions regarding the creation of protected territories or NRF objects. This information is sufficient to meet the primary needs of users.

There is an increasing demand for landscape and cartographic data, not only for the extensive territories encompassed by the NRF but also for the individual objects within this fund (reserved tracts, natural monuments, etc.). As of March 2023, the boundaries of 1,851 objects within Ukraine's NRF have been created and specified, with their mapping on a cartographic basis [27], which will facilitate the future creation of a cadastral database of nature protection territories. The interactive map "Nature Reserve Fund of Volyn Region" can serve as a prototype for the regional cadastral database of NRF objects [28].

Regarding the experience of creating cadastral databases in other countries for nature protection areas, it is worth noting the concept of utilizing components of the water cadastre database to construct a multidimensional cadastre in Poland [29], a model of geographic management of nature. The Goksu River Delta in Turkey provides an example of a protected area [30], while the USA has a modern database of protected areas [31]. Greece has a system for monitoring individual lakes [32], and other countries have similar systems in place.

For an extended period, we have been engaged in research on the inventory of lakes in the NRF of the Polissia region of Ukraine. This has involved the development of digital cartographic landscape models of water bodies, or LBSs [33,34]. The research results can be utilized as cartographic information for the basis of the lake cadastre and the database for the interactive atlas of NRF objects [35]. Alternatively, they can be incorporated into the GIS atlas of lake basins [36]. Concurrently, there is a necessity for meticulous methodologies to be employed in the construction of cartographic landscape models that will accurately reflect the geo-ecological characteristics of lakes of diverse types. The foundational study in this regard is the work of R. Mauersberger [37], which deals with the geo-ecological classification of lakes in the landscapes of the northeastern part of the German lowland. In this work, the author undertook a comprehensive examination of the genesis of lakes, the relief of the landscape (forms, angles of inclination and exposure of slopes, and absolute marks of the height of lakes above sea level), hydrological features of water bodies (including the level of groundwater and the level regime of lakes), the morphology and thermal regime of lakes, hydrochemical conditions, species composition of aquatic organisms, lake sediments, land use structure, and so forth. Among the studies that are essentially close to the assessment of the geo-ecological condition of lakes and which take into account the connections in the "lake-landscape" system, it is worth highlighting the works of S. Martin & P. Soranno [38] on the relationship between the hydrological parameters of the lake and the features of the landscape (northern Michigan, USA); L. Česonienė et al. [39], which examines the relationship between the water quality elements of Lithuanian water bodies and their hydrometric parameters; and R. Dondajewska et al. [40], which assesses the water quality of a shallow lake in an agricultural landscape in western Poland.

It is also important to consider the studies on the transformation of lake water bodies under the influence of natural and anthropogenic factors [41–44], which utilized archival materials, analysis of historical maps, and remote sensing data to assess the current geo-ecological situation. Unfortunately, these studies rarely employ landscape mapping of the lakes and their catchment areas, limiting the applicability of their findings in the practice of complex geographic visualization of lake basin systems (LBSs).

The aim of this research is to analyze the geo-ecological condition of the hydrological reserve "Lake Doshne" (Volyn Polissya, Ukraine) using cartographic landscape methods. The findings will serve as a foundation for developing a cadastre of water bodies within the Nature Reserve Fund and will provide a rationale for implementing comprehensive water protection measures within the lake basin system.

2. Materials and Methods

2.1. Study Area

Lake Doshne is situated within the Upper-Pripyat physical geographical district of Volhynian Polissia, Ukraine (Figure 1).

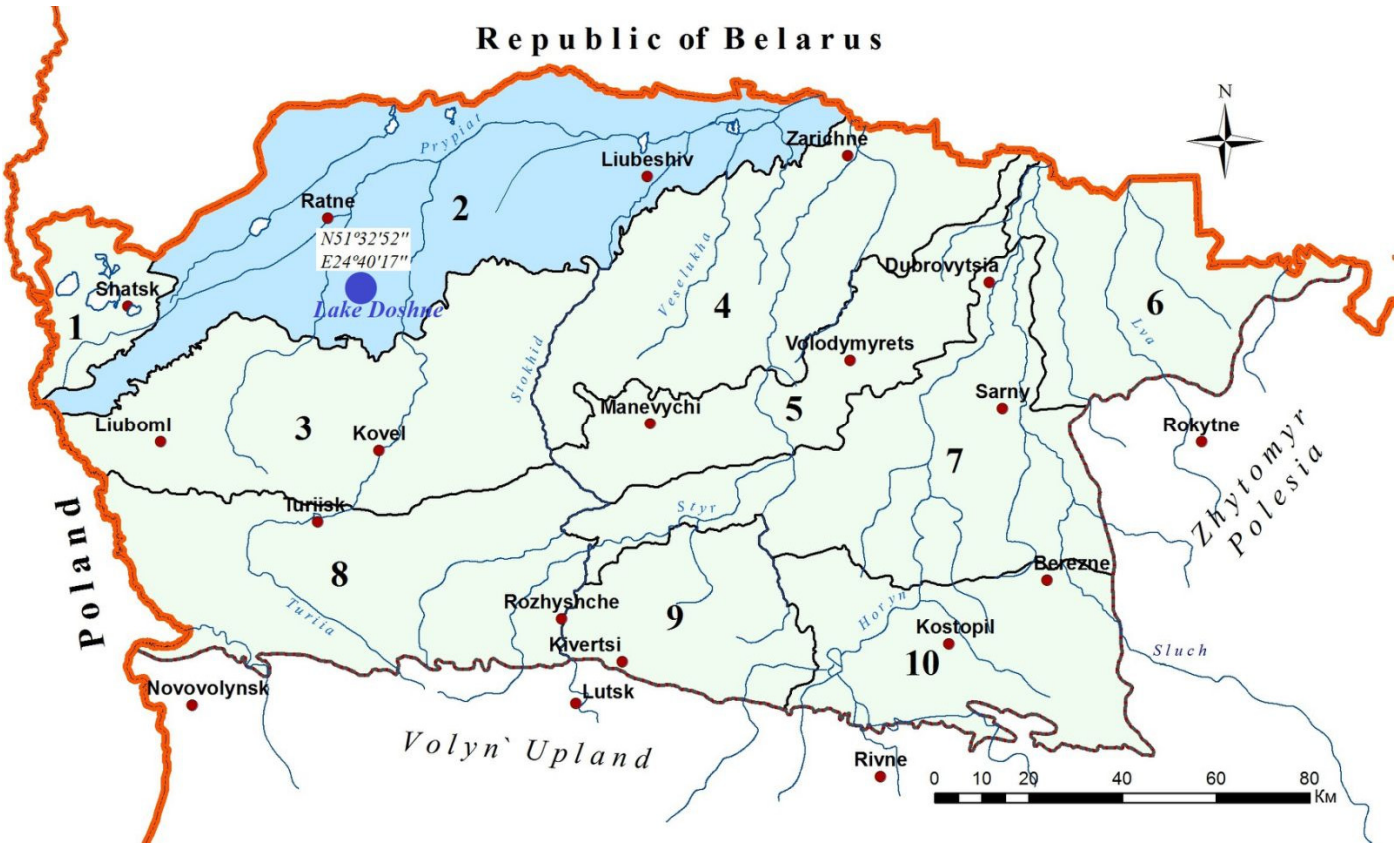

Figure 1. The localization of Lake Doshne within the broader context of the physical and geographical zoning of Volyn Polissia, Ukraine. Symbols: Physiographic regions 1—Shatsk, 2—Upper-Prypiat, 3—Liuboml-Kovel, 4—Lower-Styr, 5—Manevychi-Volodymyrets, 6—Lva-Horyn, 7—Kolky-Sarny, 8—Turiisk-Rozhyshche, 9—Kivertsi-Tsuman, and 10—Kostopil-Berezne.

