Spatial-factorial analysis of background status of the Danube River basin state on the northeastern slopes of the Ukrainian Carpathians

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Abstract. The study solved the problem of analyzing the background spatial-factorial patterns of distribution of quantitative and qualitative indicators of groundwater sources and surface waters within the upper part of the Prut River that belongs to the Danube River basin. The studies have been conducted within the Carpathian National Nature Park, located on the northeastern slopes of the Ukrainian Carpathians. The basic regularities and peculiarities of the distribution of springs in the researched territory have been studied by means of factor analysis of the set of estimation parameters and the relationships between them. Patterns of changes in the concentrations of the natural components of the qualitative composition of the hydro-ecosystem have been found, depending on the altitude of the terrain. Similar data has been obtained in the analysis of the relationship between the average geometric components of the chemical composition of natural waters and the length of the river. Trend lines and equations have been obtained, which can be used to determine the background normative values of natural water components along the length of the stream and the altitude of the basin for individual seasons and phases of water. In this paper, for the first time, the functional natural pattern of hydro-ecosystems of the upper part of the Danube basin within the northeastern slopes of the Ukrainian Carpathians is shown to increase its qualitative potential with increasing absolute altitude above sea level for nature conservation territory.

1. Introduction
One of the priorities of Ukraine's national interests is the state's environmental safety. Ecological problems of hydro-ecosystems are limiting factor of water use and water consumption of the majority of the population of the country [1]. The analysis of previous studies shows that there is insufficient study and generalization of spatial-factorial patterns of surface and underground catchments of river basins, as well as problems of environmental safety management, especially at the regional level of the
tourist and recreational Carpathian region of Ukraine [2-4]. The peculiarity of the formation of surface waters and the existence of springs, their background natural purity in the study area makes it necessary to consider them as special water bodies that require constant attention from scientists, detailed, comprehensive study and protection [5], [6].

Both surface water and groundwater sources are a major factor in meeting the drinking and economic needs of private households not provided with centralized water supply and sewerage in this area [7]. At present, the population is experiencing a shortage of water resources in the western region of Ukraine due to climate change [8], [9]. Nowadays, the management of the sheep breeding in the Carpathians is not possible without constant water supply, which are often natural springs [10]. Therefore, the study of the background physicochemical indices of natural waters and their spatial patterns is an important problem for transboundary water basins.

2. Problem statement
The analysis of previous researches reflects an insufficient study and generalization of water quality indicators of Prut River basin considering safe water management [11-13]. Therefore, the study has solved the problem of analyzing the background spatial-factorial patterns of distribution of quantitative and qualitative indicators of groundwater and surface waters within the upper part of the Prut River within the Carpathian National Nature Park (CNNP).

The EU Water Framework Directive 2000/60 / EC does not define the term “spring”, does not distinguish it from other water bodies and does not refer directly to surface or groundwater [14], [15]. However, observations of springs in European countries are conducted mainly in the framework of groundwater monitoring [16]. However, the same methods are often used to determine groundwater quality and flow as for surface water bodies [17].

3. Presentation of the fundamental material
3.1 Hydro ecosystem monitoring studies
The system of diagnostic monitoring of water quality in the Prut River Basin - tributary of the Danube within the Carpathian CNNP has been conducted for more than 30 years. The results of processing this database of analytical studies of the physical, chemical, biochemical composition of natural waters have formed the basis of this work. In 2019, monitoring observations included the determination of 12 indicators (twater, pH, O₂, O₂%sat., BOD₅, water mineralization, NH₄⁺, NO₃⁻, SO₄²⁻, PO₄³⁻, CaO, CaCO₃) on 14 hydrochemical water sampling sites (Figure 1). Water samples are usually sampled 4 times a year, at different seasons of the year, necessarily in the most environmentally intense summer and autumn periods [18].

Any river of the study area originates from a natural groundwater source and that can may significant impact due to previous studies of Austrian and Polish scientists. The sources from which the river originates are locally called “head”. The head, for example, is called the outflow of the Prut-Mykulychynskyi stream (the right tributary of the Prut River, Mykulychyn village, Yaremche district) [19].
**Hydrochemical water sampling sites**

1. River Prut – above the sports base “Zaroslyak”
2. River Prut – checkpoint of Goverlyansky Nature Protective Scientific Research Department
3. River Prut – Vorokhta town, upstream the place of discharges of household waste water of the sanatorium “Mountain air”
4. River Prut – Vorokhta town, downstream the place of discharges of household waste water of the sanatorium “Mountain air”
5. River Prut – Tatariv village, upstream the place of discharges of household waste water of the medical rehabilitation center of the Ministry of Internal Affairs of Ukraine “Kremintsi”
6. River Prut – Tatariv village, downstream the place of discharges of household waste water of the medical rehabilitation center of the Ministry of Internal Affairs of Ukraine “Kremintsi”
7. River Prut – Yaremche town, Hutsul souvenir market
8. River Prut – Dora village, near the road bridge
9. River Prutets Chemygivsky – Mykulychyn village, near the road bridge
10. River Meresnyi – Mykulychyn village, near the road bridge
11. River Zhonka – Yaremche town, the mouth of the river
12. River Chorny Cheremosh – Shybeny (Zelene village)
13. River Shybenka – Shybeny (Zelene village)
14. River Pogorilets – Shybeny (Zelene village), the mouth of the river

**Figure 1.** Scheme of the location of diagnostic surface monitoring water sampling sites in the Carpathian National Nature Park in 2019:

