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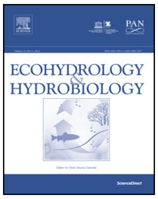

Autotrophic communities' diversity in natural and artificial water-bodies of a river estuary — A case-study of the Dnieper–Bug Estuary, Ukraine

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ABSTRACT

Spatial distribution of plant communities in the human-modified aquatic ecosystem within the Dnieper–Bug Estuary is marked by discrete-continuous patterns. Continuity is caused by hydrological interconnection between the subsystems, and discreteness — by habitat diversity. For higher aquatic plants, the continuity aspect consists in overgrowth of emergent plants all-round the shoreline in both subsystems. The discreteness aspect is noticed in presence of floating-leaf plants' and submerged plants' belts in the natural subsystem only (the lake) and their absence in the artificial one (the sand quarry). For algal communities, continuity is observed in predominance of the same divisions in both subsystems. Discreteness manifests itself in higher taxonomic and floristic diversity of algae in the natural subsystem, than in the artificial one. The process of hydrological interaction between phytoplankton and epiphytic algae is another important mechanism sustaining continuity of algal communities.

1. Introduction

Estuaries are unique aquatic ecosystems inhabited by freshwater and marine organisms and distinguished by high productivity and life concentration (Odum, 1953; Wolanski, 2013). These are dynamic ecosystems with perpetual fluctuations of physical, chemical and biological parameters (Paturej, 2006; Lobry et al., 2008; Nyitrai et al., 2012). Estuaries exhibit high structural and functional biodiversity (Ahel et al., 1996; Meire et al., 2005) and act as ecological gateways for alien aquatic species' migration (Gruszka, 1999).

These aquatic ecosystems are very important from economic and recreational points of view. Therefore, it is essential to assess environmental risks for estuarine ecosystems, in order to integrate ecological management with sustainable economy (Kowalewska-Kalkowska and Kowalewski, 2004). Today serious ecological risks are associated with hydrotechnical works on sand recovery and bottom dredging for navigation purposes. Hydrotechnical operations cause fragmentation or loss of aquatic and wetland habitats (Waltham and Connolly, 2007), and can reduce aquatic biodiversity (Mohamamad and Jalal, 2018).

This type of human impact often transforms estuaries and creates new natural–artificial water bodies within

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them. Sand extraction is among key factors affecting the Dnieper–Bug Estuary. For instance, a large artificial quarry was dug near Kardashynskyi Liman Lake in the early 2000s. After the quarry had connected with the natural lake, a new type of aquatic ecosystem emerged within the Dnieper–Bug Estuary — a human-modified one. At present this human-modified ecosystem consists of two interconnected subsystems: a natural one (the lake itself) and an artificial one (the newly created sand quarry).

In order to develop scientific rationale for protection, conservation and sustainable use of unique estuary ecosystems it is necessary to assess their biodiversity. This is particularly important for plant communities' diversity, because they compose the primary link of energy flow and regulate the water quality. It is known (Manoylov et al., 2016) that serious environmental risks (such as hypoxia, fish mortality) are often preceded by changes in the primary producers' species composition. Therefore, data on autotrophic communities' diversity in estuarine ecosystems can become a scientific background for preventing large-scale hazards to their functioning.

One should note that publications on biodiversity in interconnected natural–artificial ecosystems within estuaries are quite scarce (Waltham and Connolly, 2007, 2013). As regards Kardashynskyi Liman Lake, the most recent published data relate to its natural subsystem only and were obtained during 2003–2013 (Ovechko et al., 2015). However, the ecological situation in the lake has changed for the past five years. Among other things, it is explained by reduction of water volume flowing via the North Crimean Canal and, respectively, by increase in the water releases through the Kakhovka Hydropower Plant dam to the Dnieper–Bug Estuary. In the view of the above, it is required to obtain the latest data on the diversity of autotrophic communities in the subsystems of Kardashynskyi Liman Lake. This paper deals with the results of field studies carried out in summer 2017. Given the fact that this natural–artificial subsystem is very interesting from hydrological and hydrobiological viewpoints, there is an urgent necessity to continue these preliminary studies. Therefore, in the years to come we will explore seasonal and long-term dynamics of plant communities and the main abiotic factors making effect upon them, including water salinity and nutrient content. We will also consider present-day climate change, primarily, the increase in the Dnieper water temperature.

In accordance with the abiotic–biotic regulatory concept (Zalewski and Naiman, 1985), aquatic communities' structure and functioning in riverine ecosystems are driven by hierarchy of abiotic and biotic factors. Only when abiotic factors become stable and predictable, biotic interactions start to manifest themselves. Since the abiotic–biotic regulatory concept can be extrapolated to other types of freshwater ecosystems (Zalewski, 2015), we will apply this concept to our research object. The autotrophic communities' diversity in the natural and artificial water bodies will be considered in close connection with abiotic factors.

The aim of this research is to analyze the taxonomic diversity of higher aquatic plants, phytoplankton, epiphytic algae and to reveal some abiotic factors making effect upon continuity and discreteness of autotrophic communities in two interconnected subsystems (natural and artificial) within the Dnieper–Bug Estuary.

2. Materials and methods

2.1. Study area

The ecosystem under study is a part of the Dnieper–Bug Estuary. It is located on the left-bank floodplain of the Dnieper delta in Kherson Region of Ukraine. The ecosystem consists of two hydrologically connected subsystems: the natural Kardashynskyi Liman Lake and the artificially created sand quarry (Fig. 1).