The geographical coordinates of the lake's center is 51°32′52″ N, 24°40′17″ E. The lake basin is characterized by outwash plains with green moss and bilberry pine forests, interspersed with small-leaved trees on sod-low- and medium-podzolic soils, which have been partially transformed by reclamation systems. The lake basin is located within the Velymchenska Territorial Community, Kovel district, Volyn region, Ukraine. The lake is designated as a hydrological reserve of local importance, covering a total area of 29.2 hectares. This designation was made by the Volyn Regional Council on 9 December 2000, under resolution No. 4/3 [28].

2.2. Methodological Basis

The methodological foundation of this research is based on the Directive of the European Parliament and Council concerning water policy [45], which underscores the principles of the basin approach to integrated water resource management. Additionally, guiding

documents from the Foundation of the International Committee on the Environment on the management of lakes and their basins for sustainable use [46] and the ecological principles of sustainable water resource management [47–49], including lakes [50,51], were employed. The conceptual framework for the geo-ecological approach to analyzing the Lake Basin System (LBS) was informed by monographs from I. Nesterchuk [52], O. Pylypovych & I. Kovalchuk [53], E. Bajkiewicz-Grabowska [54], and I. Kruhlov [55], along with works on geo-ecological research methodologies [56,57], and basin system mapping [58–60].

To create a landscape map, it is essential to conduct field limnological and geographical studies of the lake and its basin. The methodology used in field geo-complex research and geographic landscape mapping was based on the works of G. Miller et al. [61], I. Chervanov & S. Ihnatiev [62], M. Hrodzynskyi & O. Savytska [63], among others. Hydrological profiling of the water bodies and the development of a bathymetric model of the lake are crucial components of the instrumental research. The methodology for bathymetric research was based on scientific works [64,65] and personal experience in developing bathymetric models of lakes [66].

2.3. Fieldwork and Data Collection

For the fieldwork on echo sounding of Lake Doshne, the Lycky FFW718 (wireless) echo sounder was used. The error in depth measurement ranged from 0.15 to 0.20 m, attributed to finely dispersed silts in the surface layer of bottom sediments, which the device can sometimes perceive as a water layer. The geographic coordinates of the water depth measurement points were recorded using a Garmin Oregon 650 GPS navigator. Sampling for hydrochemical analyses was conducted on 22 August 2018 in the northeastern sector of the lake, 70 m from the shore. The hydrochemical analyses were performed in the sanitary and hygienic laboratory of the state institution "Rivne Regional Centre for Disease Control and Prevention" of the Ministry of Health of Ukraine (Rivne).

Three boreholes were drilled within the lake: two in the terraced part of the catchment area and one in the lake's water area. The research also included probing the bottom sediments to develop a stratigraphic section of the sediments of Lake Doshne (Figure 2).

To determine the lithological composition of the lakeside terrace, the bottom sediments of the lake, and pre-Quaternary deposits, boreholes were drilled using a manual percussive-rotary method. The borehole depth within the lake terrace was 5.0 m, while within the lake, it penetrated the underlying pre-Quaternary sediments to a depth of 2.5 m. During the drilling, the sediments were examined and described, noting their name, grain size, color, age, moisture content, density, the presence of impurities and inclusions, and their quantity. The thickness and depth of various lithological layers of sediments and the groundwater level were also determined. The latest publications on the research into the lithology of sedimentary complexes [67] and lake sapropel [68–70] have provided an essential basis for studying the species composition, strength, and geochemical properties of lake bottom sediments.

From a landscape ecology perspective, the lake is classified as a natural aquatic complex (NAC) of the rank of a complex aquatic tract. This classification is based on the micro-relief of the basin, the lithological composition and strength of bottom sediments, aquatic plant communities, and the thermal factor on aquatic sub-tracts and aquafacies [71,72]. A survey of the species composition of surface and underwater macrophytes, as well as temperature conditions, was conducted during the summer season. To develop a landscape map of the Lake Doshne NAC, the research utilized materials from the Kyiv Geological Exploration Expedition (Kyiv GEE) in the search for sapropel. Studying these properties of the NAC is a prerequisite for developing a map of the landscape structure of the lake and its catchment area.

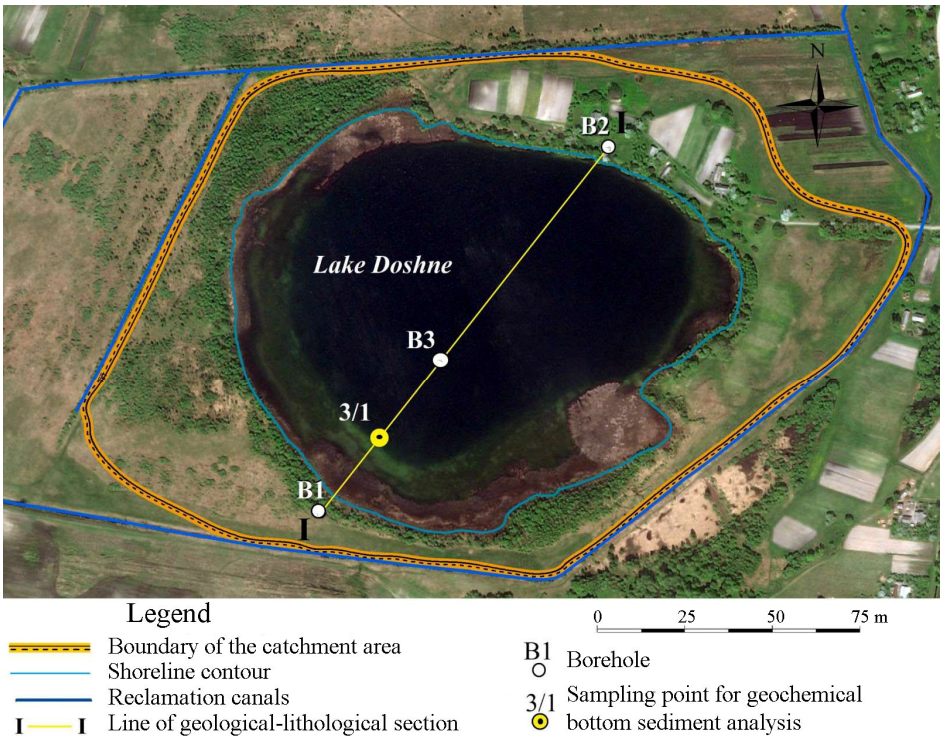

Figure 2. The catchment area of Lake Doshne, along with the location of the geological–lithological section (I-I) and points of probing (B1, 3/1) of Quaternary sediments.

The structure of geographic landscape studies of the LBS in nature protection territories includes the following components (Figure 3). The first block comprises geo-component and geo-complex methods, including geological–geomorphological, hydrological–hydrochemical, soil–geochemical, landscape, and other methods. The second block encompasses cartographic modeling of lithogenic component conditions, relief, water component, land use, and anthropogenic influences. The third component is the integral ecological landscape block, which synthesizes information on the geo-ecological parameters of the "lake-catchment area" system and component cartographic models, developing a complete geographical landscape model of the LBS.

