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Phytocenological approach in biomonitoring of the state of aquatic ecosystems in Ukrainian Polesie

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Abstract

The results of a research into the scale and consequences of the degradation of aquatic ecosystems in Ukrainian Polesie have been detected in article, and the areas of increased anthropogenic pressure have been identified which greatly affect the condition and number of aquatic macrophytes. The biodiversity of sites with different anthropogenic load was evaluated using the biodiversity criteria.

In the research, the structural and functional features of macrophytic species diversity within Teteriv River ecological corridor as a typical river landscape of Ukrainian Polesie were determined and described, the floristic composition was determined. Within the ecological zones, the number of species and their projective coverage in areas with different anthropogenic pressures within Teteriv River ecological corridor were determined.

The basic criteria for the implementation of deferred biomonitoring based on the analysis of the dynamics of the species composition of the phytocoenoses of Teteriv River ecological corridor on the indicators of ecological stability and plasticity using the species-specific criteria, are: Margalef species richness index, Sørensen–Dice index, Shannon diversity index, Simpson's index, and Pielou's evenness index. Based on the results, correlation dependencies have been constructed, which will allow to obtain data on the stability of the development of aquatic ecosystems according to the data of species surveys. Interconnections between biodiversity indicators and indicators of surface water quality within the Ukrainian Polesie were found; they are the fundamental component of a long-term monitoring of the stability in the development of aquatic phytocenoses.

Key words: *biodiversity, biomonitoring, macrophytes, Margalef index, Pielou index, Shannon index, Simpson index, surface water, water quality*

INTRODUCTION

Increasing anthropogenic load along with rising levels of consumption of natural water and extensive type of economic management in the river basins of Ukraine have led to the deterioration of the ecological state not only of surface water, but also to a significant modification of the composition and condition of living organisms, including aquatic macrophytes [BAHROUN, CHAIB 2017; GRIB, GROKHOVSKAYA 2001; JANKOWSKA-HUFLEJT 2006; KLIMEN-

KO, BIEDUNKOVA 2016; MIATKOWSKI, SMARZYŃSKA 2017; ROMANCHUK *et al.* 2018]. Current methods for assessing water quality used by the inspecting services come down to establishing the presence of certain amount of toxic substances in water, while their influence on a number of inhabitants of reservoirs is levelled. In recent years, there has been an increasing need for strategic level operations aimed at providing an integrated assessment of the environmental sustainability of aquatic ecosystems; and it has gained significant importance [FRÄNZLE 2006; KLYMENKO *et al.* 2018; MIODUSZEWSKI 2015]. Such an integrated assessment is also stipulated in the EU Water Framework Directive 2000/60/EC. However, in the territory of Eastern Europe, it requires significant adjustments, which involve an increase in the role of the biological component, expansion of the list of biological indicators suitable for inclusion in the system of integrated assessment of surface water quality. As there is increasing evidence in the literature that the method of using species indicators is inadequate, the use of various parameters of phytocenoses for this purpose is potential importance. It is this method of bioindication that has proven to be more informative and accurate [AFANASIEV 2001; PADISAK *et al.* 2006; PROTASOV, 2002].

Many scientists highlight that the species structure of ecosystems changes as a result of anthropogenic impact; therefore, methods for analyzing the structure of phytocenoses can serve as indicators of sustainable development of aquatic ecosystems [DIDUKH, PLIUTA 1994; LACOUL, FREEDMAN 2006; ROMANCHUK *et al.* 2017; SPELLERBERG 2005]. Such a phytocenological approach was proclaimed in the work of Odum, where species diversity and evenness were determined as fundamental elements in assessing the stability of ecosystem development [ODUM 1986]. "Conceptual diversicology" was identified as a separate direction in different works [AKASAKA *et al.* 2010]. This term summarizes multidirectional studies of the biodiversity phenomenon. Subsequently, this term was often found in the works of other hydrobiologists [ROMANCHUK *et al.* 2018].

In a number of scientific publications, it is emphasized that changes in the phytocenological indicators of ecosystems are closely related to the issues of ecological successions [DUBYNA *et al.* 1993; FEDONIUK *et al.* 2019]. It is obvious that the stronger the environment is changed as a result of anthropogenic load, the faster succession changes complete, that is, the species diversity of ecosystems decreases [BOEDELTJE *et al.* 2002; KORZENIAK 2002]. In ecosystems that have spatially homogeneous conditions, biocenoses that are relatively "poor" in species composition are often formed [BIRK, WILLBY 2010; BUNN, ARTHINGTON 2002]. As a result of an intense anthropogenic load, the spatial differences of ecosystems can significantly decrease [RASPOPOV 2000].