2.2. Sampling procedure and laboratory processing of samples

Field studies of plant communities in Kardashynskyi Liman Lake and the sand quarry were conducted in summer 2017. In order to assess higher aquatic plants diversity, route surveys were carried out in the lake and the sand quarry water areas with botanical specimens being taken. Phytoplankton and epiphytic algae sampling was performed at six observation sites (Fig. 1). Simultaneously with algae sampling water temperature and Secchi-disk transparency were measured. Water samples were taken for measuring the oxygen concentration in both subsystems and salinity in the natural lake subsystem.

1 dm^3 water samples for phytoplankton study were taken with the help of a Ruthner's bathometer, preserved with 40% formalin solution in the ratio of 1:100, concentrated by sedimentation method and processed in the laboratory according to Shcherbak (2006), and Shcherbak and Zadorozhnaya (2013). The epiphytic algae were sampled in the following way: plant fragments 5–8 cm long were carefully cut down under water, put into wide-necked 100 cm^3 jars and covered with distilled water. Back in the laboratory algae were removed from the plant fragments with a brush and preserved by adding 5 ml of 40% formalin solution into the jar (Semenyuk and Shcherbak, 2016).

Species similarity of planktonic and epiphytic algal communities was assessed with the Sørensen similarity index (Sørensen, 1948). Habitat association of algae was analyzed according to Barinova et al. (2006), salinity preferences — in accordance with classifications set forth in AlgaeBase (Guiry and Guiry, 2019), Barinova et al. (2006) and Van Dam et al. (1994).

3. Results and discussion

3.1. Abiotic factors

According to our field survey results and literature data (Zhukinskiy et al., 1989; Ovechko et al., 2015; Korzhov, 2016), the lake and the sand quarry are considerably different in abiotic factors: hydromorphological, hydrophysical, and hydrochemical (Table 1).

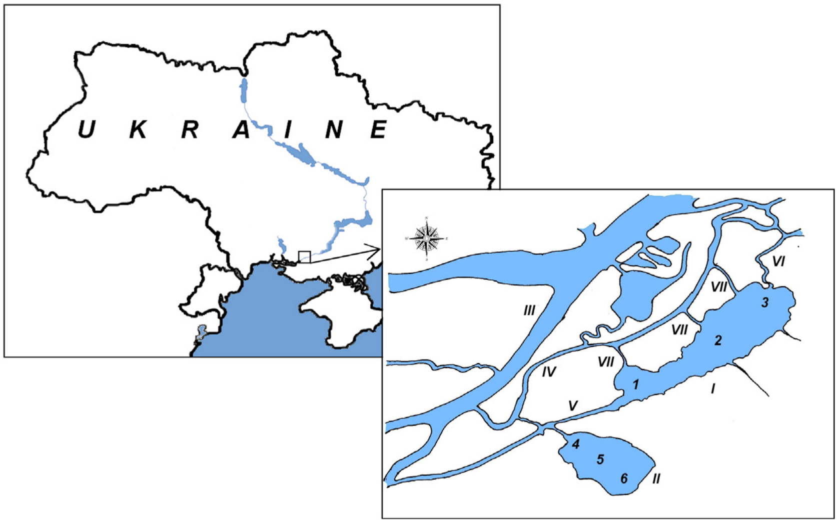

Fig. 1. Schematic map of Kardashynskyi Liman Lake and its geographic location within Ukraine: I — lake subsystem, II — sand quarry subsystem, III — the Lower Dnieper, IV — the Konka River, V — the Chaika River, VI — the Chaika Channel, VII — other channels; 1–6 — sampling sites.

3.1.1. Hydromorphological parameters

Hydromorphological parameters of the water bodies under study differ significantly. The lake subsystem is shallow, and the sand quarry subsystem is considerably deeper (Table 1). The lake is twice as large as the sand quarry in area, however the water volume in the sand quarry is about 25% larger than in the lake.

The lake is hydrologically connected with the Lower Dnieper and exchanges water with it mainly via the Chaika Channel, to a lesser extent via the Chaika River and several smaller channels. Water exchange of the sand quarry is fulfilled via the channel, which connects the quarry with Kardashynskyi Liman Lake. Complete replacement of all water volume in the sand quarry is almost 1.5 times slower than in the lake (Ovechko et al., 2015; Korzhov, 2016). It is because water volume in the sand quarry is larger than in the lake. Moreover, the sand quarry has only one source of water exchange (one channel), and the lake — several sources (several channels) (Fig. 1, Table 1).

3.1.2. Hydrophysical parameters

Hydromorphological dissimilarities between the lake and the sand quarry bring about differences in their temperature conditions. The lake is almost homothermal: the divergence between the subsurface and near-bottom temperatures does not exceed 0.9 °C. The sand quarry demonstrates temperature stratification in summer, with the divergence between the temperature in the subsurface and near-bottom layers reaching 2.8 °C.

There was no noticeable difference in Secchi-disk transparency between the lake and the sand quarry. However, due to greater depths, the sand quarry has lower relative thickness of photic layer in respect of the depth, than the lake (Table 1).

3.1.3. Hydrochemical parameters

Significant differences are observed in oxygen conditions between the subsystems under study. The dissolved oxygen content in the lake is more than twice as high as in the sand quarry (Table 1). The oxygen saturation in the lake is far above 100%, which is indicative of active photosynthetic aeration. At the same time, the sand quarry's oxygen saturation is below 100%.