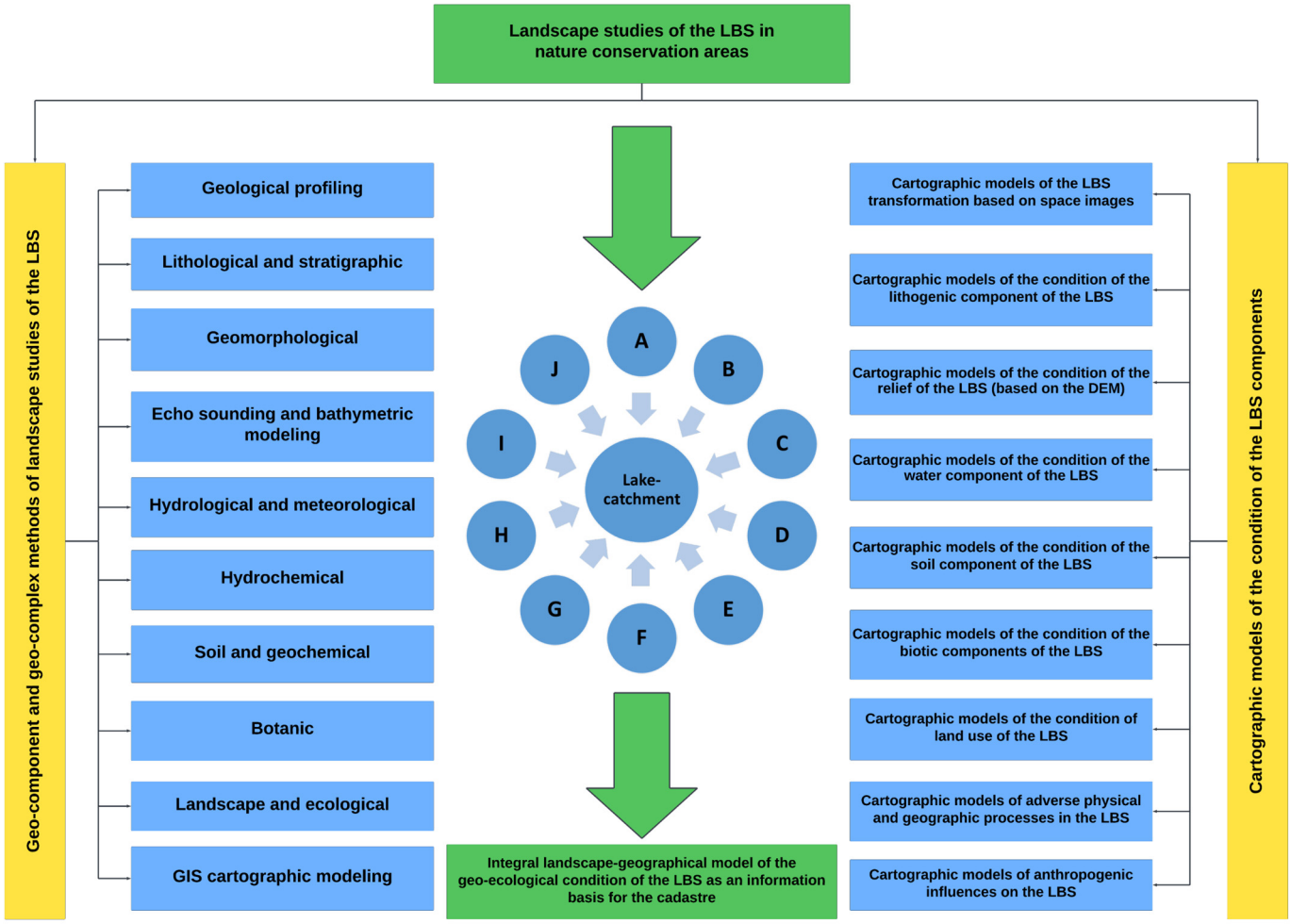

Figure 3. The structure, methods, and results of landscape and geographic studies of lake basin systems (LBSs) in nature conservation areas. Legend of the geo-ecological parameters of the "lake-catchment area" system: A—geological; B—geomorphological; C—meteorological; D—hydrological; E—hydrochemical; F—lithological and stratigraphic; G—soil; H—geochemical; I—biotic; and J—anthropogenic.

3. Results

To assess the geo-ecological conditions of Lake Doshne, it is essential to consider the individual elements that influence these conditions.

3.1. Morphometric and Hydrological Parameters

The area of Lake Doshne, as determined by our assessment, is 0.19 km^2. The lake is relatively deep, with a maximum depth of 28.5 m and an average depth of 6.5 m. The slopes of the lake basin are steep, becoming less pronounced in the nearshore zone. The peripheral zone of the lake is characterized by tall aquatic vegetation, clearly visible in satellite images. Based on the results of a sounding survey conducted using the Lucky FFW718 sounder, we developed a bathymetric model of the lake with a depth interval of 2.0 m (Figure 4).

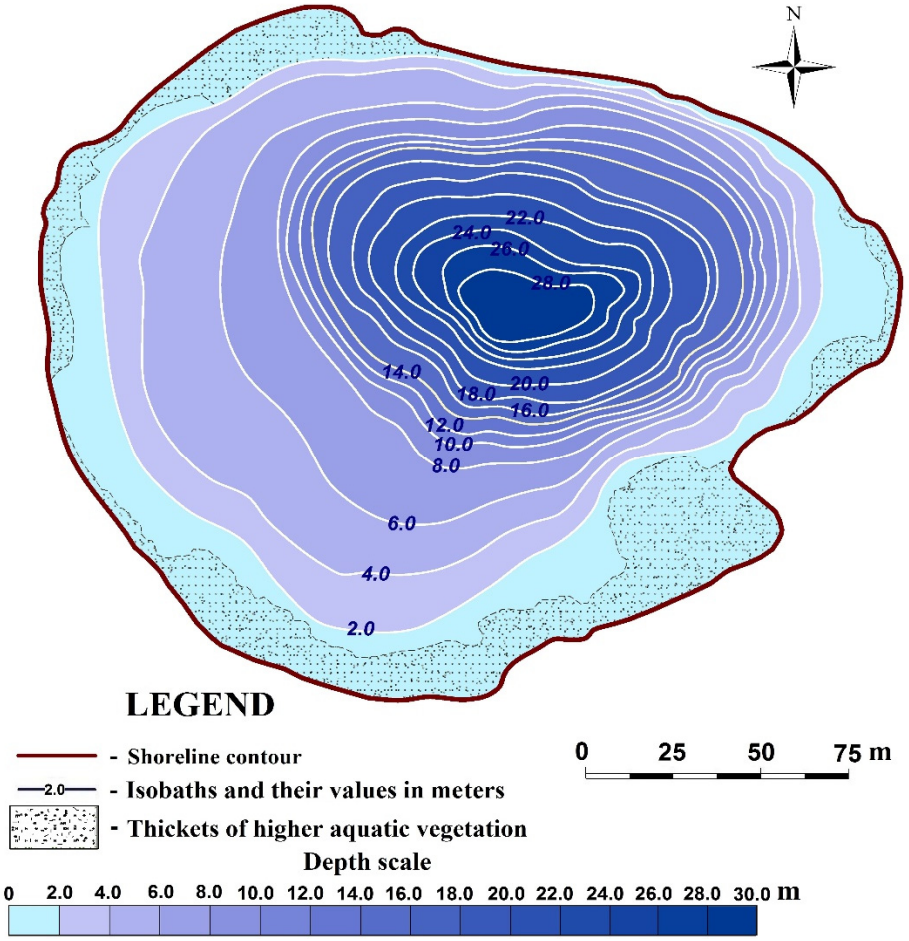

Figure 4. Bathymetric model of the Lake Doshne.

The catchment area of Lake Doshne is relatively small, measuring 0.38 km^2. It is bordered by drainage canals, which limit surface runoff. These canals range from 3.0 to 5.0 m in width and 0.5 to 0.9 m in depth, and are overgrown with Carex, Typha, Scirpus lacustris, and occasionally willow bushes. The lake itself is 0.567 km in length, with a maximum width of 0.448 km and an average width of 0.335 km. The total length of the lake's coastline is 1.71 km. The volume of water in the lake is 1239 million m^3 (Table 1).

