The impact of the ecological sustainability of landscapes on the formation of the hydro-ecological state in the upper part of the Prypiat River basin

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Abstract. The relevance of this study is caused by the need to improve the methods of assessing the ecological sustainability of landscapes and their impact on the hydro-ecological state of river basins in the context of sustainable territorial development. The importance of the research is underscored in view of the increase in anthropogenic load on natural ecosystems, which requires new approaches to the assessment and forecasting of environmental changes. The purpose of the article is to study the interrelationships between the ecological sustainability of landscapes and the hydro-ecological state of water bodies using the example of the headwaters of the Prypiat River.

The research used methods of mathematical modelling and statistical data processing to assess changes in the quality of surface water and the macrophyte index of rivers depending on the sustainability of landscapes by Spearman and Pearson correlation. The regions with a high coefficient of ecological sustainability of landscapes have better water quality indicators and a higher macrophyte index, which indicates a lower anthropogenic impact and a better hydro-ecological condition. The calculated Spearman rank correlation coefficients reveal the strong nature and probability of the relationship of independent variables (r=0.750–0.833). Pearson's rank correlation coefficients described the connection from medium (r=0.454) to strong (r=0.870). Both direct and inverse linear dependencies between indicators were found.

Generally, the results confirm the hypothesis that increasing the ecological sustainability of landscapes contributes to the improvement of the hydro-ecological condition of rivers. This opens up new perspectives for planning the use of land and water resources in the agricultural sector, as well as for the development of measures for the protection and restoration of water ecosystems in the catchment basins.

Keywords: river basin, land use, landscape stability, hydro-ecological state, mathematical modelling, ecosystem services

1. INTRODUCTION

The river basin with its component subsystems (valley, slope and watershed) is a self-regulating system that is capable of functioning independently of the influence of external factors. However, anthropogenesis and changes in the structure of the basin increasingly lead to negative or even irreversible consequences for aquatic ecosystems. Human activity and diverse land use within river basins leads to changes in landscape elements, transformation of land plots, which ultimately causes a reaction of the river network (Zhang et al., 2020; Dou et al., 2022). Intensive land use within catchments leads to negative changes in the hydrological regime of rivers occur (Zhao et al., 2023; Statnyk, et al., 2023), affecting the quality of their surface waters (Julian et al., 2017), the state of the biological environment (Damseth et al., 2024) and most ecosystem services (Aryal et al., 2022). Today, the direction of reducing anthropogenic impact on watersheds using natural sorbents and biological methods that mimic natural self-healing processes is actively developing (Malyovany et al., 2020). Due to the deliberate organisation of these methods, purifying groundwater and soils from pollutants is much more effective (Malyovany et al., 2021). Efficient technological approaches to the reclamation of disturbed lands to restore landscapes within catchments are actively being researched (Tymchuk et al., 2020, Tymchuk et al., 2021).

Modern research proves that understanding these complex relationships and adjusting the landscape structure is a promising way to achieve sustainable development (Turkelboom et al., 2018; Metzger, et al., 2020). There is an opinion that the basis for achieving sustainable regional development is the assessment of past and forecasting future environmental risks for landscapes (Wu et al., 2021). At the same time, the majority of similar studies are conducted within the catchment basins of rivers and lakes, which are taken as regional boundaries of landscapes.

It is known that the safety of aquatic ecosystems depends on the combination of various structural components of landscapes (He et al., 2024; Wang et al., 2024; Kang L., et al., 2024). However, the evidence of indirect anthropogenic changes associated with the change in land use of the catchment basin, in addition to a wide range of information on the hydro-ecological characteristics of water bodies, also requires taking into account the contrasts of regional natural conditions. Therefore, in each specific case, researchers develop models based on a large set of unique data and combine multidimensional approaches and research methods.

For instance, quantitative assessment of landscape models and observation of river flows were used to identify feedbacks of land use and changes in the hydrological regime of watercourses, with verification of their variations using Pearson correlation and variance analysis. This made it possible to propose optimization of the landscape configuration to improve the regulatory potential and use of water resources in the studied catchments (Liu et al., 2020). The same correlation dependences turned out to be an effective tool for confirming the influence of the catchmentland use structure on the state of the lake, where the macrophyte index was used as a hydroecological indicator (Grzybowski et al., 2023). Another example is the search for mathematical relationships between geological conditions, moisture availability, temperature factor, level of urbanisation, industrial, agricultural and forest areas in catchment landscapes with water quality indicators and the level of heavy metals in bottom sediments of rivers (Mbonaga et al., 2024). Attention is also paid to the consequences of large-scale land reclamation. Particularly, the methodology for determining the sensitivity of the landscape based on mathematical calculations of ecosystem services revealed that drainage reclamation resulted in a 60% reduction of forest areas and an increase of urban and irrigated agricultural areas by 5% and 20%, respectively (Keleş Özgenç & Uzun, 2024). The influence of bushes and dams within the catchment area on increasing the flow and improving the river water quality parameters was proven using a system of equations in hydraulic modeling (Kim, 2020).

During aggregating statistical data on the configuration of land use and ecological changes of the environment, researchers reveal the imbalance of the spatial structure within the catchment basins. At the same time, digital models are formed by quantitative assessment of climate conditions, chemical indicators, hydrological and hydrobiological characteristics of water bodies, etc., and a number of solutions are proposed to reduce the supply of nutrients from the surface of the water catchment (Tikuye et al., 2023), risk assessments and zoning of aquatic ecosystems (Malekmohammadi et al., 2014), improvement of water quality and resistance of aquatic ecosystems to disturbances (Shehab et al., 2021; Zhang et al., 2022), and preservation of species biodiversity (Zhang et al., 2024).