Therefore, the purpose of our work was to determine the possibilities, criteria and parameters of parameters of using phytocenological indicators in assessing water quality in Teterevskyi ecological corridor as a general example.

MATERIALS AND METHODS

The research into the possibilities of using phytocenological approach to define ecological tolerance and sustainability of development of aquatic ecosystems was conducted within the zone of Ukrainian Polesie. Among the various types of water reservoirs, rivers belonging to the class of medium and large water courses were selected, including Teterev, Gnilopiat, Irsha, Guiva and Zdvizh, as well as rather large water storage basins such as Chudnovskoie, Otsechnoie, Zhytomyrskoie, Malinskoie and Irshanskoie (Fig. 1).

Water quality at the observation points was assessed in accordance with the "Methodology of ecological evaluation of surface water quality by corresponding categories" [ROMANENKO, ZHUKINSKIY 1998]. Based on the data obtained, *Ie* – the general ecological index of water quality, it was calculated as the average of three block indices: *Is* – the index of the content of substances of salt composition; *Its* – the index of trophic-saprobological indicators; *It* – the index of the content of specific substances of toxic and radiation effects.

In the course of research, the method of long-term bioindication was tested. According to this method, geobotanical descriptions of groups of aquatic higher plants were carried out and the data obtained was evaluated using the phytocenological approach. The primary materials for the bioindication analysis were independent studies of the authors, which included descriptions of aquatic ecosystems of certain sections of the river ecosystems of Ukrainian Polesie. The authors collected the materials during 2011–2015. The research was conducted at 57 points with simultaneous sampling of water. Over the length of the Teterevskyi ecological corridor, at the observation points, phytocenoses were studied on both banks, which were located as parallel as possible, as far as the terrain permitted, and as close to the zone of anthropogenic load as possible. For a more detailed analysis of the influence of anthropogenic load on the species composition of macrophytes, samples were also taken along the river flow before and after the territories of settlements.

In order to assess the ecological state of landscapes within the location of observation points, the methodology of KLEMENTOVA and HEINIGE [1995] was applied. In accordance with this methodology, the coefficient of ecological stabilization of landscapes ($CESL_1$) was calculated.

To determine the similarity of the species composition of aquatic higher plants of the left-bank and right-bank parts of the Teterevskyi ecological corridor, we applied the Sørensen similarity criterion for biosystems at all oppositely located points on the left and right banks. The criterion was determined as the ratio of the number of coincident features to their total number based on statistical analysis. This criterion assesses the degree of difference between the comparative ecosystems of the multidimensional phase space.

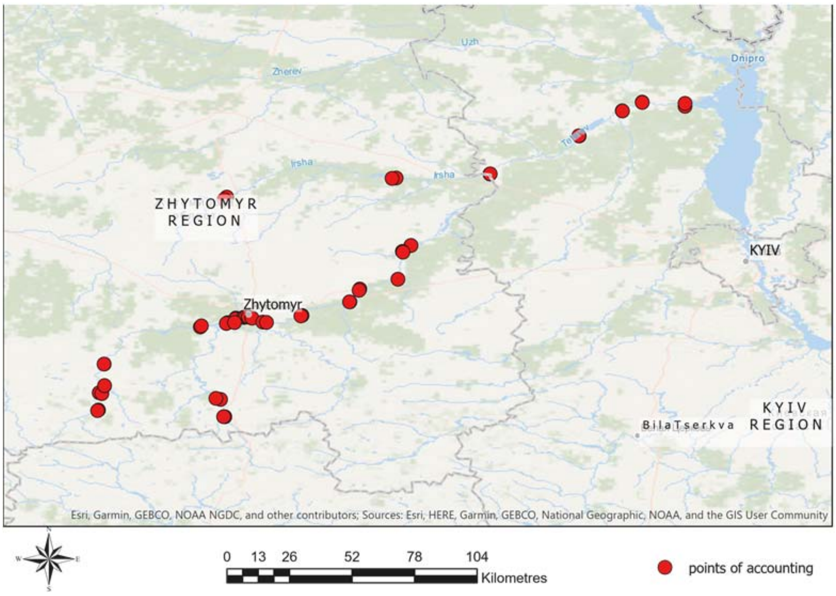

Fig. 1. Distribution of record points of aquatic higher plants in the territory of Ukrainian Polesie; source: Google Earth 6.2.2.6613, aerial photograph with author's marking

Owing to the fact that wetland phytocenoses are dynamic and sensitive components in relation to the level of anthropogenic pollution, we performed complex calculations that mathematically interpret the species diversity of these ecosystems: species richness – Margalef index, species abundance – index, evenness – Pielou index, the dominance index – Simpson index, the index of general diversity – Shannon index.