Table 1. Morphometric and hydrological characteristics of the Lake Doshne.

* F_{lake}, km^2	$H_{abs.}$, m	$h_{mid.}$, m	$h_{max.}$, m	L, km	$W_{max.}$, km	$W_{mid.}$, km	ι, km	$C_{t.}$	$C_{len.}$
0.19	162.5	6.50	28.50	0.567	0.448	0.335	1.710	0.619	1.693
$C_{cap.}$	**$C_{op.}$**	**$C_{dep.}$**	**V_{lake}, million m^3**	**A**	**ΔS, km^2**	**$W_{influx.}$**, thous·m^3**	**$a_{wat.}$**	**$\Delta_{awat.}$, mm**	**$A_{layer.}$ mm**
0.228	0.029	11.304	1239	0.500	2.002	47.9	0.039	25.866	3258.0

* Area (F_{lake}); 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 ($C_{t.}$); of the lake lengthening ($C_{len.}$); of capacity ($C_{cap.}$); of openness ($C_{op.}$); of 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—4.0.

The lake has no outflows and is sustained by precipitation, snowmelt, and groundwater from the Upper Cretaceous horizon.

3.2. Hydrochemical Characteristics

The lake's water is clean and transparent. Hydrochemical studies, conducted according to the methodology outlined in [73–75], indicate that the lake water belongs to the first category (class I) based on salt composition indicators. According to tropho-saprobiological parameters, the water corresponds to the third category (class II). However, the nitrate nitrogen content (18.07 mg N/dm^3) and dissolved oxygen levels (2.89 mg O_2/dm^3) place the water in the seventh category. The total iron content (toxic action indicators) in the water is less than 0.1 mg Fe/dm^3 (Table 2), meeting the standards for water bodies intended for domestic and recreational use, as well as for fish farming. The lake water is soft, weakly alkaline, and bicarbonate-calcium. The combined ecological assessment of the hydrochemical indicators of the lake water is 1.7, corresponding to the second category (class I) of the ecological classification system. The recreational load on the lake is minimal.

Table 2. Hydrochemical indices of Lake Doshne (as of 22 August 2018).

Serial No	Index	Unit of Measurement	TLV for Recreational Use [73]	TLV for Fishery [74]	Measurement Results	Quality Categories and Water Classes	
						Category	Class
			A. Indicator of salt composition				
1	Mineralization (dry residue)	mg/dm^3	≤1000	<300	168.1	**1**	**I**
2	Chloride ions	mg/dm^3	350	300	10.64	**1**	**I**
3	Sulfates	mg/dm^3	500	100	30.04	**1**	**I**
		Integral index by salt block I_1 = 1.0				**1**	**1**
			B. Tropho-saprobiological indicators				
4	General stiffness	$mmol/dm^3$	7	7	2.24	–	–
5	Suspended substances	mg/dm^3	0.75 + background (30)	15	9.03	**2**	**II**
6	Transparency	m	>1.0	>1.5	2.8	**1**	**I**
7	pH	pH units	6.5–8.5	6.5–8.5	7.6	**2**	**II**
8	Ammonium nitrogen	mgN/dm^3	0.5	0.5	0.1	**1**	**I**
9	Nitrite nitrogen	mgN/dm^3	3.3	0.08	0.01	**1**	**I**
10	Nitrate nitrogen	mgN/dm^3	45	40	18.07	**7**	**V**
11	Phosphorus phosphates	mgP/dm^3	3.5	2.14	0.036	**3**	**II**
12	Chemical oxygen consumption (Mn)	mgO_2/dm^3	≥4	≥6	2.89	**7**	**V**
13	Biological oxygen consumption, BOC_5	mgO_2/dm^3	≤6 (t = 20)	≤3.0	1.91	**3**	**II**
14	Calcium	mg/dm^3		180.0	44.97	–	–
15	Magnesium	mg/dm^3		40.0	<0.5	–	–
		Integral index by tropho-saprobiological block I_2 = 3.0				**3**	**II**
			C. Specific indicators of toxic impact				
16	Iron	mg/dm^3	0.33	0.1	<0.1	**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 = 1.7				**2**	**I**

3.3. Geological and Geochemical Features of the Watershed and Lake Deposits

3.3.1. Characteristics of the Geological Structure of the Watershed and Their Impact on the Lake's Hydrochemistry

The lithogenic component plays a crucial role in the landscape structure of the natural aquatic complex (NAC). Studying the geological features of the anthropogenic and pre-Quaternary sediments of the lake and its catchment area allows for determining the water body's genesis, nutritional conditions, and evolutionary aspects. The topography of the lake's catchment area is generally flat, except for the northeastern part, which is hilly with a sharp decrease in elevation closer to the lake. The Quaternary sedimentary complexes of the catchment area are composed of silty sands. In the areas of the lake terrace adjacent to the lake from the western and southern shores, the sands are covered with peat.

Borehole B1 (Figure 5), located at the surface, revealed dark brown peat (bIV) with a thickness of up to 1.6 m. This peat was distributed throughout the terrace strip, except for the northern shore. The peat was overlain by chalk and marl (K_2cn), with the borehole uncovering 3.4 m of chalk deposits. Borehole B2 identified a soil–vegetation layer com-

prising dark gray sand with weak peat (aIV) up to 0.3 m thick. On elevated ground, this soil–vegetation layer is found only near the northern shore. Modern fine- and medium-grained yellow sands and sandy loams (aIII), with a thickness of up to 3.6 m, lie beneath the soil cover. These are underlain by Upper Cretaceous sediments of the Coniacian layer (K_2cn). The salinity of groundwater ranges from 0.1 m at Borehole B1 to 2.5 m at Borehole B2. Borehole B3 was drilled from the water surface, with the lake depth reaching 7.5 m. The bottom sediments consist of sapropel (lIV) with a thickness of 4.2 m, underlain by Upper Cretaceous sediments.

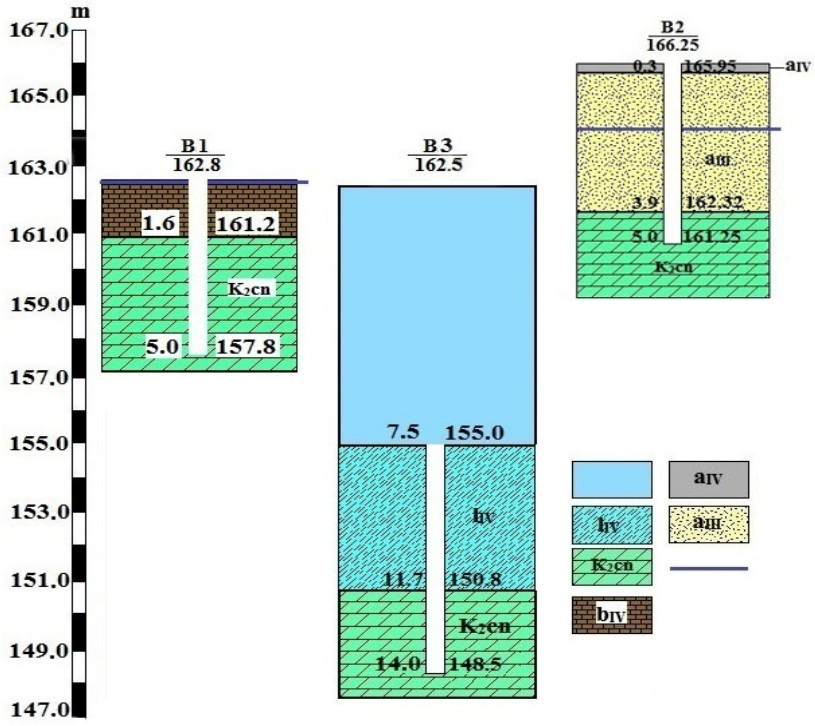

Figure 5. Litho-stratigraphic columns (B1, B2, B3) of anthropogenic and pre-Quaternary sediments of Lake Doshne and the lake terrace. Legend: $\frac{B1}{162.8}$—the numerator is the number of the borehole, the denominator is the absolute mark of the relief (according to the Baltic Height System); l_{IV}—modern lake sediments—sapropel; K_2cn—the Coniacian—chalk, marl; b_{IV}—modern swamp sediments—peat; a_{IV}—modern alluvial sediments—sands; a_{III}—Upper Quaternary alluvial sediments—sands and sandy loams; ——mark of the appearance of the groundwater level.