The maximum oxygen concentrations both in the lake and in the sand quarry were observed near the sources of water exchange. The highest oxygen content in the lake (15.91 mg O_2 dm^{-3}) was registered at Site 3, nearest to the Chaika Channel, through which the lake is filled with water (Ovechko et al., 2015). The highest oxygen concentration in the sand quarry (6.80 mg O_2 dm^{-3}) was observed at Site 4, nearest to the channel connecting the quarry with the lake. So, water exchange makes a positive effect upon oxygen conditions in Kardashynskyi Liman Lake. It is explained by influx of oxygen-saturated water masses from the Lower Dnieper. Besides, water flow creates favorable conditions for autotrophic organisms' photosynthesis (Mass et al., 2010). Similar results were obtained for floodplain lakes of the Vistula River. The oxygen content in lakes hydrologically connected with the river was much higher than in isolated lakes (Dembowska and Napiórkowski, 2015).

Water salinity in the lake subsystem fluctuated within 0.70–1.24 g dm^{-3} at different observation sites. In accordance with the Venice System (International Symposium for the Classification of Brackish Waters, 1958) the lake water is oligohaline. According to Ovechko et al. (2015) the ammonium nitrogen concentration in the lake in summer season makes up 0.28–0.45 mg N dm^{-3}, and inorganic phosphorus concentration — 0.032–0.145 mg P dm^{-3}, therefore, the lake is eutrophic. We have not found any data on the sand quarry's salinity and nutrients concentration in the available literature. So, it is necessary to study these important abiotic factors in the future. On the whole, each of the water bodies under study is marked by a distinctive complex of abiotic factors which make effect upon autotrophic communities.

3.2. *Autotrophic communities*

Plant communities (higher aquatic plants, phytoplankton, epiphytic algae) are distributed in Kardashynskyi Liman Lake and the sand quarry according to discrete-continuous patterns.

3.2.1. *Higher aquatic plants*

Higher aquatic plants' communities are represented by 12 species. The continuum in their spatial distribution can be described as follows. Both subsystems have a distinct belt of emergent plants all-round the shoreline. This belt is dominated by *Phragmites australis* (Cav.) Trin. ex Steud. and *Typha angustifolia* L. Besides, *Scirpus lacustris* L. and *Juncus conglomeratus* L. (J. Ieersi Marss) are observed, but in lower quantities.

Signs of local discreteness can be seen further off-shore of the emergent plants belt. In the lake there is a belt of floating-leaf plants *Hydrocharis morsus-ranae* L., *Nymphaea alba* L., *Nuphar lutea* (L.) Smith. It is followed by a belt of submerged plants *Myriophyllum spicatum* L., *Ceratophyllum demersum* L., *Stratiotes aloides* L., *Potamogeton crispus* L., *Vallisneria spiralis* L.

Unlike the lake, the sand quarry does not have any distinct belts of floating-leaf and submerged vegetation. Such discrete pattern is explained by morphometry and light conditions of the water-bodies under study. The lake is mainly shallow, and photic layer occupies almost the whole water column (Table 1). The sand quarry has significant depths, and the depth increases abruptly from the shoreline. Moreover, the photic layer thickness is about 50% of the water body's depth. Our observation results are confirmed by the data from literature. It is known, that submerged plants can spread only to certain depth limit, below which the solar radiation availability becomes too low for them to photosynthesize (Vestergaard and Sand-Jensen, 2000; Zingel et al., 2006; Rosińska and Gołdyn, 2015; Phillips et al., 2016). Such depth limit is highly correlated with water clarity.

3.2.2. *Phytoplankton*

Phytoplankton of the natural–artificial water ecosystem under study was represented by 88 species and infraspecific taxa from 7 divisions. Its spatial distribution demonstrated continuity in the floristic structure at the divisions level. The main portion of the floristic diversity was formed by Cyanobacteria, Bacillariophyta and Chlorophyta both in the lake and in the sand quarry (Table 2). The distribution of genera and species was distinguished by discrete patterns. The phytoplankton taxonomic diversity was higher in the lake, than in the sand quarry: at the genera level — 40% higher, and at the species level — 70% higher.

Table 1
Main abiotic factors of Kardashynskyi Liman Lake's subsystems.

Kardashynskyi Liman Lake's subsystems	Hydromorphological parameters[a]							Hydrophysical parameters					Hydrochemical parameters				
	Length, km	Width, km	Area, km^2	Volume, 10^6 m^3	Depth, m		Water retention time, days	t, °C		Secchi-disk transparency, m	Photic layer thickness[b]		Oxygen content		Water salinity[c], g dm^{-3}	Nutrient content[a]	
					Average	Maximal		Subsurface layer	Near-bottom layer		Absolute, m	In relation to average depth, %	mg O_2 dm^{-3}	Oxygen saturation, %		NH_4^+, mg N dm^{-3}	PO_4^{3-}, mg P dm^{-3}
Natural subsystem (lake)	4.40	1.20	5.30	7.88	1.5	2.2	16.0	26.1–26.6	25.2–26.0	0.50	1.50	100	15.30–15.91	186–198	0.70–1.24	0.28–0.45	0.032–0.145
Artificial subsystem (sand quarry)	2.00	1.30	2.62	9.96	3.8	6.5	24.5	24.5–26.0	22.4–23.2	0.60	1.80	50	5.65–6.80	70–85	No data available		

[a] According to data from literature (Ovechko et al., 2015; Korzhov, 2016).
[b] Photic layer thickness is equal to Secchi-disk transparency multiplied by three.
[c] We are grateful to Mariia Linchuk, researcher of the Institute of Hydrobiology of the NAS of Ukraine, for measuring water salinity.

Table 2
Phytoplankton taxonomic diversity in the natural–artificial aquatic ecosystem.