Presented examples show that a wide range of evaluation indicators of the impact of landscape characteristics on water ecosystems contains mathematical methods of varying complexity. In the last decade, machine learning algorithms which have increased accuracy and are able to process non-linear data of space-time, quantitative and empirical characteristics, are gaining in popularity (Xue et al., 2024). Scientists agree that the variability of ecological conditions and the rate of changes in land use are the driving forces behind the evolution of catchment landscapes. But the issue of assessing the impact of spatial non-uniformity of landscapes and dynamic changes of natural and anthropogenic factors on the state of water bodies still does not have a single solution.

The search for dependences and analysis of the stability of the surface of catchments and the state of water ecosystems requires the integration of various data, and therefore the use of appropriate mathematical tools in each specific case. The size of catchments often requires consideration of the situation for their individual parts (Kuemmerlen et al., 2019; Kutyła et al., 2023). It is clear that the effectiveness of such individual approaches allows for the development of strategies for the balanced use of the surface of catchments for the preservation of water ecosystems, strengthening their resistance to environmental challenges, and thus sustainable development of the agrosphere.

The purpose of this study was to track the effect of the land use structure within the catchment sub-basins on the formation of landscape stability and the hydro-ecological condition of the upper courses of the Prypiat River, using integral methods of assessment and analysis of the relationship of obtained results by means of mathematical correlation.

2. MATERIALS AND METHODS

2.1. Study Area

According to the hydrographic zoning of Ukraine, the Prypiat River is marked out as a separate sub-basin in the area of the Dnieper basin (Khilchevskyi et al., 2019). The total length of the river is 775 km, of which 254 km are within Ukraine. The total area of the Prypiat river basin is 114.300 km^2, of which 68.370 km^2 is in Ukraine (Fig. 1). The river flows in a northeast direction within the boundaries of Kovel and Kamin-Kashyrskyi districts of the Volyn region. The source of the Prypiat River is located near Budnyky village in the Kovel district. Near the Senchytsi village of Varash district of the Rivne region, the Prypiat crosses the state border with the Republic of Belarus, where it flows through the Polissia lowlands in a weakly defined valley of the Pinsk marshes district. Downstream, the last 50 km of the channel, the Prypiat River crosses into the Kyiv region in Ukraine, and near the city of Chernobyl, flows into the Kyiv reservoir of the Dnieper.

The Prypiat valley is weakly expressed in the upper reaches but more distinct in the lower course. The floodplain is developed along the entire length of the river, with two above-floodplain terraces distinguished. In the upper course, the floodplain width is 2-4 km or more, while in the lower course, it reaches 10-15 km and can remain flooded for several months in certain years. The Prypiat River’s channel in the upper reaches is meandering, forming oxbow lakes and meanders, and is partially canalised. The river's width in the upper course is up to 40 m, in the middle course 50-70 m, and in the lower course 100-250 m. The riverbed consists of sand and sandy silt. The river slope is

0.08 m/km. The average water discharge in the upper Prypiat is about 370 m³/s, while at the mouth, it is 460 m³/s (with a maximum of about 6,000 m³/s). The peak flow is formed due to snowmelt or heavy rainfall. Spring accounts for 60-65% of the annual flow, which totals 14.5 km³/year. Water levels rise by up to 2 m in the upper course, 3.5 m in the middle course, and 5-7 m in the lower course, causing extensive flooding. Additionally, summer-autumn floods are significant and cause the greatest damage to agriculture and other economic sectors (Khilchevskyi et al., 2022).