Margalef species richness index (*d*) was calculated using Equation (1):

$$d = \frac{S-1}{\log N} \tag{1}$$

Where: S = number of species, N = number of specimens.

Simpson dominance index (*c*) was calculated using Equation (2):

$$c = \sum \left(\frac{n_i}{N}\right)^2 \tag{2}$$

Shannon index of general diversity (*Hs*) was calculated using Equation (3):

$$Hs = -\sum_{i=1}^{s} \left(\frac{n_i}{N}\right) \ln \left(\frac{n_i}{N}\right) \tag{3}$$

Where: n_i = number of specimens belonging to species i; N = total number of specimens; S = number of species.

Pielou evenness index (*E*) was calculated using Equation (4):

$$E = \frac{H}{\log S} \tag{4}$$

Where: H = Shannon index; S = number of species.

RESULTS

Within the Teterevskyi ecological corridor, we described 43 species belonging to three divisions. The most numerous of them was *Magnoliophyta*, which included 41 species from all recorded. One species belonging to the division *Equisetophyta* and one belonging to *Filicophyta* were detected. Within the *Magnoliophyta* division, there were three classes: monocotyledons (Liliopsida) which included 3 orders, 6 families, 9 genera, and 15 species; dicotyledons (*Magnoliophyta*) which included 11 orders, 11 families, 12 genera, and 14 species. The group of surface water-air species was the most numerous; among the total number of species it occupied about 53.8%. Most phytocenoses belonged to the boreo-meridional chorological group with a circumpolar type of area. In accordance with the Raunkiær subdivision by life forms, 100% of plants were assigned to three main groups: hydrophytes, hemicryptophytes and geophytes.

An analysis of the distribution of species diversity showed that aquatic ecosystems dominate within the Teterevskyi ecological corridor. These aquatic ecosystems are inhabited by species with wide ranges of tolerance to thermal-, ombro-, continental-, and cryo-modes; such species are able to exist in ecotopes of continuous overmoistening of floodplain, in moist swampy ecotopes, and in places with temporary overmoistening, low levels of dissolved oxygen in water, the presence of silty deposits and the predominance of anaerobic processes of substances transformation, neutral or acidulated substrates, with a considerable range of nitrogen availability and mineral composition of media, as well as the presence of traces of substrate salinization.

It was established that the most uniform phytocenoses are found in areas of intense anthropogenic load, that is, starting from points No. 1–15 and 1–16 (the place where pollutants enter from the Kamenka River), where this criterion was 0.8750 (Fig. 2).

The lowest similarity indices were recorded within the points No. 1–03 ... 1–14, 1–25 ... 1–26, 1–31 ... 1–32, 1–37 ... 1–38 and others. In general, this indicates a favourable ecological situation for the development of significant species diversity (i = 0.5294 ... 0.7586).

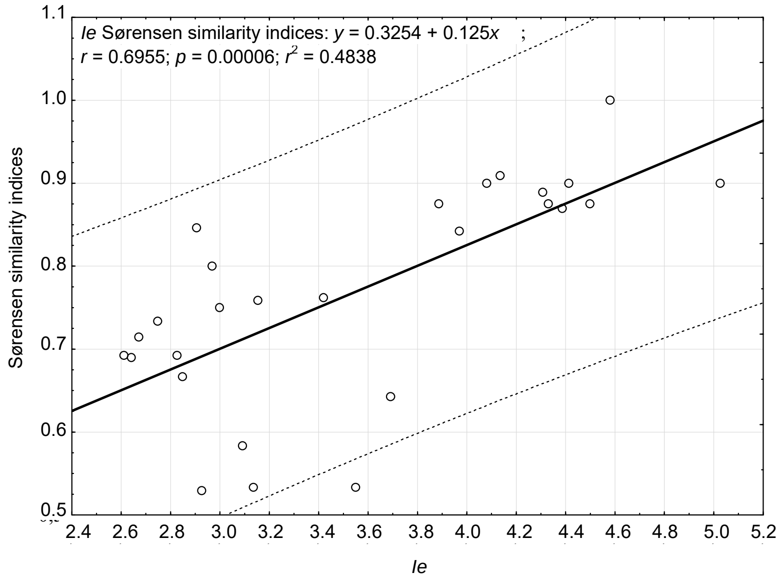

Fig. 2. Correlation between general ecological index *Ie* and Sørensen indices; source: own study

The species diversity of hydrobiont clusters was also characterized using the Margalef species richness (*d*) and the Pielou evenness indices, which are common informative indicators in environmental research. They are a mathematical relationship between the number of species and their quantity [ELMQVIST *et al.* 2003; MAGURRAN 2013].