The chalk aquifer horizon plays a significant role in the lake's water supply. Analysis of the grain size composition of sands in Borehole B2 revealed that, within the horizon from 1.0 to 2.5 m, the majority (83.3%) consists of fractions sized 0.25–0.10 mm (43.8%) and 0.5–0.25 mm (39.5%). In the horizon from 2.5 to 3.5 m, 73.7% of the sand comprises fractions sized 0.25–0.10 mm (38.7%) and 0.5–0.25 mm (35.0%) (Table 3).

Table 3. The grain size composition of sands in Borehole B2 of the Lake Doshne watershed.

№	Sampling Depth, m	Grain Size Composition, %							
		* 5.0–2.0, mm	2.0–1.0, mm	1.0–0.5, mm	0.5–0.25, mm	0.25–0.10, mm	0.10–0.05, mm	0.05–0.01, mm	0.01–0.005, mm
1	1.0–2.5	–	0.7	3.8	39.5	43.8	10.4	1.2	0.6
2	2.5–3.5	0.6	10.8	6.1	35.0	38.7	6.7	1.0	1.1

* Particle size fractions of sand, mm.

In Borehole B2, various water-related and sand physical properties were measured, including total moisture content, maximum molecular moisture content, water yield, vol-

umetric weight in the extremely loose state, density, and porosity in the extremely loose state. The results indicated that the porosity in the extremely dense state was 35.8%, while the porosity coefficient in the extremely loose state was 0.86. Additionally, a filtration coefficient of 1.27 m/day was recorded. The porosity coefficient in the extremely dense state was 0.56 (Table 4).

Table 4. Hydrophysical properties of the sands in Borehole B2 of the Lake Doshe watershed.

Indicator	Measurement Unit	Min–Max Values	Average Value
Hygroscopic moisture	%	0.23–0.25	0.24
Total moisture content	%	21.8–28.2	25.0
Maximum molecular moisture content	%	3.3–4.4	3.85
Water conductivity	%	18.5–18.8	18.65
Bulk density in loose state	g/cm^3	1.41–1.44	1.43
Bulk density in dense state	g/cm^3	1.69–1.71	1.7
Density	g/cm^3	2.64–2.66	2.65
Porosity in loose state	%	45.8–46.6	46.2
Porosity in dense state	%	35.2–36.4	35.8
Porosity coefficient in loose state	%	0.85–0.87	0.86
Porosity coefficient in dense state	%	0.54–0.57	0.55
Filtration coefficient	m/day	1.15–1.39	1.27

The grain size composition and hydro-physical properties of the sands in Borehole B2 are crucial for understanding the infiltration characteristics of the watershed. As the Upper Cretaceous rocks line the bottom of the lake basin, there is a close hydrological connection with the lake. The dissolution of mineral-bearing rocks affects the hydrochemical properties of the Upper Cretaceous aquifer and, consequently, the waters of Lake Doshne.

The depth of groundwater in the marl–chalk deposits of the Turonian–Maastrichtian stage (K2t-m) in the sub-basin of the western part of the Pripyat River, where the Lake Doshne basin is located, ranges from 11.5 to 25.0 m. However, in river valleys, it can reach up to 60.0 m. The groundwater is predominantly fresh, bicarbonate-calcium, and calcium–magnesium, with prevailing mineralization of 200–600 mg/dm^3. Regarding the hydrogen content of the waters, they are neutral, with an occasional tendency towards alkalinity. The waters are typically moderately hard, although they may occasionally be soft or hard. Elevated levels of nitrates, nitrites, and ammonia are only recorded in areas of water pollution within settlements or on sites of current and buried peat bogs.

3.3.2. Organic–Mineral Deposits of the Lake, Their Composition, and Reserves

The sediment composition of the lake comprises three main types: peaty, sandy–muddy, and sandy. Additionally, a carbonate sapropel layer is present beneath a layer of chalk and marl (Figure 6). In the peripheral regions of the littoral zone, peat is the dominant sediment type, except for the northern shore. According to data from the Kyiv Geological Exploration Expedition (GEE), the distribution of sapropel within the lake covers an area of 19.0 hectares. The average thickness of the sapropel layer is 4.96 m, with a maximum thickness of 9.5 m. The estimated sapropel reserve is 512,000 cubic meters. Given the maximum water depth and the thickness of the sapropel layer, the depth of the lake basin is estimated to be 34 m.

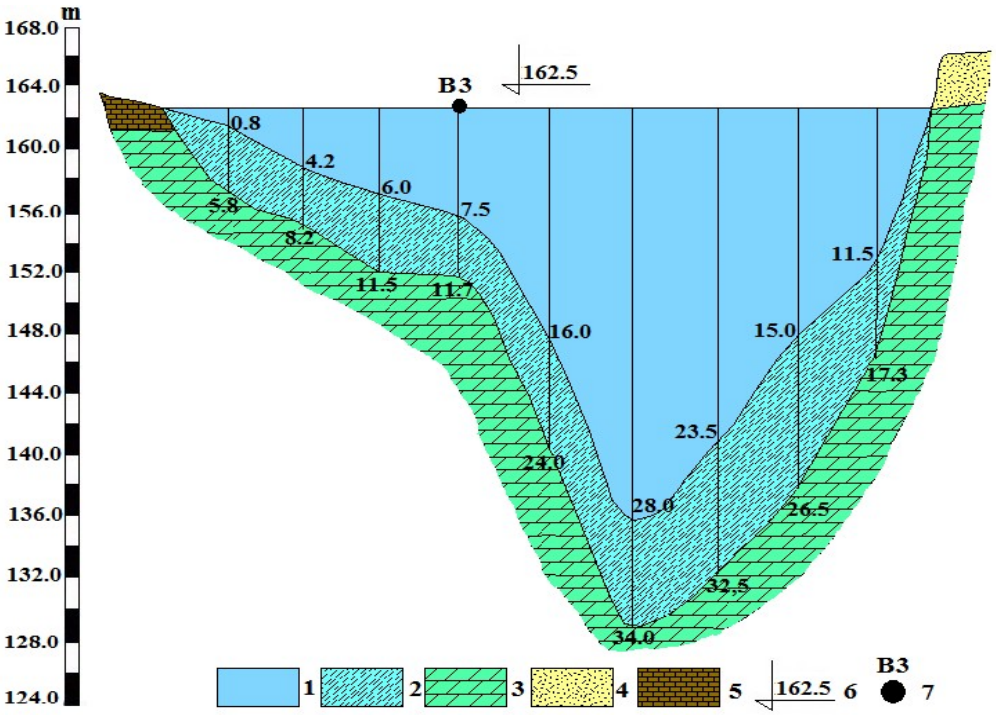

Figure 6. Geological–lithological cross-section of Lake Doshne basin. Legend: 1—water, 2—carbonate sapropel, 3—chalk, marl, 4—sand, 5—peat, 6—absolute mark of the water surface, m (according to the Baltic Height System), and 7—B3 borehole.