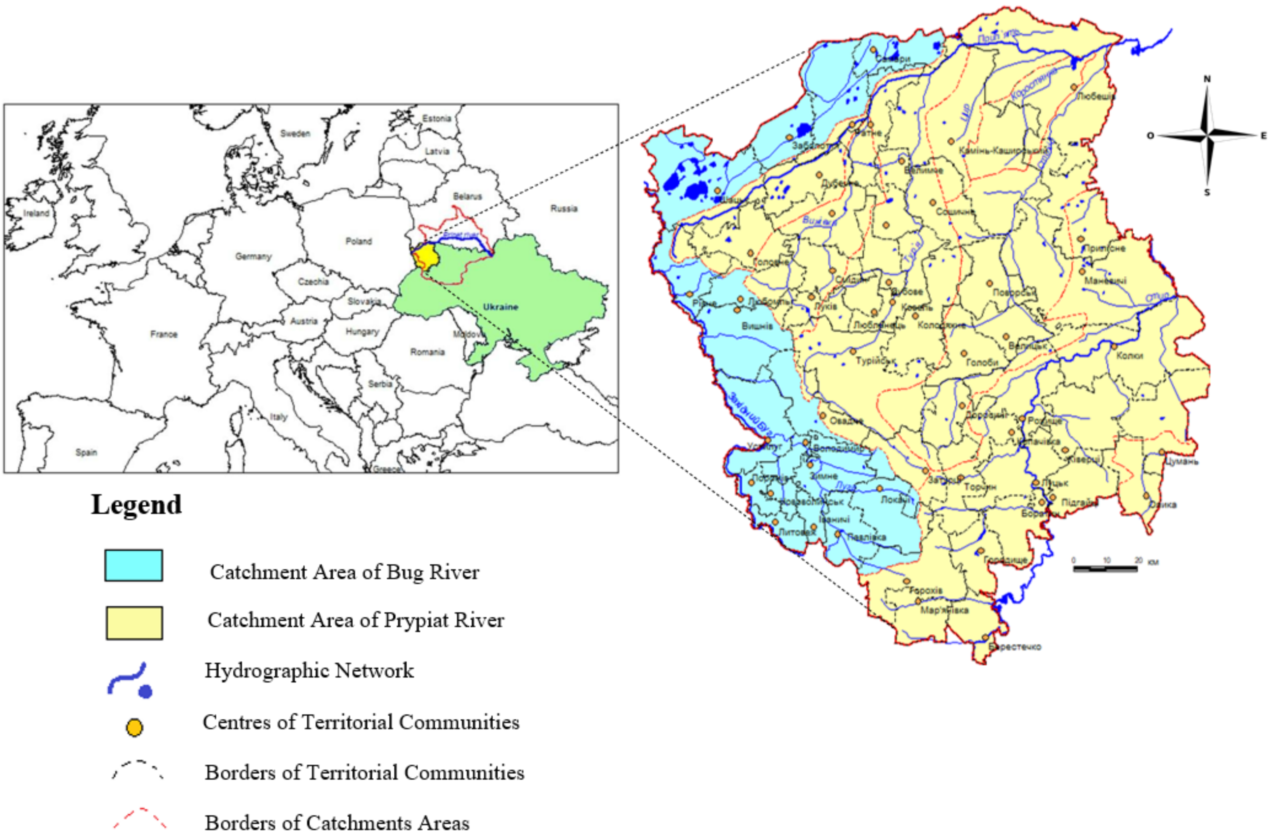

Figure 1. Territorial Distribution and Hydrographic Network of the Upper Basin of the Prypiat River: a) situational location map-scheme of the Prypiat River basin in Europe; b) research area - the upper Ukrainian part of the Prypiat River basin (Volyn region)

Within the boundaries of the Volyn region, part of the Prypiat river bed, 72 km long, had been transformed into the main channel of the Upper Prypiat drainage system, one of the largest in Europe (Khilchevskyi et al., 2022).

The upper courses of the Prypiat River include the sub-basins of its tributaries, the Tsyr River, the Vyzhivka River, the Turia River, the Stokhid River, the Styr River, as well as the bed of the Prypiat River itself. Most of the territorial communities of the Volyn region are concentrated here, except for those located along the western borders of the region. These belong, in hydrographic terms, to the basin of the Western Bug River.

Analyzing anthropogenic activities and pressures in the upper Prypiat basin, the following environmental problems and their causes have been identified: pollution by organic substances as a result of insufficient or absent wastewater treatment; pollution by biogenic elements due to inadequate wastewater treatment and runoff from agricultural lands; contamination by hazardous substances entering with industrial and municipal wastewater, pesticides, and other chemical plant protection agents; pollution by household waste (including plastic); and the impact of climate change, including floods and droughts (Myroslav S. Malovanyy et al., 2023).

Eighteen sites along the course of the studied river and its tributaries were selected as representative test sites for observations and ecological assessment of surface water quality of the upper part of the Prypiat River basin (Table 1).

Table 1. General characteristics of the river sampling sites

No.	Location	Distance from the mouth, km	Justification of representation; territorial community
the Turia river			
1	village of Zaturtsi, near the source of the river	176.90	Background sampling site, river source; Zaturtsi
2	city of Kovel, 500 m above the Kovel Water Canal (city water supply) outflow	79.29	Sampling site, effect of agricultural development of the basin, middle Kovel Water Canal course of the river; Kovel
3	village of Bakhiv, 500 m below the Kovel Water Canal outflow	78.29	Sampling site, effect of the wastewater discharge, middle sampling Kovel Water Canal course of the river; Kovel
4	village of Buzaky	20.26	Sampling site, near the river mouth; Kamin-Kashirskyi
the Vyzhivka river			
5	villages of Khvorostiv and Ruda, near the source of the river	70.18	Background sampling site, river source; Lukiv
6	town of Stara Vyzhivka, 500 m above the town's water supply outflow	34.58	Sampling site, effect of agricultural development, middle course of the river; Stara Vyzhivka
7	near the town of Ratne, at the intersection of the Kovel–Ratne highway	6.45	Sampling site, near the river mouth; Ratne
the Tsyr river			
8	town of Kamin-Kashirskyi	41.33	Background sampling site, above the recreation area; Kamin-Kashirskyi
9	near the village of Vyderta, Kamin-Kashirskyi district	26.60	Sampling site, effect of the Tsyr drainage system, middle course of the river; Kamin-Kashirskyi
the Stokhid river			
10	village of Lynivka	176.90	Background sampling site, river source; Holoby

11	town of Lubeshiv	20.26	Sampling site, near the river mouth; Lubeshiv
the Styr river			
12	village of Shchurovychi	430.2	Background sampling site, middle course of the river; Berestechko
13	city of Lutsk	338.3	Sampling site, effect of the wastewater discharge of the city water supply, middle course of the river; Lutsk
14	village of Mlynok	126.3	Sampling site, near the river mouth; Prylisne
15	town of Zarichne	40.5	Sampling site, near the river mouth; Zarichne
the Prypiat river			
16	village of Richytsia	751.4	Background sampling site, river source; Shatsk
17	village of Luchytsi	700.4	Sampling site, middle course of the river; Ratne
18	town of Lubeshiv	623.9	Sampling site, middle course of the river; Lubeshiv

2.2. Data Collection

The structure of land use within these sub-basins and the quality of the surface waters of the rivers were analysed according to the statistical reporting data of the Department of Ecology and Natural Resources and the Department of Agro-Industrial Development of the Volyn Regional State Administration. The data were gathered within the framework of the implementation of the "State-wide target program for the development of water management and ecological improvement of the Dnieper River basin for the period until 2021" and the Regional Environmental Program "Ecology 2016-2022".