The Margalef species abundance or species richness index (*d*) is a significant qualitative indicator of biodiversity at local, landscape and regional environmental levels [CAO *et al.* 1996]. In the context of the research, the Margalef index (*d*) reached high values in ecosystems with the lowest anthropogenic load (No. 1–01 ... 1–06, 1–09 … 1–10 and others).

It was found that the value of the Margalef index significantly depended on the water quality and on the level of stabilization of landscapes (Fig. 3).

We created the three-dimensional model of distribution of the species richness Margalef indices (*d*), which makes it possible to carry out a fairly reliable assessment of the stability of the development of aquatic ecosystems:

$$d = 31.2346 - 10.5881x + 5.7058y + 1.0904x^2 + 0.0568x - 2.11y^2 \quad (5)$$

Where: x = integrated ecological index of water quality; y = coefficient of ecological stabilization of landscapes.

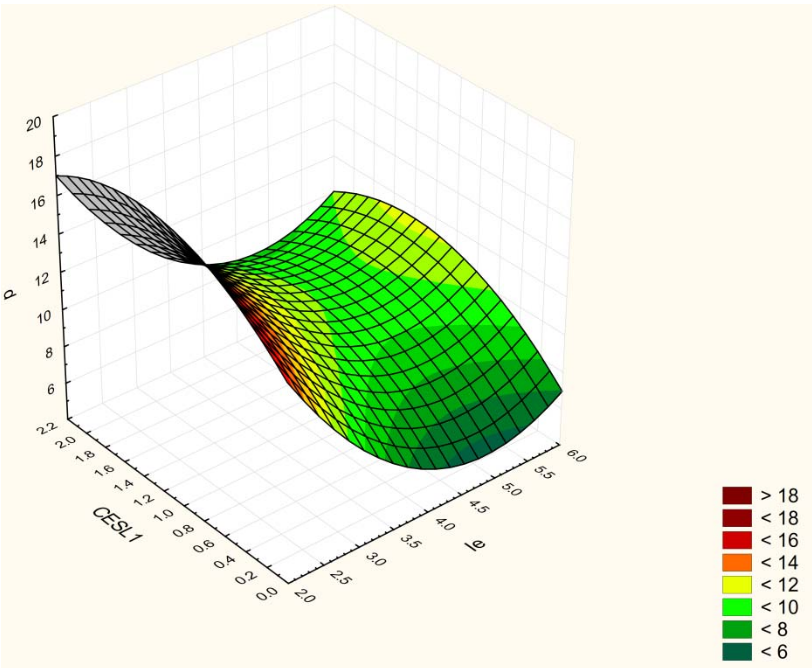

Fig. 3. Dependence of the Margalef index (*d*) on the general ecological index of water quality (*Ie*) and on the level of ecological stabilization of landscapes ($CESL_1$); source: own study

Thus, Equation (5) makes it possible to determine and forecast the patterns of the distribution of the total number of species to the number of specimens depending on the indicators of stabilization of landscapes and water quality indicators. This statement is also consistent with a conducted joint correlation analysis of the observation points in the investigated area, which showed a high degree of correlation between the Margalef species richness index, the ecological index of water quality and the level of stabilization of landscapes ($r = -0.6697$). In addition, the degree of connection between the individual blocks of the ecological classification of surface water quality and the Margalef index was significantly different.

Thus, the value of the Margalef species richness index (*d*) depended less on the surface water quality in terms of hydrochemical and hydrophysical indicators (block *Is*); and the degree of linear correlation can be estimated as "moderately tight inverse" ($r = -0.453$).

The dependence of the Margalef species richness index on the *Its* block, which was based on the values of surface water quality by the chemical trophic and saprobological criteria, can be described as the most significant. A linear dependence between these indicators showed a tight inverse correlation similar to the previous block ($r = -0.580$).

A weak inverse correlation was also noted for the Margalef index with the last It block (by the criteria for the content of substances of toxic and radiation exposure) – $r = -0.265$.

Many researchers consider the Shannon index to be the most optimal for evaluating the state of aquatic ecosystems [GRIB, GROKHOVSKAYA 2001; KLOCHENKO *et al.* 2014; KLYMENKO *et al.* 2018]. This is the best indicator to assess how well biocenoses are structured or to define the degree of orderliness (awareness) of the system. It is obvious that the indices of general biodiversity and species richness decrease inversely to the intensity of the action of anthropogenic factors on biological objects [FRÄNZLE 2006].