3.3.3. Geochemical Properties of Lake Sapropel

The results of geochemical studies of bottom sediments at sounding point 3/1 demonstrated considerable variability in the ash content (% on dry matter) of sapropel, ranging from 41.0% to 47.0%, with an average value of 44.64%. The content of Fe_2O_3 compounds in sapropel deposits showed similar variability, ranging from 0.11% to 0.50%, with an average of 0.39%. The concentration of sulfate compounds varied from 32.64% to 42.66%, with an average content of 37.11%. The degree of acidity (salt extract, pH) in the profile of bottom sediments ranged from moderately alkaline (7.9) to strongly alkaline (8.1), with an average value of 7.97 (Figure 7).

The analysis of the content of some heavy metals in the sapropel (data from the Kyiv GEE) revealed the following concentrations (mg/kg): Hg—0.16, Zn—12.0, Cu—9.0, Pb—64.0, Cd—3.2, Be—1.0, Ni—16.0, Co—10.3, Cr—8.0, and Mo—0.63. To estimate the levels of heavy metal accumulation in the sapropel, we used the concentration coefficient, calculated as the ratio of the content of the element in the bottom sediments to its average concentration in the Earth's crust (clarke).

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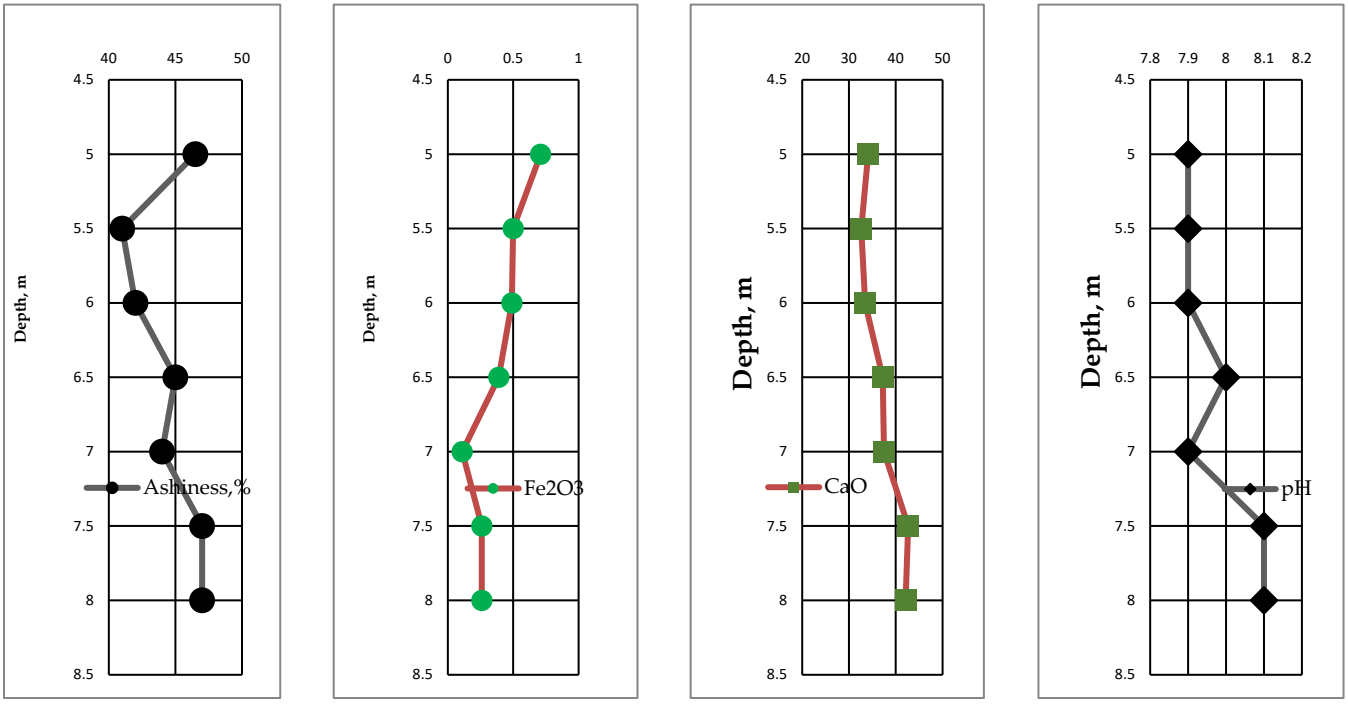
$$Cc = \frac{C_{bot.}}{C_{clarke}}, \quad (1)$$

where $C_{bot.}$—concentration of the metal in bottom sediments, mg/kg or %;

C_{clarke}—average concentration of the metal in Earth's crust (clarke), mg/kg or % [76].



Distribution of ash content (% on a dry-matter basis) in bottom sediments

Distribution of Fe_2O_3 (% on a dry-matter basis) in bottom sediments

Distribution of CaO (% on a dry-matter basis) in bottom sediments

Ph distribution (salt extraction) in bottom sediments

Figure 7. Distribution of ashiness and chemical elements (compounds). and pH in the bottom sediment profile of Lake Doshne (the graphs are based on the data of the Kyiv GEE).

The research revealed that the concentration of Pb in the sapropel is 4.9 times higher than in the Earth's crust, Cd by 18.8 times, and Hg by 2.2 times. According to researchers [77], these heavy metals are conservative pollutants that undergo transformation in natural waters and can accumulate in aquatic organisms, being transmitted through trophic chains. The content of these heavy metals in the water, suspended substances, aquatic organisms, and bottom sediments is influenced by hydrological processes both within the lake and its catchment area. Additionally, these substances enter the lakes from the atmosphere, polluted by gas and human-made emissions, falling with precipitation, and during the construction and operation of reclamation systems. The content of other heavy metals in the bottom sediments did not exceed their average concentration in the Earth's crust. The research also identified high concentrations of nitrates (551.0 mg/kg) and nitrites (25.0 mg/kg) in the lake sapropel. The primary causes of this phenomenon can be attributed to the influx of surface and internal soil runoff from the reclaimed catchment areas of the lake, which were exploited during the latter half of the 20th century.

3.4. Landscape Structure of the Lake and Its Landscape-Metric Parameters

Taking into account the specific characteristics of the lake basin's topography, the species composition and thickness of the bottom sediments, and the pre-Quaternary deposits, along with the generalization of results from field geo-ecological studies, we have developed a landscape map of the Lake Doshne natural aquatic complex (NAC) (Figure 8).