2.3. Integrated methods for assessing environmental characteristics

The assessment of the ecological sustainability of the landscape of the investigated catchment basins of the rivers utilized the methodology of (Klementova E. & Geynige B., 1995), the essence of which is to determine the coefficient of ecological stability of landscapes k_{ESL1} from the share of areas occupied by various elements of the landscape, taking into account their positive or negative impact on the environment:

$$k_{ESL_1} = \sum_{i=1}^{n} F_{stb\ i} \Big/ \sum_{j=1}^{m} F_{stb\ j} \tag{1}$$

where $F_{stb\ i}$ are areas under agricultural crops and plant groups that have a positive impact on the landscape (stable landscape elements), e.g. forests, green spaces, natural meadows, nature reserves, nature sanctuaries, hayfields and arable land used for cultivation of perennial grasses such as alfalfa, clover, grass mixtures, etc.; $F_{stb\ j}$ are areas of land with low ecological self-regulation occupied by unstable elements of the landscape, e.g. annually cultivated arable land, land with unstable grass cover, built-up areas, street and road network, silted and overgrown reservoirs, locations of mineral resources extraction, other lands that have undergone anthropogenic influence.

The calculated k_{ESL1} values were used to provide a qualitative characteristic of the ecological stability (territorial integrity) of the landscape such as "unstable, with clearly expressed instability" ($k_{ESL1} \leq 0.51$), "unstable" (k_{ESL1} = 0.51–1.0), "conditionally stable" (k_{ESL1} = 1.0–3.0), "stable" (k_{ESL1} = 3.0–4.5), "stable, with clearly expressed stability" ($k_{ESL1} \geq 4.5$).

The ecological assessment of surface water quality of the studied rivers was made according to a set of chemical indicators of water quality, according to the methodology (Romanenko et al., 1998), including the assessment of water according to three sets of indicators, salt composition (I_1), tropho-saprobiological (sanitary and hygienic) composition (I_2), and specific toxic substances (I_3). The method allows comparing the water quality in separate areas of water bodies on the basis of uniform ecological criteria, and consists in calculating the integral index of water quality (Ie) by the formula:

$$I_e = (I_1 + I_2 + I_3)/3 \quad (2)$$

The closeness of index values by categories to the limit of the next worst category was estimated by the formula:

$$K_c = K + \frac{A_s - K_{min}}{K_{max} - K_{min}} \quad (3)$$

where K_c is the refined value of the category; K is an integer of the water quality category which corresponds to the number of the category which contains the absolute value of the indicator; A_s is the absolute value of the water quality indicator at the sampling site; K_{min} and K_{max} are the smallest and largest value of the range of the water quality category with the absolute value of the indicator.

Obtained Ie values were compared with the following quality state of water: excellent state 1.0-1.4 (standard of comparisons); intermediate between excellent and good 1.5-1.6; good 1.7-3.4; between good and satisfactory 3.5-3.6; satisfactory 3.7-5.4; between satisfactory and poor 5.5-5.6; bad 5.7-6.4; between bad and very bad 6.5-6.6; very bad 6.7-7.0.

Bioindicative assessment of the hydroecological state of the studied rivers was tested on sections at least 100 m length of along the river channel, in accordance with the Polish methodology for assessing the ecological state of rivers (Ciecierska & Dynowska, 2013; Nekos et al., 2023). The methodology is based on field observations and determination of quantitative and qualitative indicators of aquatic and coastal macrophytes, followed by determination of the Macrophyte Index for River MIR:

$$MIR = \frac{\sum(L_i + W_i + P_i)}{\sum(W_i + P_i)} \cdot 10 \quad (4)$$

where MIR is the Macrophyte Index for Rivers; L_i is the quantitative value of the indicator for the species i; W_i is the weight factor for species i; P_i is the coverage coefficient of the species on a scale from 1 to 9.

Calculated MIR values can range from 10 (most degraded rivers) to 100 (very good ecological state). In the case of analysed lowland rivers, the highest MIR cannot exceed 60. During the calculation, 151 indicator types of macroliths are used (Melzer, 1999). The method has boundary values of the MIR for 5 classes of the ecological state of rivers developed in accordance with of the EU Water Framework Directive (EU Directive, 2006), where each class, "very good", "good", "moderate or satisfactory", "bad", and "very bad", characterizes the ecological state of the river.

2.4. Data analysis

Descriptive statistics of obtained values utilized the Statistica 8.0 software which reduced to the presentation of the following parameters: *N* is the number of sampling sites used in the calculation; *Mean* is the average value of the indicator for the river; *Standard Error* is the standard error of average values; *Min*, *Max* are the minimum and the maximum values of the indicator for the river; *Std.Dev.* is the mean square deviation; *Coef.Var.* is the variation coefficient of the calculated indicators for the sampling sites of the river.

Mathematical modeling and assessment of the impact of ecological sustainability of landscapes on the hydro-ecological condition of the upper courses of the Prypiat River in the Volyn region was performed by the technique of establishing a pairwise correlation between the values of hydro-ecological indices and coefficients of landscape sustainability, a non-parametric measure of statistical dependence between two variables according to Spearman and Pearson coefficients. The concordance correlation coefficient was used to study the set density of connections and its quantification (Levine et al., Kartashov, 2007; Vasylenko & Sencha, 2011).