The Shannon criterion, as well as the Margalef criterion, is higher in ecosystems with anthropogenic factors increases. The Shannon index (*H*) is often used to determine anthropogenic load on the medium. Phytocenoses were characterized by the lowest Shannon indices at the points where completely unfavourable conditions for the development of species diversity were formed, i.e. all points where pollutants from surface runoff or wastewater are discharged.

Based on the obtained data, we constructed a three-dimensional model of distribution of Shannon indices of general diversity (*H*), which makes it possible to conduct a fairly reliable assessment of the stability of the development of aquatic ecosystems:

$$H = 1.5346 - 0.003466x^3y - 0.000956xy^3 \quad (6)$$

Where: x = integrated ecological index of water quality; y = coefficient of ecological stabilization of landscapes.

Provided there are indicators of landscape destabilization and the dynamics of changes of the water quality, the suggested equation 6 makes it possible to forecast the possible changes in the structures of phytocenoses, and also to determine the critical development limits of rarer species.

The proposed equation 6 allows, in the presence of indicators of landscape destabilization and the dynamics of changes in water quality, to predict possible changes in the structure of phytocenoses, and also allows you to determine the critical development limits of rarer species. Depending on the ecological state of water and the level of stabilization of landscapes, the distribution of Shannon indices showed an inverse strong correlation between the indicated indices ($r = -0.582$) – Figure 4.

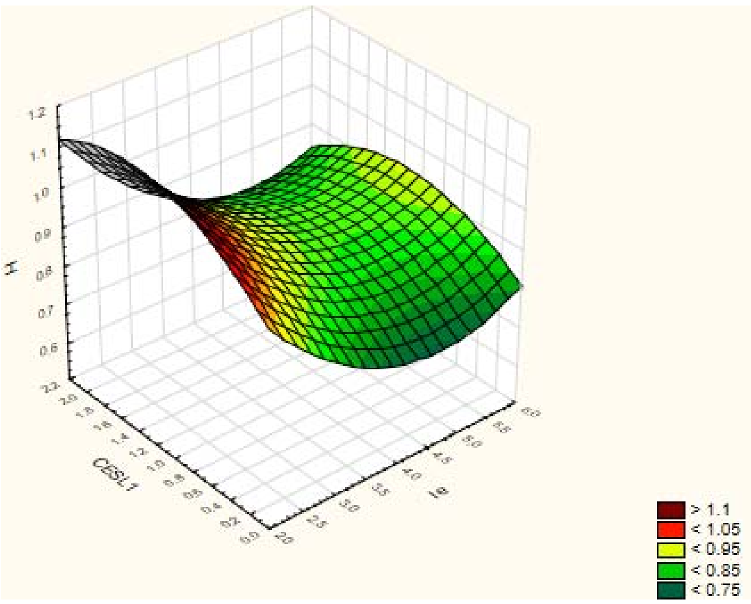

Fig. 4. Dependence of the Shannon index (*H*) on the general ecological index of water quality (*Ie*) and on the level of ecological stabilization of landscapes ($CESL_1$); source: own study

In addition, the degree of correlation between the individual blocks of water quality showed that the distribution of Shannon indices of general diversity tended to be similar to the distribution of the Margalef species richness criteria. Thus, the ecological blocks of water quality *Is* and Its were characterized by the correlation coefficients $r = -0.396$ and $r = -0.614$, respectively, which are defined as "inverse close" correlations. A weak inverse correlation was noted for the ecological block *It* ($r = -0.299$).

A criterion for the dominance of one or several species in a phytocenosis or the Simpson dominance index (c) may serve as an indicator of the duration of the impact of a certain factor on individual site. This index grows with an increase in anthropogenic load on an ecosystem [NAGENDRA 2002]. According to our research, in the city centres, fewer species with a larger number of specimens were found, i.e. the dominance index was higher.

This criterion is inversely related to the Shannon and Margalef criteria ($r = -0.948$ and $r = -0.757$). According to previous research, the anthropogenic impact on a specific section of a river ecosystem leads to a decrease in the number of species and their diversity.

This is especially true for highly sensitive species with low tolerance to a certain negative factor. As a result, this causes excessive reproduction of species that are less sensitive to certain factors. These species occupy a dominant position in the phytocenosis, that is, the Simpson index is higher at record points where stress is intense.

However, if the value of the Simpson dominance index is high, there is a general trend towards an increase in the total biodiversity of species; one can argue that there is a decrease or absence of the previously negative effect on this phytocenosis. For example, this trend was noted at points No. 1–09, 1–10.

During the analysis of the distribution of the Simpson dominance indices, depending on the general ecological index of water quality *Ie* and the level of stabilization of landscapes in the Ukrainian Polesie, a close correlation dependence was noted ($r = 0.506$). Thus, the dominance of individual species against the background of a decrease in the Margalef and Shannon indices indicates a clearly defined trend towards the development of less sensitive species in excessive quantities (Fig. 5).