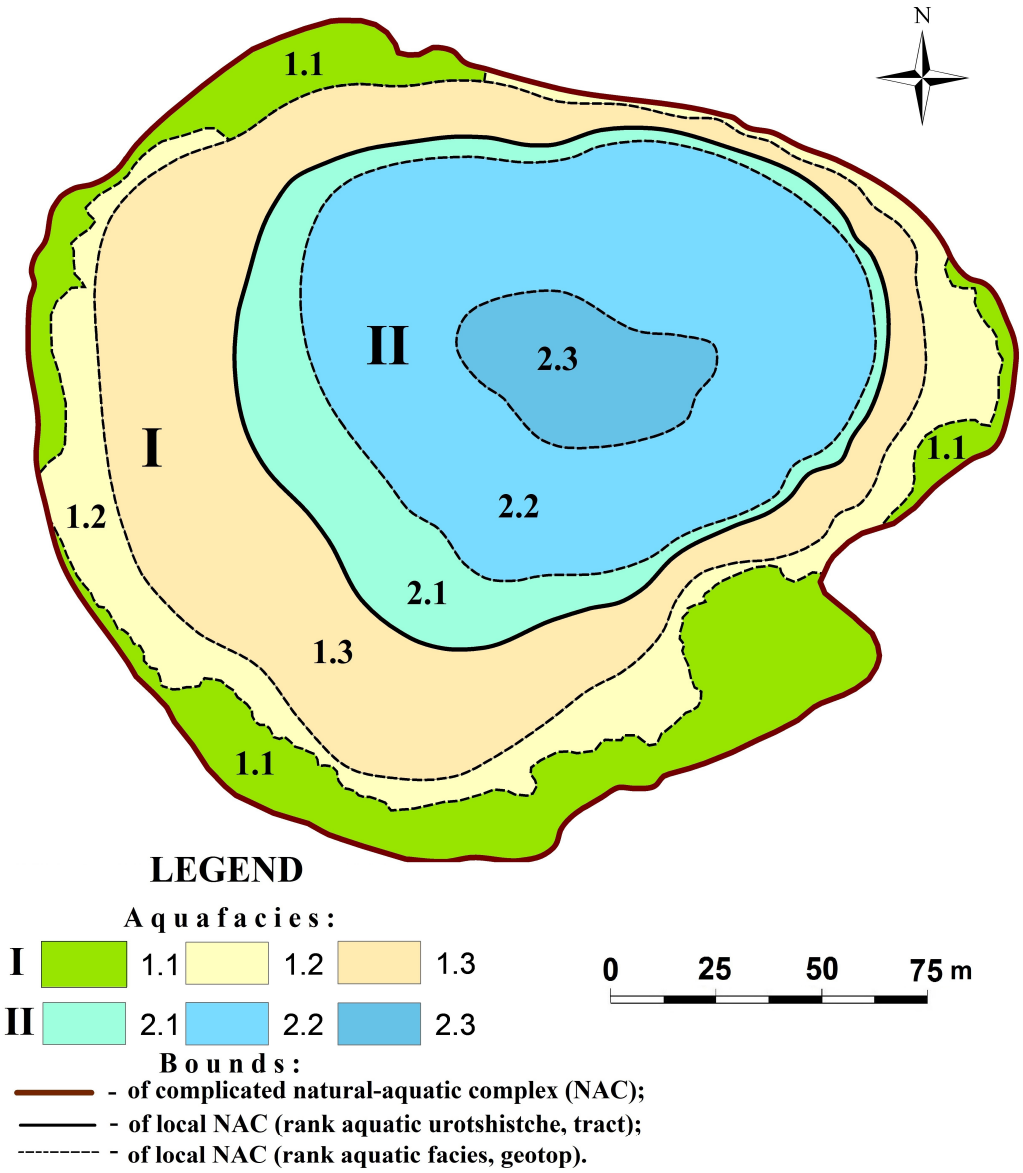


Figure 8. Landscape map of the natural aquatic complex of Lake Doshne.

I. Littoral–sublittoral aquatic sub-tract on peaty, sandy–muddy, and sandy sediments and sapropel featuring species diversity of surface and underwater macrophytes.

Aquafacies: 1.1. Littoral, accumulative peaty and sandy–muddy of low thickness (0.3–0.9 m), *Phragmites-Typha-Juncus*, with a homogeneous temperature regime in summer. 1.2. Littoral, abrasion-accumulative muddy–sandy and limestone–sapropel of low thickness (0.5–1.2 m), *Elodea* and locally *Nymphaéa*, with a homogeneous temperature regime in summer. 1.3. Sublittoral, accumulative-transit carbonate-sapropel of low thickness (1.0–2.5 m), *Chara*, with a heterogeneous temperature regime in summer.

II. Profundal aquatic sub-tract on carbonate sapropel underlain by Upper Cretaceous deposits.

Aquafacies: 2.1. Profundal, transit-accumulative carbonate-sapropel of low and medium thickness (2.5–5.0 m), free-floating algae, with clearly expressed temperature stratification in summer. 2.2. Profundal depressions of the bed of the basin, accumulative-transit carbonate-sapropel, medium-thick and thick (5.0–8.0 m), with isolated floating algae and clearly expressed temperature stratification in summer. 2.3. Profundal funnel-shaped depressions

of the basin bed, accumulative carbonate-sapropel, thick (8.0–9.5 m), with free-floating algae and clearly expressed temperature stratification in summer.

In the structure of Lake Doshne's natural aquatic complex (NAC), littoral–sublittoral and profundal aquatic sub-tracts are distinguished. The littoral–sublittoral aquatic sub-tract is the largest, covering 56.5% of the area, and is represented by three types of aquafacies.

Aquafacies 1.1: This shallow coastal zone accounts for 16.05% of the area and is formed on peat and sandy–muddy, low thick sediments, covered with emergent vegetation. The dominant species include Juncus, Scirpus lacustris, and Typha. The surface vegetation range is 35.0–55.0 m and is easily identified in satellite images.

Aquafacies 1.2: Covering 12.28% of the area, this zone extends to a depth of 2.0 m in the littoral zone and is formed on silty–sandy and limestone–sapropel deposits. Underwater vegetation is mainly represented by Elodea canadensis, with floating-leaved plants such as Nymphaea candida and Nuphar lutea occurring locally.

Aquafacies 1.3: The sublittoral zone covers 28.17% of the area and is formed on carbonate-sapropel deposits.

At depths greater than 6.0 m, the central part of the lake basin is occupied by the profundal aquatic sub-tract, covering 43.5% of the area and containing three types of aquafacies. This sub-tract is characterized by low species diversity of vegetation and pronounced temperature stratification during the summer. Bottom sediments in these aquafacies are composed of carbonate sapropel, underlain by chalk and marl of the Coniacian layer (K_2cn). The differentiation of aquafacies is based on the varying thickness of the sapropel deposits.

The average area of the NAC landscape aquafacies is 2.42 hectares, the fragmentation index is 0.41, the complexity coefficient is 3.31, and the landscape fragmentation coefficient is 0.88. More detailed landscape metric characteristics of the NAC are provided in Table 5.

4. Discussion

Given the limited catchment area of the lake (0.38 km^2) and the presence of reclamation canals, this study does not include a model of the landscape structure and land areas, which is traditionally performed in similar research [79]. Nevertheless, we consider the lake and its catchment to form a paragenetic and paradynamic lake basin system (LBS). Lake Doshne, like other lake basins in the Volyn Polissya region, underwent a series of Pleistocene glaciations [80], during which the sedimentary cover was subjected to denudation, exposing Upper Cretaceous rocks near the surface. Tectonic and hydrogeological processes at the beginning of the Holocene intensified karst formation, creating most lake basins [81]. Field instrumental research has confirmed the deep funnel-shaped form of Lake Doshne's basin, characteristic of karstic origin. This is supported by the geological structure of its basin and surrounding landscape complexes, with deposits composed of thin (up to 10.0 m) sand deposits of fluvioglacial, alluvial, and aeolian-deluvial genesis lying on a thick chalk-marly layer of Coniacian-Turonian age. The lake basin is filled with non-lithified sapropelic deposits lying directly on carbonate formations of the Upper Cretaceous. Similar structures have been identified in adjacent lakes, with their modern (Holocene) origin confirmed by radiocarbon dating. For example, the age of the Lake Okunin formation is estimated at approximately 10,370 $\pm$ 170 years [81], and that of Lake Bolotne at approximately 11,250 $\pm$ 90 years [17], with other data provided by M. Pasichnyk [68].