Pearson correlation coefficient between two features was calculated using the formula:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (5)$$

Spearman rank correlation coefficient was calculated as:

$$R = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \quad (6)$$

where $d_i = x_i - y_i$ is the difference in ranks for the i-th object of observation based on point indicators *x* and *y*.

In the case when the ranks for each feature did not repeat, the concordance correlation coefficient (multiple rank correlation coefficient) was calculated using the formula:

$$W = \frac{12S}{m^2\,(n^3-n)} \quad (7)$$

or

$$W = \frac{12S}{m^2(n^3-n)-m\sum_{i=1}^{k}(k^3-k)} \quad (8)$$

where *m* is the number of factors (characteristics), *n* is the number of observations, *k* is the number of identical ranks, *S* is the mean square deviation of the sum of *n* ranks from their mean value:

$$S = \left(\sum_{i=1}^{n}\sum_{i=1}^{m} R_{ij}\right)^2 - \frac{\left(\sum_{i=1}^{n}\sum_{i=1}^{m} R_{ij}\right)^2}{n} \quad (9)$$

The concordance correlation coefficient was checked for significance using χ^2 criterion, which, in the absence of related ranks, was calculated using the formula:

$$\chi^2 = \frac{12S}{mn(n+1)} \quad (10)$$

In a the ranks for each feature were repeated, the χ^2 criterion was calculated by the formula:

$$\chi^2 = \frac{12S}{mn(n+1) - \sum_{i=1}^{k}(k^3-k)/(n-1)} \quad (11)$$

Multiple Pearson correlation coefficient (between three rankings) was calculated as:

$$r_{xyz} = \sqrt{\frac{r_{xz}^2 + r_{yz}^2 - 2r_{xy}r_{xy}r_{yz}}{1-r_{xy}^2}} \quad (12)$$

2.5. Visual presentation of results

Visualization of obtained results of the evaluation of the ecological sustainability of the landscape, the Macrophyte Index for Rivers and the quality class of surface water within the studied territory utulized the means of ecological mapping of the spatial distribution of evaluation criteria, with reference to the sampling sites of the river, using the capabilities of the geographic information programs MapInfo and ArcGIS Pro.

3. RESULTS AND DISCUSSION

3.1. Results of assessing environmental characteristics

The calculation of K_{ESL1} at the sampling sites of 6 rivers of the upper courses of the Prypiat river basin produced average values of the indicator ranging from 2.44±0.70 to 4.01±0.83, with the largest variation coefficients for the Styr and the Stokhid rivers, 137.41% and 86.46%, respectively (Table 2).

Table 2. Descriptive statistics of the calculated $\mathbf{K_{ESL1}}$ values at the sampling sites of the studied rivers

Rivers	Statistical parameters						
	N	Mean	Min	Max	Std.Dev.	Coef.Var.	Standard Error
Turia River	4	2.70	0.90	3.86	1.26	46.80	0.63
Vyzhivka River	3	2.44	1.18	3.61	1.22	49.89	0.70
Tsyr River	2	3.86	3.86	3.86	0.00	0.00	0.00
Stokhid River	2	3.35	1.30	5.39	2.89	86.46	2.05
Styr River	3	3.09	0.54	8.00	4.25	137.41	2.45
Prypiat River	4	4.01	2.53	5.39	1.43	35.72	0.83

A comparison of the ecological stability of landscapes within the territorial communities of the Volyn region located in the upper courses of the Prypiat River basin shows that "unstable" and "unstable with pronounced instability" landscapes are typical of the southern part of the studied territory, which coincides with the sources of rivers which form the flow of the Prypiat River in the upper part of the catchment area. The central part of the territory is mainly represented by landscapes characterised as "conditionally stable". The northern part of the territory is represented by "stable" and "stable with pronounced stability" landscapes (Fig. 2).