A classic case of this trend is the record point No. 1–22. There the high nitrite content in the water along with the low level of dissolved oxygen indicate organic pollution of the river and the decomposition of organic substances in water resulting from the discharge of insufficiently treated wastewater from the treatment plants in Zhytomyr. At this point, insignificant species diversity is observed. However, the inadequate hydrochemical regime caused overgrowth of river with the species *Salvinia natans*.

As the ecological status of the reservoir improves, the dominance index decreases, which, against the background of an increase in the general species diversity, indicates that a part of the area is occupied by other species [DUBYNA *et al.* 1993].

We also constructed a three-dimensional model of the distribution of Simpson dominance indices (*c*), which makes it possible to determine an approximate and fairly reliable assessment of the stability of the development of aquatic ecosystems based on the data on the dominance of individual species in phytocenoses:

$$c = -0.0015 + 0.0913x - 0.1252y - 0.0106x^2 + \\ + .0114xy + 0.0341y^2 \quad (7)$$

Where: x = integrated ecological index of water quality; y = coefficient of ecological stabilization of landscapes.

Equation (7) makes it possible to forecast the possible development of dominant species under the influence of changes in the stability of landscapes and qualitative indicators of water. One author point out that the Simpson dominance index within the range of 0.05–0.20 is typical for stressed ecosystems [DAVARI *et al.* 2011]; therefore,

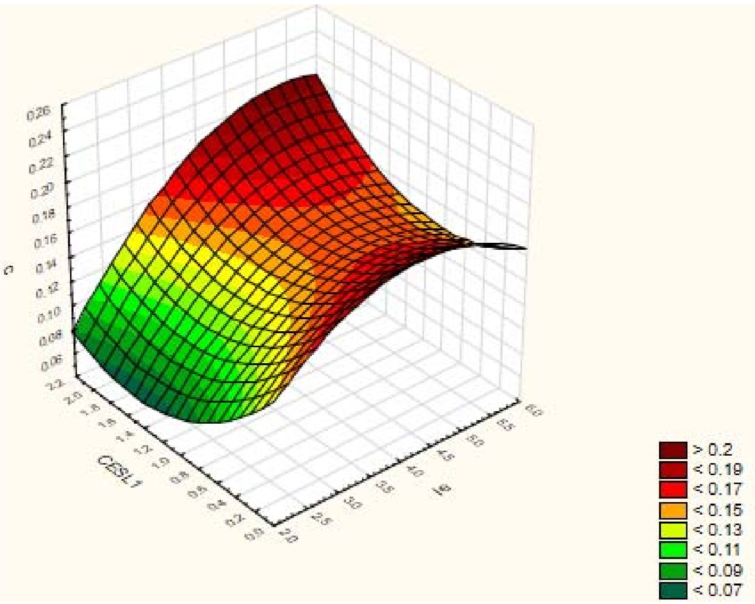

Fig. 5. Dependence of the Simpson index (*c*) on the general ecological index of water quality (*Ie*) and on the level of ecological stabilization of landscapes ($CESL_1$); source: own study

the equation allows for the determination of critical values of water quality that will favour the dominance of one or several of the species most resistant to these conditions.

An analysis of the distribution of the Simpson indices showed that this indicator depended to a large extent on the quality of surface water in the block of salt composition (Is block); and the character of the straight-line correlation can be defined as tight (r = 0.395). The dependence of the Simpson index on the indices of *Its* block, based on values of surface water quality according to chemical trophic and saprobological criteria, can be characterized as the most significant. The linear relationship between these indicators showed similarities with the previous block, where a tight direct correlation was also noted (r = 0.540).

There is no correlation for the ecological block *It* (r = 0.225), which may indicate that, as with the two previously described indices, the block of trophic-saprobological indicators and the mineral composition of the reservoir had the most significant effect on the development of aquatic plants. At the same time, in the studied aquatic ecosystems, the overall index of the block related to the content of specific substances of toxic and radiation effects reduced significantly due to the high iron content, which is the background for this territory. Species diversity is adapted to exist in such conditions. Therefore, the deterioration of the indices of this block did not particularly affect its main parameters.