Divisions	Natural subsystem (lake)			Artificial subsystem (sand quarry)			Total for the ecosystem under study		
	Orders	Genera	Species and infraspecific taxa	Orders	Genera	Species and infraspecific taxa	Orders	Genera	Species and infraspecific taxa
Cyanobacteria	$\frac{5}{25}$	$\frac{19}{36}$	$\frac{23}{33}$	$\frac{4}{21}$	$\frac{10}{26}$	$\frac{11}{27}$	$\frac{5}{22}$	$\frac{20}{29}$	$\frac{25}{29}$
Bacillariophyta	$\frac{7}{35}$	$\frac{10}{19}$	$\frac{13}{19}$	$\frac{6}{32}$	$\frac{7}{19}$	$\frac{7}{17}$	$\frac{8}{36}$	$\frac{13}{19}$	$\frac{17}{19}$
Cryptophyta	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{3}{4}$	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{3}{3}$
Miozoa	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{5}$	$\frac{2}{5}$	$\frac{2}{5}$	$\frac{1}{5}$	$\frac{2}{3}$	$\frac{3}{3}$
Ochrophyta	$\frac{1}{5}$	$\frac{1}{2}$	$\frac{1}{1}$	$\frac{2}{11}$	$\frac{3}{8}$	$\frac{3}{7}$	$\frac{2}{9}$	$\frac{3}{4}$	$\frac{3}{3}$
Chlorophyta	$\frac{4}{20}$	$\frac{19}{36}$	$\frac{26}{37}$	$\frac{4}{21}$	$\frac{13}{34}$	$\frac{15}{37}$	$\frac{4}{18}$	$\frac{25}{37}$	$\frac{33}{38}$
Euglenozoa	$\frac{1}{5}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{1}{5}$	$\frac{2}{5}$	$\frac{2}{5}$	$\frac{1}{5}$	$\frac{4}{6}$	$\frac{4}{5}$
$\sum$	$\frac{20}{100}$	$\frac{53}{100}$	$\frac{70}{100}$	$\frac{19}{100}$	$\frac{38}{100}$	$\frac{41}{100}$	$\frac{22}{100}$	$\frac{68}{100}$	$\frac{88}{100}$

Above the bar — number of taxa in the division, below the bar — % of the total number of taxa.

Table 3
Sørensen species similarity indices for phytoplankton at different observation sites in Kardashynskyi Liman Lake.

Observation sites		Lake			Sand quarry		
		Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Lake	Site 1	1	0.45	0.36	0.28	0.32	0.30
	Site 2	–	1	0.49	0.32	0.38	0.34
	Site 3	–	–	1	0.32	0.38	0.37
Sand quarry	Site 4	–	–	–	1	0.83	0.51
	Site 5	–	–	–	–	1	0.78
	Site 6	–	–	–	–	–	1

We have compared the phytoplankton communities at different observation sites in the lake and the sand quarry with Sørensen species similarity index (K_S). The highest species similarity is pertaining to phytoplankton within the sand quarry: K_S 0.51–0.83 (Table 3). Lower similarity is observed for phytoplankton at different sites in the lake: K_S 0.36–0.49; and the lowest — between the lake phytoplankton and the sand quarry phytoplankton: K_S 0.28–0.38. Thus, phytoplankton species composition in the lake and the sand quarry differs considerably.

It was shown (Thomas et al., 2007; Yuan et al., 2018) that phytoplankton similarity in the connected water-bodies decreased in low-water years as compared to high-water years. It is explained by the fact that water exchange between the water-bodies in low-water years becomes less intense, which increases the spatial heterogeneity. According to the data from the Central Geophysical Observatory (Kyiv, Ukraine), the Dnieper River flow rate has been low during the recent years (www.cgo.kiev.ua). In the view of the above, we suppose that the low flow rate is an important abiotic factor, contributing to the differences in the lake's and the sand quarry's phytoplankton species composition. Therefore, further studies are required to build a fuller picture of phytoplankton spatial distribution in Kardashynskyi Liman Lake. In particular, it is necessary to conduct a similar research in high-water years.

Floristic spectrum nucleus is an important taxonomic parameter widely used in comparative floristics. It is a list of genera, represented by the highest numbers of species and infraspecific taxa. As it can be seen from Table 4, the phytoplankton floristic structure at the level of genera was marked by higher diversity in the lake, than in the sand quarry.

Given that the water-bodies under study are located within an estuary, it is interesting to look into the ratio of freshwater and marine organisms in them. We have analyzed the phytoplankton species composition in both subsystems according to salinity preferences, applying three different classifications (Guiry and Guiry, 2019; Barinova et al., 2006; Van Dam et al., 1994) (Table 5). In accordance with the classification of AlgaeBase (Guiry and

Table 4
Comparative characteristics of phytoplankton floristic spectra at the level of genera in Kardashynskyi Liman Lake subsystems.

Parameters	Natural subsystem (lake)	Artificial subsystem (sand quarry)
Number of species in a genus	1–3	1–2
Species/genera ratio	1.32	1.08
Floristic spectrum nucleus at the genera level	*Merismopedia* (3) *Cryptomonas* (3) *Nitzschia* (3) *Chlamydomonas* (3)	*Dolichospermum* (2) *Chlamydomonas* (2) *Desmodesmus* (2)

Here and in Table 8, number of species is given in brackets.

Table 5
Ratio of planktonic algae in Kardashynskyi Liman Lake according to salinity preferences.