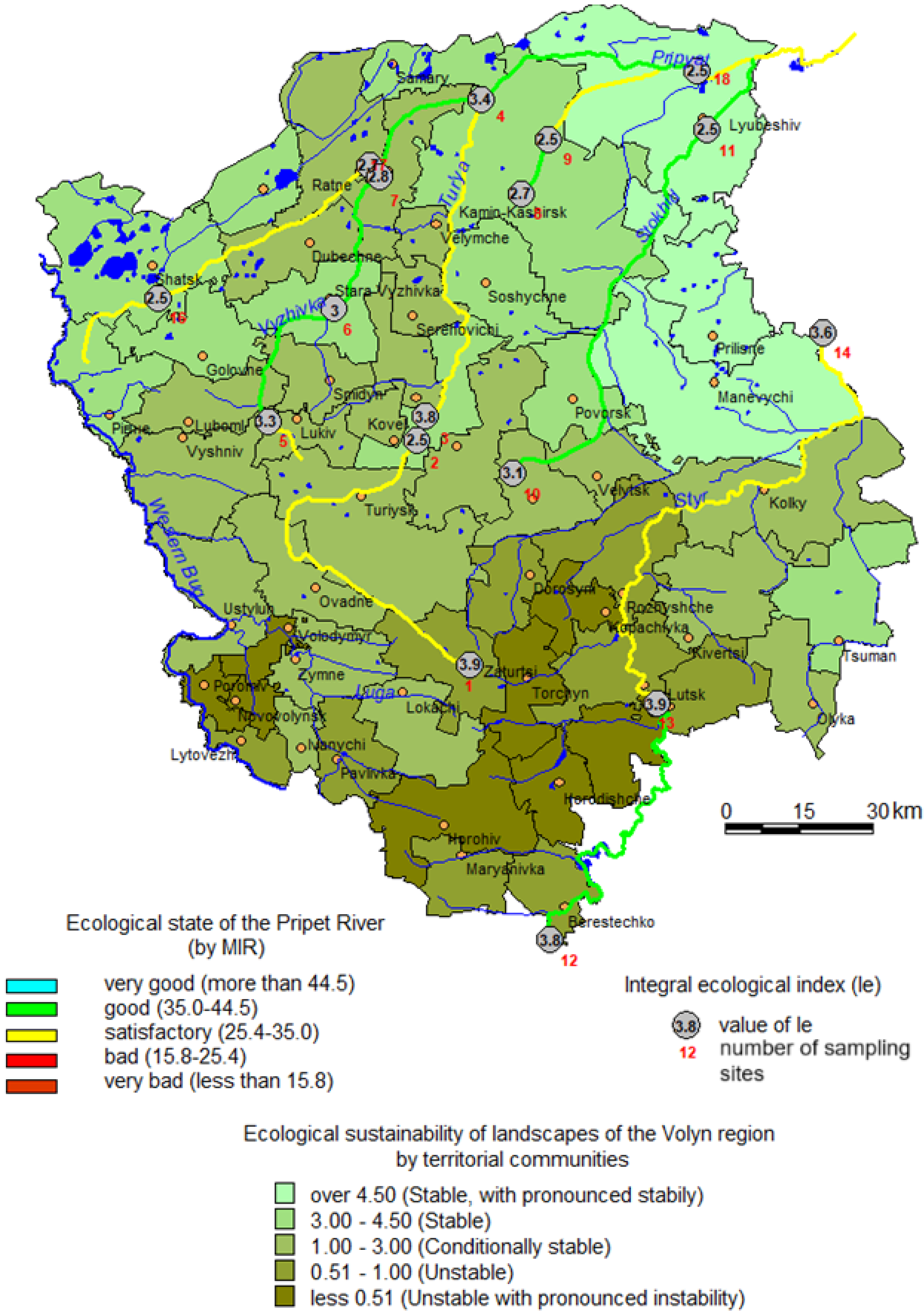

Figure 2. Comprehensive map of the ecological state of the upper Prypiat River catchment basin

This situation is explained by the largest percentage of arable land in the south of the studied territory, and the largest percentage of forested areas and objects of the nature reserve fund in its northern part (Boiaryn et al., 2023).

The calculated values of the Macrophyte Index for Rivers (MIR) at the sampling test sites within the channels of 6 rivers of the upper courses of the Prypiat river basin had average values ranging from 34.98±1.75 to 36.95±2.45, with variation coefficients that did not exceed 11% in all cases (Table 3).

Table 3. Descriptive statistics of the calculated **MIR values** in the sampling test of the studied rivers

Rivers	Statistical parameters						
	N	Mean	Min	Max	Std.Dev.	Coef.Var.	Standard Error
Turia River	4	34.98	32.90	40.20	3.50	10.01	1.75
Vyzhivka River	3	36.72	32.65	39.60	3.62	9.87	2.09
Tsyr River	2	36.25	33.50	39.00	3.89	10.73	2.75
Stokhid River	2	36.95	34.50	39.40	3.47	9.38	2.45
Styr River	4	36.08	33.57	40.60	3.21	8.89	1.60
Prypiat River	3	36.16	33.84	40.60	3.85	10.64	2.22

The MIR values determined at the sampling sites of the upper courses of the Prypiat River basin revealed that the Turia River (except for the area within the city of Kovel), the Styr (within the city of Lutsk and the village of Zarichne), the Tsyr (near the village of Vyderta, Kamin-Kashirskyi district), the Stokhid at its source, as well as the Prypiat River itself in the area near its source are characterised by “satisfactory” ecological condition. The rest of the sampling sites on the studied rivers were characterised by “good” ecological condition according to the MIR.

Mean values of the complex ecological index of surface water quality Ie at the sampling sites ranged from 2.57±0.67 to 3.77±0.06. The highest correlation coefficients were found of the Ie values at the sampling sites of the Turia river (18.96%) and the Stokhid river (15.15%) (Table 4).

Table 4. Descriptive statistics of the calculated **Ie** values in the sampling sites of the studied rivers

Rivers	Statistical parameters						
	N	Mean	Min	Max	Std.Dev.	Coef.Var.	Standard Error
Turia River	4	3.40	2.50	3.90	0.64	18.76	0.32
Vyzhivka River	3	3.03	2.80	3.30	0.25	8.30	0.15
Tsyr River	2	2.60	2.50	2.70	0.14	5.44	0.10
Stokhid River	2	2.80	2.50	3.10	0.42	15.15	0.30
Styr River	4	3.77	3.60	3.90	0.13	3.33	0.06
Prypiat River	3	2.57	2.50	2.70	0.11	4.49	0.67

Generally, the ecological state of the rivers by MIR was similar to the results of the assessment using chemical indicators of the quality of surface water by the relevant categories. The exceptions were the sites of the Vyzhivka river within the town of Stara Vyzhivka, the Tsyr river near the village of Vyderta, the Styr River near the villages of Vyderta and Mlynok, and the Prypiat River within the villages of Richytsia and Luchytsi (Fig. 2). The difference between the results of water quality assessment did not exceed one class. However, no clear regularity was observed regarding deviations to better or worse characteristics.