Table 5. The complexity of NAC territorial structure of the Lake Doshne.

NAC Type		Area (S) of NAC Type, ha		% of the Type Area from 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 *
Sub-Tract	**Aqua-Facies, *n***	**Sub-Tract**	**Aqua-Facies**	**Sub-Tract**	**Aqua-Facies**						
						n	**%**	$S_0 = S/n$	$If.c. = n/S$	$Il.c. = n/S_0$	$Il.f. = 1 - S_0/S$
I		10.95		56.50		5	62.5	2.19	0.46	2.28	0.80
	1.1		3.11		16.05						
	1.2		2.38		12.28						
	1.3		5.46		28.17						
II		8.43		43.50		3	37.5	2.81	0.36	1.07	0.67
	2.1		2.09		10.78						
	2.2		5.42		27.97						
	2.3		0.92		4.75						
Total		19.38	19.38	100.0	100.0	8	100.0	2.42	0.41	3.31	0.88

* Indices and coefficients were calculated according to the formulas proposed by A. Domaranskyi [78].

The paradynamic LBS is linked with landscape dynamics processes [82–85], particularly hydro-functioning, geochemical migration of dissolved substances, bio-productive and accumulative processes in the lake, sapropel layer formation, and aeolian and erosional processes in the catchment area. The landscape map of the lake reflects aspects of aquafacies dynamics, particularly abrasion-transit-accumulative processes related to the topography of the lake basin and geophysical landscape and geochemical processes in the NAC. The intensity and direction of these processes are largely determined by the morphology of the catchment area and lake basin relief, the chemical and physical properties of native and loose sediments, the nature of the vegetation cover in the catchment area and the lake, and economic activities in the LBS, which have undergone significant changes in the 20th and 21st centuries. The data in Tables 1–3 indicate that the condition of the LBS deteriorated significantly in the second half of the 20th century. Similar phenomena have been observed in other lakes in the Polissia region of Ukraine [86,87], the Netherlands [88], Poland [89], Germany [90], Sweden [91], and other countries.

Our research involved comparing the hydrological parameters of Lake Doshne with bathymetric studies conducted by Polish scientists during the 1930s [92]. The comparison revealed a decrease in the lake's area by 0.023 km^2, its maximum length by 0.26 km, its average width by 0.57 km, its maximum depth by 4.0 m, and the length of its coastline by 65.0 m. Some hydrological coefficients of the lake also do not coincide, as they are calculated based on fundamental parameters. These findings indicate significant transformations in the water area, the maximum length and width of the lake, and the morphology of Lake Doshne's coast over the past 95 years. Additionally, inaccuracies in measurement works, particularly concerning the echo-sounding of water bodies, may exist.

The study demonstrates the necessity of addressing another critical issue—the creation of a cadastre of lakes, including their catchment areas, i.e., lake basin systems. An essential preliminary step is the collection and organization of data concerning the condition of lakes, their economic utilization, the distribution and intensity of contemporary natural and anthropogenic processes within the lakes and their catchment areas, and the presentation of this data in thematic cartographic models of the LBS.

The application of remote sensing methods and GIS technologies to cartographic studies of lakes is increasingly prevalent worldwide. These studies assess the quality and quantity of natural lake resources and quantify transformational changes in hydrological and geo-ecological processes [93–99]. This urgency arises from the necessity of evaluating freshwater lake reserves, considering the impact of global climate change, and addressing the negative consequences of human activity [100,101]. Cadastral studies indicate that most lakes globally are small, with an area of less than 1 km^2. In fact, 94.39% of all lakes are smaller than 1 km^2, and there are 1.91 million lakes with an area of less than 0.1 km^2 [102]. This research also confirms that small lakes undergo the greatest natural and anthropogenic transformations [103].

Our landscape and geographic research aim to form a cartographic database of small lakes within the Nature Reserve Fund of the Polissia region. Historically, these lakes have undergone significant anthropogenic changes due to drainage reclamation and are currently experiencing climatic stress from prolonged seasonal droughts. Given the current geo-ecological condition of the lake basin systems (LBSs), such cartographic landscape models will provide valuable information for creating a cadastre of lakes and their basins in protected territories, as well as for the integrated management of water resources.

4.1. Limitations

One limitation of this study is the absence of a detailed model of the landscape structure and land areas, which is traditionally included in similar research, due to the limited catchment area and the presence of reclamation canals. Additionally, potential inaccuracies in hydrometric measurements, particularly echo-sounding, may have affected the precision of our findings. Despite these limitations, the study provides valuable insights into the geo-ecological conditions and landscape dynamics of Lake Doshne and its basin.

4.2. Further Research

Future research should aim to enhance the study of the geo-ecological condition of specific lake basin systems (LBSs) by employing methods of multi-criteria ecological assessment of lakes. These methods have been tested on examples from the Transboundary Biosphere Reserve "Western Polissia" [104] and degraded lake ecosystems in Romania [105]. Another promising area of research is the development of a comprehensive cadastral model for the lake basin system and its integration into the national cadastral geo-information system.

5. Conclusions

In summary, the findings of this study underscore the importance of understanding the geo-ecological conditions and landscape dynamics of Lake Doshne and similar lake basin systems. The following conclusions can be drawn:

1. The presented scheme of geographic landscape studies of lakes and their basins was tested on small lakes in the Polissia region, primarily those used for protection and recreation. This methodological approach aligns with the European Landscape Convention. The scheme adheres to the principles of the European Parliament and the Council of Europe in water policy, contributing to the implementation of the 2030 Sustainable Development Goals, particularly in ensuring the availability of quality services for the supply of safe drinking water and preserving the biotic diversity of terrestrial aquatic ecosystems.
2. The proposed cartographic landscape models (based on Lake Doshne) of the LBS can be considered an informational basis for the cadastre of the NRF objects and the planned GIS atlas of the LBS of the Polissia region. These cartographic landscape models of lakes (or LBS) are significant for the spatial development of territorial communities and the ecological and landscape planning of local areas. The developed maps (bathymetric, landscape, etc.), stratigraphic profiles, and hydrological, hydrochemical, and geochemical parameters of the LBS constitute a prerequisite (or reference basis) for conducting geo-ecological monitoring and integrated management of surface water bodies located in the lake basin. The data will underpin the development of schemes for optimizing the protected and recreational use of a specific lake basin based on sustainable development goals.
3. The research established that the basin of Lake Doshne is 29.24% filled with sapropel deposits. Furthermore, more than 16.05% of the NAC water area is covered with higher aquatic vegetation. Macrophytes are common in the peripheral zone of the littoral and are mainly limited to sandy-silty and peat deposits. The combined ecological assessment of the hydrochemical parameters of the lake water in three blocks (salt composition, trophic-saprobiological, and toxic effect) is 1.7, and the water resources of this lake correspond to the second category, class I.
4. Given the close hydrological connection between the lake and the waters of the Upper Cretaceous horizon, it is proposed that the water protection zone around the lake be increased to prevent the ingress of pollutants into the underground aquifers. It is recommended that only organic farming be implemented within the boundaries of the agricultural lands of the farms adjacent to the lake.

Author Contributions: Conceptualization, V.M. and I.K. (Ivan Kirvel); methodology, V.M.; data curation, V.K. and I.Z.; validation, V.M.; formal analysis, I.A.; investigation, V.M.; resources, V.M. and I.Z.; writing—original draft preparation, V.M.; writing—review and editing, I.K. (Ivan Kovalchuk), I.A. and V.K.; supervision, I.K. (Ivan Kirvel); project administration, V.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors upon request.

Acknowledgments: We extend our sincere gratitude to Yaroslav Kurepa for their invaluable support and assistance throughout the development of this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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