Subsystems of Kardashynskyi Liman Lake	Species groups according to salinity preferences													
	According to AlgaeBase (Guiry and Guiry, 2019)					According to Barinova et al. (2006)					According to Van Dam et al. (1994)			
	Freshwater	Freshwater/ brackish	Marine/ freshwater	Marine	∑	Halophobous	Non-differentiated oligohalobous	Indifferent	Halophilous	∑	Fresh	Fresh-brackish	Brackish-fresh	∑
Natural subsystem (lake)	63 90	2 3	4 6	1 1	**70** **100**	2 3	12 20	40 68	5 9	**59** **100**	2 17	10 83	–	**12** **100**
Artificial subsystem (sand quarry)	36 88	1 2	4 10	–	**41** **100**	1 3	8 23	23 66	3 8	**35** **100**	1 14	5 72	1 14	**7** **100**
Total for the ecosystem under study	78 89	3 3	6 7	1 1	**88** **100**	3 4	14 19	50 68	7 9	**74** **100**	3 19	12 75	1 6	**16** **100**

Above the bar – number of species with the salinity preference indicated, below the bar – % of the total number of species with known salinity preferences. The results are statistically significant, because the number of species with known salinity preferences in a given subsystem (bold entry) makes up a major part of the total number of species in the respective subsystem: 100% according to the classification of AlgaeBase (Guiry and Guiry, 2019); 84-85% according to Barinova et al. (2006); and 92-100% for Bacillariophyta according to Van Dam et al. (1994).

Guiry, 2019) the lake's and the sand quarry's phytoplankton is dominated by freshwater species. However, one should mention occurrence of *Cylindrotheca closterium* (Ehrenberg) Reimann & J. C. Lewin, a marine diatom, in the lake's phytoplankton. Besides, both system also contain species, which could inhabit both fresh and marine waters. These are, as a rule, widespread cosmopolite species. For example, cyanobacteria *Merismopedia tenuissima* Lemmermann, *Microcystis aeruginosa* (Kützing) Kützing are found in the lake, diatoms *Cyclotella meneghiniana* Kützing, *Diploneis elliptica* (Kützing) Cleve are found in the sand quarry, and *Nitzschia acicularis* (Kützing) W. Smith, *Stephanodiscus hantzschii* Grunow occur in both subsystems.

According to another classification (Barinova et al., 2006), indifferent species prevail in both subsystems. It is also necessary to note, that the portion of halophilous species exceeds that of the halophobous species.

The classification developed by Van Dam et al. (1994) takes into account diatoms only. In accordance with this classification both the lake and the sand quarry are dominated by brackish-freshwater species. So, the taxonomic composition of planktonic algae reflects the water salinity range in Kardashynskyi Liman Lake, which makes up 0.70–1.24 g dm^{-3}.

On the whole, the ratio of species with different salinity preferences is similar in both subsystems. So, it can be expected that there is no significant difference in water salinity between the lake and the sand quarry due to hydrological connection between them. However, further studies are required to confirm this assumption. In particular, it is necessary to measure salinity in both water-bodies in seasonal and long-term aspect with account taken of the Dnieper flow rate.

3.2.3. *Epiphytic algae*

Epiphytic algal communities of the natural–artificial ecosystem include 170 species and infraspecific taxa from 8 divisions. Their spatial distribution is characterized by similar patterns as for phytoplankton. As regards the continuity aspect, both the lake and the sand quarry are dominated by Bacillariophyta, and Chlorophyta are registered as subdominants. However, the lake has higher taxonomic diversity of epiphytic algae than the sand quarry (146 versus 52 species and infraspecific taxa), and this can be considered the discreteness aspect.

Significant taxonomic diversity of epiphytic algae in the lake is explained by high diversity of macrophytes. It is well known that a large number of available habitats is a factor supporting high biodiverstity (Wehr and Sheath, 2015; Alsterberg et al., 2017).

To assess spatial distribution of epiphytic algae it is essential to compare their communities on various substrata, i. e. plants of different ecological groups. The lowest taxonomic diversity was pertaining to epiphytic algae in the emergent plants belt, higher — in the floating-leaf plants belt, and the highest — in the submerged plants belt. It may be explained by larger surface area of submerged plants as compared to emergent and floating-leaf macrophytes. Cyanobacteria, Cryptophyta and Ochrophyta were more diverse on floating-leaf plants and submerged plants, than on emergent plants (Table 6).

Table 6
Taxomonic diversity of epiphytic algae in the belts of plants relating to different ecological groups in Kardashynskyi Liman Lake.

Divisions	Belt of emergent plants			Belt of floating-leaf plants			Belt of submerged plants			Total		
	Orders	Genera	Species and infraspecific taxa	Orders	Genera	Species and infraspecific taxa	Orders	Genera	Species and infraspecific taxa	Orders	Genera	Species and infraspecific taxa
Cyanobacteria	4 19	7 16	8 12	4 16	10 18	12 14	4 15	12 21	13 12	4 13	18 23	21 14
Bacillariophyta	9 43	19 43	37 54	9 36	23 42	44 51	11 42	23 41	61 56	11 37	26 34	72 49
Cryptophyta	–	–	–	1 4	1 2	3 4	2 8	2 4	3 3	2 7	2 3	4 3
Miozoa	–	–	–	1 4	1 2	1 1	–	–	–	1 3	1 1	1 1
Ochrophyta	1 5	1 2	1 1	3 12	3 5	3 4	1 4	2 4	2 2	3 10	4 5	4 3
Charophyta	2 9	2 5	3 4	1 4	1 2	2 2	1 4	1 1	6 6	2 7	2 3	7 5
Chlorophyta	4 19	13 29	18 26	6 24	16 29	21 24	6 23	14 25	21 19	6 20	21 27	34 23
Euglenozoa	1 5	2 5	2 3	–	–	–	1 4	2 4	2 2	1 3	3 4	3 2
$\sum$	21 100	44 100	69 100	25 100	55 100	86 100	26 100	56 100	108 100	30 100	77 100	146 100

Above the bar — number of taxa in the division, below the bar — % of the total number of taxa.