The effect of ecological sustainability of the basin landscapes on the hydro-ecological state of the Prypiat River which is formed under the influence of various factors was investigated by multifactor correlation analysis, which enables to estimate the degree of the effect of each of the factor variables entered into the model on the resulting indicator, with other factors fixed at the mean level.

3.2. Statistical data processing and modelling

According to the indicators of the ecological state of the upper reaches of the Prypiat River basin included in the research, the variables of the correlation analysis were the landscape stability $\mathbf{K_{ESL1}}$ (*X*), the Macrophyte Index for Rivers **MIR** (*Y*), and the integral ecological index of surface water quality $\mathbf{I_E}$ (*Z*).

An important condition was the absence of a functional connection between them, which determined the expediency of conducting a correlation analysis of the effect of factor variables, which were indicators of ecological sustainability of landscapes, on the resulting variable, the hydro-ecological state of the river basin. This made it possible to track the elasticity of the studied indicator in accordance with the dynamic fluctuations of the factor variables.

The following nature and probability of the relationship of the independent variables of the ecological state of the studied territory were established from the calculations of Pearson rank correlation coefficient:

- r_{xy}= 0.454907 is a moderate direct relationship with an average probability and a direct linear relationship. Describes the increase of the indicator of ecological sustainability of landscapes $\mathbf{K_{ESL1}}$ (*X)* with the Macrophyte Index for Rivers **MIR** (*Y*);
- r_{xz}= – 0.87093 is a strong inverse relationship with high probability and inverse linear relationship. Describes that the integral ecological index of surface water quality $\mathbf{I_E}$ (*Z*) decreases with the increase in ecological sustainability of landscapes $\mathbf{K_{ESL1}}$ (*X)*;
- r_{yz}= – 0.55491 is a moderate inverse relationship, with an average probability and a inverse linear relationship. Describes that the integral ecological index of surface water quality $\mathbf{I_E}$ (*Z*) decreases with the increase in the Macrophyte Index for Rivers **MIR** (Y).

The determination of the score of these indicators in the range from 1 to 4 (Table 5) was used in the further calculation of the Spearman rank correlation coefficient in pairs between the three environmental indicators (Table 6).

Table 5. Rank data for correlation analysis

(X) $\mathbf{K_{ESL1}}$	(Y) **MIR**	(Z) $\mathbf{I_E}$
2	4	1
4	3	1
1	2	2
3	1	1

Table 6. Calculated parameters of Spearman rank correlation coefficient

Xb	Yb	Rank difference	Square of the rank difference
2	4	–2	4
4	3	1	1
1	2	–1	1
3	1	2	4

Calculated Spearman rank correlation coefficients enabled additional assessment of the nature and probability of the relationship between the independent variables of the ecological state of the studied territory:

- r_{xy}= 0.833 – a strong connection with high probability and linear direct relationship. Describes the Macrophyte Index for Rivers **MIR** (*Y*) increases with the indicator of Ecological sustainability of landscapes $\mathbf{K_{ESL1}}$ (*X)*;
- r_{xy}= 0.750 – a strong connection with high probability and linear direct relationship. Describes the Integral ecological index of surface water quality $\mathbf{I_E}$ (*Z*) increases with the indicator of Ecological sustainability of landscapes $\mathbf{K_{ESL1}}$ (*X)*;
- r_{xy}= 0.783 – a strong connection with high probability and linear direct dependence. Describes the Integral ecological index of surface water quality $\mathbf{I_E}$ (*Z*) increases with the Macrophyte Index for Rivers **MIR** (*Y*).

According to the calculations, Kendall's coefficient of concordance W_{xyz} (multiple rank correlation coefficient) had a value of 0.025, which characterised it as weak.

The actual (calculated) χ^2 value was compared to the tabulated data. This was found in the χ^2 criterion table depending on the significance level α (0.05 or 0.1) and the parameter $v=n-1$. If $\chi^2 > \chi^2_{tab}$, then the W_{xyz} coefficient is significant. As a result, the calculated χ^2 value equals 0.231. Since $\chi^2 > \chi^2_{tab}$, then at the significance level α=0.05, the found coefficient of concordance is recognised as significant. This means a direct relationship between the three indicators with a confidence level of $p = 0.95$.

The calculated multiple Pearson correlation coefficient between the three features (r_{xyz}) equals 0.889, which characterises a strong connection with high probability.

Thus, as a result of a mathematical modelling of the impact of ecological sustainability of landscapes on the hydro-ecological state of rivers in the upper course of the Prypiat River basin within the Volyn region, it was established that:

- the Macrophyte Index for Rivers **MIR** increases with the indicator of Ecological sustainability of landscapes $\mathbf{K_{ESL1}}$. The direct linear dependence has moderate probability, with Pearson rank correlation coefficient $r_{xy} = 0.454907$;

- the Integral ecological index of surface water quality $\mathbf{I_E}$ decreases with the increase in ecological sustainability of landscapes $\mathbf{K_{ESL1}}$. The inverse linear dependence has high probability, with Pearson rank correlation coefficient $r_{xz} = -0.87093$;

- the Integral ecological index of surface water quality $\mathbf{I_E}$ (Z) decreases with the increase in the Macrophyte Index for Rivers **MIR**. The inverse linear dependence has moderate probability, with Pearson rank correlation coefficient $r_{yz} = -0.55491$.