A comprehensive bioindication assessment of the state of phytocenoses that exist within anthropogenically transformed landscapes should also include the Pielou evenness criterion (E). As one of the main criteria for the structure of phytocenosis, this indicator interprets the level of homeostasis and the diversity of the cluster under study under certain natural and anthropogenic conditions. As a rule, the higher is the Pielou index, the richer is the diversity of phytocenosis. This criterion determines the value of the possible fluctuation in the number of species in a population, i.e. it is a kind of indicator of the uniform distribution of individual species by the number of specimens in a population. Biocenoses with a diverse species composition are marked by a higher environmental tolerance than biocenoses smaller in number [BIRK, WILLBY 2010]. The lowest values of the evenness of species composition and abundance were noted at points No. 1–15, 1–18, 1–22, 1–35, 2–06 and others, that is, at the sites of the most intense anthropogenic load (Fig. 6).

At the same time, a clear inverse dependence of the Pielou criterion on the ecological index of water quality and the level of stabilization of landscapes was established (r = –0.592). Consequently, when water quality deteriorates, the stability of the population of higher aquatic plants is destroyed, and this indicator can be used in the Polesie zone to determine the deterioration of the water quality index as a bioindication indicator.

We also created a three-dimensional model of the distribution of the Pielou evenness indices (E), which makes it possible to evaluate the parameters of stability of the development of aquatic ecosystems:

$$E = 0.4592 - 0.0724x + 0.0506y + 0.0069x^2 - 0.0013xy - 0.0186y^2 \qquad (8)$$

Where: x = integrated ecological index of water quality; y = coefficient of ecological stabilization of landscapes.

Thus, the obtained equation makes it possible to forecast and bear evidence to how evenly the relative number of specimens with a given number of species is distributed in a cenosis. With an equal total number of specimens, the index goes up with an increase in the number of species and with an approximate abundance, a decrease may indi-

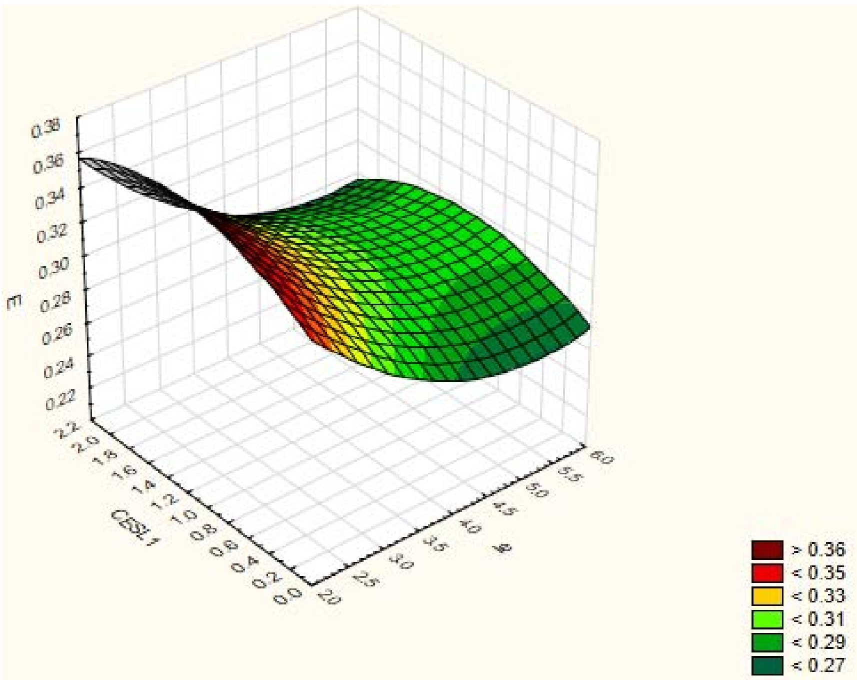

Fig. 6. Dependence of the Pielou index (E) on the general ecological index of water quality (*Ie*) and on the level of ecological stabilization of landscapes ($CESL_1$); source: own study

Table 1. Mathematical and statistical processing of the data on the species description of hydrophytes in the rivers of Ukrainian Polesie ($n = 56$)

Assessment criterion	Block *Is*			Block *Its*			Block *It*			General *Ie*		
	r	Student's criterion	character of correlation	*r*	Student's criterion	character of correlation	*r*	Student's criterion	character of correlation	*r*	Student's criterion	character of correlation
Margalef richness index (*d*)	–0.453	–3.739	close	–0.580	–5.226	close	–0.265	–2.018	close	–0.670	–6.627	close
Simpson dominance index (*c*)	0.395	3.159	close	0.540	4.714	close	0.225	1.697	absent	0.506	4.308	close
Shannon index of general diversity (*H*)	–0.396	–3.168	close	–0.614	–5.718	close	–0.299	–2.299	close	–0.582	–5.266	close
Pielou evenness index (*E*)	–0.463	–3.842	close	–0.582	–5.265	close	–0.280	–2.141	close	–0.592	–5.401	close

Explanations: *Is* = the index of the content of substances of salt composition; *Its* = the index of trophic-saprobological indicators; *It* = the index of the content of specific substances of toxic and radiation effects; *Ie* = the general ecological index of water quality; *r* = correlation coefficient; the significance of the correlation on the feature productivity is equal to the tabular value of Student's *t*-test = 2.00.
Source: own study.

cate anthropogenic load. The equation makes it possible to find criteria for the stability of landscapes and water quality indicators, beyond which there is an imbalance consisting in the development of taxa that differ considerably in the number of specimens.