Sørensen similarity index has been applied to compare the epiphytic algae species composition on plants of different ecological groups. The results have shown that epiphytic algal communities are distributed in Kardashynskyi Liman Lake in accordance with discrete pattern (Table 7). Most of the obtained Sørensen index values do not exceed 0.50. The lowest similarity (K_S 0.33–0.38) was recorded between algal communities on macrophytes relating to different ecological groups. These data confirm that Kardashynskyi Liman Lake has a large quantity of diverse habitats, each marked with a specific complex of environmental variables. This factor contributes to high taxonomic diversity of autotrophic communities.

Significant dissimilarity was also recorded in the floristic spectra of epiphytic algal communities on higher plants of different ecological groups (Table 8). In the belts of emergent and floating-leaf plants, the highest species richness was observed for *Gomphonema* and *Cymbella* genera, while on submerged plants *Nitzschia* genus was the most diverse. It may be explained by the fact, that species from *Gomphonema* and *Cymbella* genus relate to typical epiphytes. They are distinguished by heteropolar form of their frustules and are firmly attached to the substratum surface. Therefore, they can have competitive advantage on smooth substrata, such as reed stems or candock leaves or petioles. In contrast, species from *Nitzschia* genus are, as a rule, eurytopic, motile forms. More favorable conditions for their growth are observed on plants with dissected leaf blades, for example, on *C. demersum* L. or *M. spicatum* L. *Cosmarium* genus also showed high species richness in the belt of submerged plants. The point is that species from *Cosmarium* genus frequently grow in abundance in plankton among submerged vegetation and may sediment upon the plant surface.

3.2.4. *Comparison of planktonic and epiphytic algal communities*

To assess continuity and discreteness of algal diversity it is important to compare taxonomic composition of phytoplankton and epiphytic communities. The comparison was

Table 7
Sørensen species similarity indices for epiphytic algal communities on plants of different ecological groups in Kardashynskyi Liman Lake.

Substratum plants		Emergent		Floating-leaf			Submerged		
		Phragmites australis	*Typha angustifolia*	*Nuphar lutea*	*Nymphaea alba*	*Hydrocharis morsus-ranae*	*Myriophyllum spicatum*	*Stratiotes aloides*	*Ceratophyllum demersum*
Emergent	*Phragmites australis*	1	0.51	0.52	0.43	0.43	0.38	0.43	0.49
	Typha angustifolia	–	1	0.48	0.46	0.46	0.46	0.47	0.45
Floating-leaf	*Nuphar lutea*	–	–	1	0.37	0.46	0.52	0.52	0.54
	Nymphaea alba	–	–	–	1	0.36	0.33	0.43	0.40
	Hydrocharis morsus-ranae	–	–	–	–	1	0.47	0.48	0.37
Submerged	*Myriophyllum spicatum*	–	–	–	–	–	1	0.46	0.46
	Stratiotes aloides	–	–	–	–	–	–	1	0.47
	Ceratophyllum demersum	–	–	–	–	–	–	–	1

Table 8
Comparative characteristics of floristic spectra of epiphytic algal communities at the genera level on plants of different ecological groups in Kardashynskyi Liman Lake.

Parameters	Belts of substrata plants		
	Emergent plants	Floating-leaf plants	Submerged plants
Number of species in a genus	1–5	1–5	1–9
Species/genera ratio	1.57	1.56	1.93
Floristic spectrum nucleus at the genera level	*Gomphonema* (5) *Cymbella* (4) *Aulacoseira* (3) *Epithemia* (3) *Navicula* (3) *Nitzschia* (3)	*Cymbella* (5) *Gomphonema* (5) *Navicula* (5) *Nitzschia* (5) *Desmodesmus* (5) *Cryptomonas* (3) *Epithemia (3)*	*Nitzschia* (9) *Gomphonema* (8) *Cymbella* (6) *Cosmarium* (6) *Navicula* (5) *Fragilaria* (5) *Aulacoseira* (3) *Epithemia* (3) *Ulnaria* (3) *Tetradesmus* (3) *Desmodesmus* (3) *Tetraedron* (3)