According to the calculations of the Pearson multiple correlation coefficient between the three characteristics, r_{xyz} equals 0.889 (strong relationship), indicating a direct relationship between the three factors with high confidence level.

Spearman rank correlation coefficients also indicate a linear inverse relationship with strong connection and high probability between the indicator of Ecological sustainability of landscapes $\mathbf{K_{ESL1}}$, the Macrophyte Index for Rivers **MIR** and Integral ecological index of surface water quality $\mathbf{I_E}$. The respective coefficients are r_{xy} = 0,833 (strong connection), r_{xz}=0.750 (strong connection), r_{yz}=*0.783* (strong connection).

4. DISCUSSION

This study was carried out considering modern trends in ecological monitoring of river basins. An approach was used to establish relationships between integral indicators of environmental characteristics of the upper part of the Prypiat River basin. Similar studies are being conducted in other countries, as they contribute to a deeper understanding of ecosystem dynamics and their ability to self-recover in the face of environmental changes (Mo et al., 2023; Hou et al., 2025).

The water quality index used in this study was calculated taking into account compliance with the standards of hydrochemical indicators. It revealed that the water quality in the upper part of the Prypiat River basin is formed by waters coming from first-order tributaries. In turn, the formation of the water quality of the river tributaries is influenced by the distribution of areas of stable and unstable landscape elements in their catchments. At the same time, using the biotic water quality index made it possible to observe the reaction of the aquatic ecosystem to the level of river pollution, which is also confirmed by other scientific works (Zhu et al., 2023). Thus, our studies develop the ideas of integrating various ecological characteristics of river basins (He et al., 2025; Das, 2025). In particular, it has been proven that an integrated approach to assessing the ecological state of river basins significantly increases the accuracy of forecasts and the effectiveness of management decisions (Statnik et al., 2023; Li et al., 2022). Previous work within Ukraine has also shown that combining biological water quality indices with pollutant concentration data is appropriate. In all cases, modelling and statistical analysis are powerful tools for establishing correlation and cause-and-effect relationships between various environmental factors (Klymenko et al. 2018; Trach et al., 2022). Most current work suggests that this allows for an objective assessment of the health of aquatic ecosystems and identifies potential threats to their full-fledged functioning in the long term.

Other studies demonstrate that modelling of ecological processes based on the integration of different types of data allows not only to predict the impact of anthropogenic factors more accurately, but also to assess the effectiveness of environmental protection measures (Li et al., 2022; Trach et al., 2024). Our study observed that between the integral indices of the ecological state of the river and the ecological state of the catchment, there is a closer mathematical dependence according to the Spearman rank correlation coefficient (from 0.75 to 0.83). The dependences described by the Pearson coefficients had a less close relationship (from -0.87 to 0.45). The difference in the magnitude and nature of the relationship can be explained by the findings indicating the need to use multivariate models for a more detailed understanding of the ecological changes occurring in river basins (Chapagain et al., 2025). At the same time, it is worth considering changes that occur under the influence of anthropogenic activity and climate change (Buonocore et al., 2021; Katip et al., 2025).

The integration of such indicators requires a cautious approach. After all, each indicator has its specific characteristics and may be prone to errors or biases in the event of unreliable or incomplete data. In addition, in the context of multifactorial ecological systems, a complete explanation of changes using simple statistical models may be limited, since the nature of ecosystems is complex and multidimensional. Overall, our research results confirm that land use changes affect the ecological characteristics of the upper part of the Prypiat River basin. This coincides with similar modern studies of other rivers. Given that the Prypiat River is transboundary, the responsibility for the quality of its surface waters is high. Therefore, to obtain objective conclusions and forecasts about the formation of these processes, it is necessary to expand the set of integrated approaches further, including their in-depth mathematical analysis and consideration of unpredictable environmental factors. Machine learning approaches can provide such opportunities (Shaheed et al., 2025) and artificial intelligence-based forecasting (Biazar et al., 2025). It is precisely such prospects in the continuation of our research that will allow us to justify modern decisions regarding water resources management and land use structure according to the basin principle.

5. CONCLUSIONS

The results of this research show that the preservation and improvement of ecological sustainability of landscapes has a positive effect on the hydro-ecological state of rivers. Significant correlations were found between high values of the landscape sustainability coefficient and improvement of water quality, measured through the Macrophyte Index for Rivers, and the integrated ecological index of surface water quality. Quantitative correlation analysis showed that the Pearson rank correlation coefficient between ecological sustainability of landscapes **K_{ESL1}** and the Macrophyte Index for Rivers **MIR** r_{xy} = 0.454907, which indicates a linear direct dependence with moderate probability. The rank correlation coefficient between **K_{ESL1}** and the Integral ecological index of surface water quality, IE rxz = –0.87093, shows a linear inverse dependence with high probability. These results highlight the dependence of water quality on the ecological sustainability of landscapes, indicating significant opportunities for improving hydroecological status through managing landscape change.

Obtained values of Spearman rank correlation coefficients and Pearson multiple correlation coefficient can be used to analyse the impact of ecological sustainability of landscapes on the hydro-ecological state of river basins as there is a strong relationship between these indicators. Such approaches can contribute to the development of strategies to increase ecological sustainability through the restoration of natural landscapes, the increase of areas of forest plantations, and the creation of buffer zones around water bodies. These measures can provide additional protection of water resources and contribute to the sustainable development of territories. Further improvement of the used approaches for integrating environmental indices can be implemented using machine learning and forecasting.

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