An analysis of the distribution of the Pielou index for individual blocks of the ecological classification of water bodies shows that there is an inverse linear correlation with the salt composition of surface waters (block *Is*), which can be characterized as "dense" ($r = –0.463$). The dependence of the Pielou index on the indicators of the *Its* block can be described as the most significant. A linear correlation between these indicators showed similarities with the previous block and a tight correlation ($r = –0.582$). A weak correlation was noted for the ecological block *It* ($r = –0.280$), which may indicate that, just like the two indices described above, the most significant effect on the development of aquatic plants is exerted by the block of trophic-saprobological indicators and the mineral composition of the reservoir. The results of mathematical and statistical processing of the data on the species description of hydrobionts in the rivers of Ukrainian Polesie are presented in Table 1.

Thus, all the studied indicators of species diversity showed clear indicator properties regarding the ecological state of aquatic ecosystems. Averaged calculated values of the proposed indicators denote the scarcity of species richness of the experimental sites; and the comparison of phytocenological indicators and data from hydrobiological studies of water bodies using higher aquatic plants showed a number of reliable correlation dependencies.

DISCUSSION

Within the ecological zones, the number of species and their projective coverage in areas with different anthropogenic pressures within Teteriv River ecological corridor were determined, as well as the regularities of the development of the water flora of the right-bank and left-bank parts of Teteriv River and some of its inflows as places with different levels of infrastructural and economic development and their similarity by the criterion of Sørensen was evaluated. Phytocoenoses in areas of intensive anthropogenic pressure appeared to be the most similar in the study, and the dependence of this indicator on the integral ecological indicator of water quality showed a high degree of reliability.

The basic criteria for the implementation of deferred biomonitoring based on the analysis of the dynamics of the species composition of the phytocoenoses of Teteriv River ecological corridor on the indicators of ecological stability and plasticity using the species-specific criteria, are: Margalef Species Richness Index, Sørensen–Dice Index, Shannon Diversity Index, Simpson's Index, and Pielou's Evenness Index. Based on the results, correlation dependencies have been constructed, which will allow to obtain data on the stability of the development of aquatic ecosystems according to the data of species surveys and which are the basic component of deferred biomonitoring. It has been proved that with deterioration of water quality, the stability of the population of higher aquatic plants is destroyed. And indicators of species diversity are clear indicators of the ecological state of aquatic ecosystems according to all the studied indicators.

The most striking changes in the species composition are manifested at the points of the most significant anthropogenic pressure in the presence of toxic compounds in aquatic ecosystems. Phytocenological indicators and data on the ecological state of water bodies showed close reliable correlation. Coefficients of variation and indicators of variability of the values of biodiversity of the studied phytocenoses showed that Margalef species richness indices (*d*) were by 4.6 times lower for the sites without anthropogenic impact than the same indicators for anthropogenically transformed landscapes.

The difference between the value of the Simpson indices (*c*) or the dominance indices in ecologically stable landscapes that are under the anthropogenic impact was by almost 3.4 times different.

The Shannon index of general biodiversity for the same categories of landscapes differed by 1.87 times, and the Pielou evenness indices in anthropogenically transformed landscapes were by 1.5 times lower than in landscapes that are not exposed to anthropogenic factors. Similar trends are also noted in terms of variability.

CONCLUSIONS

It can be concluded that the environmental factor significantly influenced the species diversity and abundance of higher aquatic plants. The dynamics of the anthropogenic factor caused changes in absolutely all main indicators of biodiversity, which consist in fluctuation variations of the biodiversity criteria and certain statistical indicators.

Phytocenological indicators demonstrated a high sensitivity to deterioration of water quality and destabilization of landscapes. Biodiversity indicators responded most distinctly to changes in indicators of salt composition and trophosaprobological indicators. A weak response was noted for the block of the content of specific substances of toxic and radiation effects, which is associated with a high background level of the indices of this block. The study uses the optimal criteria elected for assessing the stability of the development of aquatic ecosystems; and the proposed three-dimensional dependencies make it possible to conduct a water quality assessment based on the proposed bio-indicators.

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