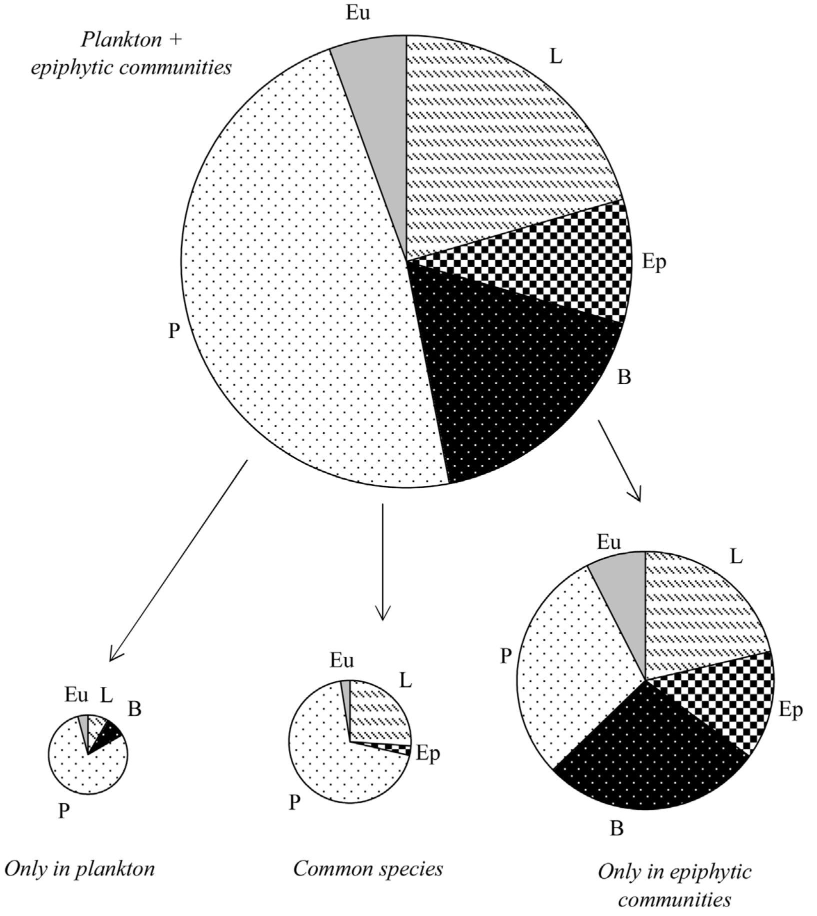

Fig. 2. Comparative analysis of habitat association of algal species in phytoplankton and epiphytic communities of Kardashynskyi Liman Lake: L — littoral forms, Ep — epiphytic forms, B — benthic forms, P — planktonic forms, Eu — eurytopic forms.

performed for the lake subsystem, because it is marked by the highest diversity of algae, both planktonic and epiphytic.

On the whole, the taxonomic diversity of algae in the lake subsystem comprised 176 species and infraspecific taxa. Out of them 42 occurred both in plankton and epiphytic communities, 29 occurred only in plankton, and 105 — only in epiphytic communities.

The Sørensen index, calculated for phytoplankton and epiphytic algal communities of the lake, was equal to 0.38. It means, that their species compositions differ significantly. However, a portion of species proved to be common for plankton and epiphytic communities.

It has been shown recently (Kasim, 2011; Liu et al., 2014; Zadorozhna et al., 2017), that phytoplankton and epiphytic algal communities are not isolated, but interact with each other and form a dynamic system. Presence of common species in plankton and epiphytic communities can be caused by three main mechanisms: habitat versatility of species, algae's sedimentation from plankton to higher aquatic plants surface and transition of typically epiphytic species to plankton due to hydrodynamic processes.

In the view of the above, it is interesting to analyze habitat association of algae recorded in water column and upon higher aquatic plants surface in Kardashynskyi Liman Lake. Out of the total phytoplankton and epiphytic algal communities' species list, 48% of species were typically planktonic, 21% — littoral, 18% — benthic, 9% — epiphytic and 6% — eurytopic (Fig. 2).

Among the species occurring only in plankton (Fig. 2) typically planktonic forms prevailed (79%), the portion of species with other habitat association being insignificant. Among the species recorded only in epiphytic communities 28% fell on benthic forms, 30% — on planktonic forms, 21% — on littoral forms, 14% — on epiphytic forms and 7% — on eurytopic forms.

As regards habitat association of common species for both groups, they were dominated by planktonic forms (69%). Thus, presence of common species in the lake phytoplankton and epiphytic communities is mainly related to the process of planktonic forms' settling down upon the higher plants' surface. This process may be considered a factor determining algal communities' continuity. In general, the discrete-continuous patterns of plant communities' spatial distribution in the natural–artificial aquatic ecosystem under study is summarized in Table 9.

In the view of the above, it can be said that hydrological connection between the lake and the sand quarry is the main abiotic factor determining the autotrophic link continuity in Kardashynskyi Liman Lake. It is confirmed by Meire et al. (2005) believing that various habitats within estuaries do not exists in isolation, but maintain different types of interaction. These interactions can be

Table 9
Continuity and discreteness of plant communities' distribution in the natural–artificial aquatic ecosystem within the Dnieper–Bug Estuary.

Communities	Parameters		Continuity	Discreteness
Higher aquatic plants	Vegetation patterns		Belt of emergent plants all-round the shoreline with *Phragmites australis* and *Typha angustifolia* dominating	**Lake** – three belts of plants (emergent, floating-leaf and submerged); **quarry** – one belt (emergent plants)
Phytoplankton	Taxonomic diversity		7 divisions and 19–20 orders	**Lake** – 70 species; **quarry** – 41 species
	Floristic spectra	Divisions	Chlorophyta 37%; Cyanobacteria 27–33%; Bacillariophyta 17–19%	–
		Genera	*Chlamydomonas* 4–5% *Dolichospermum* 3–5%	Maximal number of species in a genus: **lake** – 3; **quarry** – 2 species/genera ratio: **lake** – 1.32; **quarry** – 1.08
	Ratio of species according to salinity preferences		Indifferent 66–68%, oligohalobous 20–23%, halophilous 8–9%, halophobous 3%	–
Epiphytic algal communities	Taxonomic diversity		6–8 divisions and 21–26 orders	**Lake** – 146 species; **quarry** – 52 species; **emergent plants** 69 species; **floating-leaf plants** 86 species; **submerged plants** 108 species
	Floristic spectra	Divisions	Bacillariophyta 51–56%; Chlorophyta 19–26%; Cyanobacteria 12–14%	–
		Genera	*Gomphonema* 5–7% *Cymbella* 4–6%	Maximal number of species in a genus: **emergent plants** – 5; **floating-leaf plants** – 5; **submerged plants** – 9; species/genera ratio: **emergent plants** – 1.57; **floating-leaf plants** – 1.56; **submerged plants** – 1.93 *Nitzschia*: **emergent plants** – 4%, **floating-leaf plants** – 6%, **submerged plants** – 8% *Cosmarium*: **emergent and floating-leaf plants** – 2–3%, **submerged plants** – 6%
System "phytoplankton ↔ epiphytic algal communities"	Taxonomic diversity and habitat association		42 common species of algae, out of which 69% planktonic	29 species occurring only in plankton (out of them 79% planktonic forms); 105 species occurring only in epiphytic communities (out of them 28% benthic, 30% planktonic, 21% littoral, 14% – epiphytic forms)

physical (such as water exchange, sediments transport), chemical (transfer of nutrients and other substances) and biological (motile species migration) (Meire et al., 2005). Besides, some researchers show that hydrological connection between water bodies represents a route for passive dispersal of organisms, which cannot oppose the force of current, in particular, planktonic algae (Logue et al., 2011; Devercelli et al., 2016; Hu et al., 2017). The proponents of this theory consider phytoplankton inhabiting hydrologically interconnected water bodies as "metacommunity". Therefore, we may suppose that after completion of hydrotechnical operations the lake served as a key source of species for colonization of the newly-formed sand quarry due to water exchange between them.

At the same time dissimilarities in hydromorphological parameters between the lake and the sand quarry cause the difference in their photic layer thickness and, respectively, the irradiance conditions. The solar radiation factor, in its turn, determines the discrete patterns of autotrophic communities and explains their higher taxonomic diversity in the lake, than in the sand quarry.

We think, that the natural–artificial ecosystem of Kardashynskyi Liman Lake may serve to illustrate the abiotic–biotic regulatory concept. In accordance with this concept structure and functioning of aquatic communities in riverine ecosystems are driven by hierarchy of abiotic and biotic factors. Only when abiotic factors become stable and predictable, biotic interactions start to manifest themselves (Zalewski and Naiman, 1985; Zalewski, 2015). The sand quarry's ecosystem is rather "young", and functioning of its autotrophic communities is mainly driven by abiotic factors. The lake is an "older", developed ecosystem with rather stable abiotic conditions. So, biotic interactions become more important there. For example, oxygen saturation in the lake reaches 186–198%. Therefore, we may state that the lake's oxygen conditions in summer are mainly driven by a biotic factor — photosynthetic aeration of water by algae and higher aquatic plants. Another example of biotic interactions is that high diversity and abundant growth of aquatic plants make numerous habitats available for epiphytic algal communities. Due to this factor high taxonomic diversity of epiphytic algae is formed.

Since Kardashynskyi Liman Lake is hydrologically connected with the Lower Dnieper network, it faces an important risk of cyanobacterial blooms, observed in the Dnieper reservoirs. It is confirmed by occurrence of typical agents of water blooms in the lake and the sand quarry: *Dolichospermum flosaquae* (Brébisson ex Bornet & Flahault) P. Wacklin, L. Hoffmann & J. Komárek, *Aphanizomenon flosaquae* Ralfs ex Bornet & Flahault, *Cuspidothrix issatschenkoi* (Usachev) P. Rajaniemi, Komárek, R. Willame, P. Hrouzek, K. Kastovská, L. Hoffmann & K. Sivonen. It is well-known that planktonic cyanobacteria growth intensifies under condition of slow water exchange. For example, cyanobacterial blooms in Sulejów Reservoir (Central Poland) increase in intensity, when the water retention time exceeds 30 days (Tarczyńska et al., 2001; Zalewski, 2012). According to literature data (Timchenko, 1996; Ovechko et al., 2015) the retention time of Kardashynskyi Liman Lake tends to get longer. Thus, if water exchange processes continue to weaken in the future, water blooms may become more intense there.

The low stream-flow rate of the Dnieper River and abnormally high summer temperature, recorded in the recent years (www.cgo.kiev.ua; Shcherbak, 2019) are other important factors, which may intensify cyanobacterial blooms in Kardashynskyi Liman Lake. In the view of the above, assessing phytoplankton's seasonal and year-to-year dynamics in Kardashynskyi Liman Lake, its relation to the Dnieper flow-rate and water temperature are urgent tasks for our further studies. These factors must also be taken into account in long-term forecasts and in developing practical recommendations for conservation of the unique Dnieper–Bug Estuary and mitigation of risks for its functioning.

4. Conclusion

Current hydrotechnical impact upon aquatic ecosystems causes a unique type of water-bodies to appear, which combine natural and artificial habitats in a single system. Spatial distribution of plant communities in them is marked by discrete-continuous patterns. For higher aquatic plants the continuity aspect consists in overgrowth of emergent plants all-round the shoreline in both subsystems. The discreteness aspect is observed in presence of floating-leaf and submerged plants in the lake subsystem only and their absence in the sand quarry.

For phytoplankton and epiphytic algae, continuity manifests itself in predominance of the same divisions in both subsystems. Discreteness is noticed in higher taxonomic and floristic diversity of algae in the natural subsystem, than in the artificial one. The process of interaction between phytoplankton and epiphytic algae is another important mechanism sustaining continuity of algal communities.

The natural–artificial ecosystem of Kardashynskyi Liman Lake may serve to illustrate the abiotic–biotic regulatory concept (Zalewski and Naiman, 1985; Zalewski, 2015). The sand quarry ecosystem is rather "young", and functioning of its autotrophic communities is mainly driven by abiotic variables (morphometry, water transparency, retention time, temperature conditions). At the same time, biotic factors start to manifest themselves in the "older", developed ecosystem of the lake, especially in summer season. These biotic factors include high diversity and abundant growth of aquatic vegetation, photosynthetic aeration of water by algae and higher aquatic plants.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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