1 - borders of the Carpathian National Nature Park; 2 - the river and its name; 3 - hydrochemical water sampling sites and its serial number; 4 - the settlement and its name

The impact of ground water sources on surface water bodies can be very significant. At the end of the nineteenth century eminent Austrian scientist Forster A. E., 1894 in his classification of watercourses by thermal regime identified the source rivers. In these rivers, the water near the source retains its temperature. In ancient Polish scientific literature, all Carpathian rivers and streams were called “spring streams” (źródlowy potok) [20]. In addition, groundwater is closely related to river water (Figure 2).
3.2 Investigation of the features of the distribution of springs using factor analysis

The analytical aspect of the study of the basic patterns and features of the distribution of springs in the Carpathian NNP is related to the study of the set of estimation parameters and the relationship between them. For this purpose, factor analysis has been applied, which makes it possible to comprehensively and systematically evaluate the effect of certain factors, identifying them and determining the impact on the magnitude of the performance indicators.

As an example, an algorithm for studying the patterns of distribution of springs in the territory of the Vorokhta Nature Conservation Research Department is shown. For the estimation parameters we used the following features (indicators): geographical coordinates (X and Y), the absolute height of the groundwater outlet to the surface (H, abs. m), the springs yield (Qs), the degree of its use, water temperature, water mineralization and pH.

An important characteristic of the affinity between certain traits X and Y is the measure of correlation, expressed through the Pearson correlation coefficient (linear paired correlation coefficient) and calculated on the basis of a paired sample of values of X and Y by the formula [21]:

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

(1)

where $N$ is the sample volume; $y_i, x_i$ are the values of the $i$-th element of the samples $x$ and $y$, respectively; $\bar{x}, \bar{y}$ – sample averages $x$ and $y$ respectively; $\bar{xy}$ – the average value of the product $x_i$ and $y_i$; $\bar{x^2}, \bar{y^2}$ – the mean of the squares of signs $x$ and $y$.

According to the results of mathematical and statistical processing of the general data set, the correlation matrix of the system of applied features had been constructed and the significance of correlation between them has been established (Table 1). The characteristic of the correlation is accepted according to the [21]: $r < 0$ – feedback; $0 \leq |r| < 0.1$ – no connection; $0.1 \leq |r| < 0.3$ – weak; $0.3 \leq |r| < 0.5$ – moderate; $0.5 \leq |r| < 0.7$ – notable; $0.7 \leq |r| < 0.9$ – strong; $0.9 \leq |r| < 0.99$ – very strong; $0.99 < |r| \leq 1$ – complete.

At this stage it was possible to note a certain grouping of indicators by the relationship between them. Factor analysis was performed using the principal component method (PCM) to identify a more detailed inter-component relationship.
Table 1. Correlation matrix of relationships of features of springs in the Vorokhta NPSD of the Carpathian National Nature Park

| Sign (metric)          | X    | Y    | Absolute height | Springs yield | The degree of use | Water temperature | Water mineralization | pH   |
|------------------------|------|------|-----------------|---------------|------------------|------------------|---------------------|------|
| X                      | 1,00 |      |                 |               |                  |                  |                     |      |
| Y                      | 0,42 | 1,00 |                 |               |                  |                  |                     |      |
| Absolute height        | -0,46| -0,55| 1,00            |               |                  |                  |                     |      |
| Spring yield           | -0,19| 0,03 | -0,27           | 1,00          |                  |                  |                     |      |
| The degree of use      | -0,07| 0,52 | -0,18           | -0,07         | 1,00             |                  |                     |      |
| Water temperature      | 0,17 | -0,08| 0,45            | -0,25         | -0,32            | 1,00             |                     |      |
| Water mineralization   | -0,25| -0,18| 0,12            | -0,23         | 0,03             | 0,09             | 1,00                |      |
| pH                     | 0,19 | 0,30 | -0,23           | 0,51          | -0,24            | 0,15             | 0,21                | 1,00 |

In general, the factor structure of the \( i \)-th feature is displayed in the form \( \sum a_{ij} \cdot F_j \), which only includes significant loads. The indicative structure of each of the factors in the general form is displayed as \( \sum a_{ij} \cdot F_j \) to which only significant loads are included. Using the factor load matrix, the values of all factors were calculated for each observation of the original sample set by the formula [22]:

\[
F_{jt} = \frac{\sum_{i=1}^{k} a_{ij} \cdot X_{it}^{c,n}}{\lambda_{j}}
\]  

(2)

where \( F_{jt} \) – the value of the \( j \)-th factor in the \( t \)-th observation, \( X_{it}^{c,n} \) – the normalized (and centered) value of the \( i \)-th characteristic in the \( t \)-th observation of the original sample; \( a_{ij} \) – factor load, \( \lambda_{j} \) – eigenvalue corresponding to factor \( j \). These calculated \( F_{jt} \) values are widely used to graphically display the results of factor analysis. The calculated values of factor loadings, eigenvalues of factors and their weight are presented in Table 2.

Table 2. Factor loads, eigenvalues and weight of factors of formation and distribution of natural springs in the territory of the Voronenkivske NPSD of the Carpathian National Nature Park

| Indicators                      | Factor Loadings (Varimax raw) (Stat) Extraction: Principal components (Marked loadings are >,500000) |
|--------------------------------|-----------------------------------------------------------------------------------------------------|
|                                | Factor 1                  | Factor 2                  | Factor 3                  | Factor 4                  |
| X                              | 0,41                     | -0,29                     | -0,23                     | 0,69                      |
| Y                              | 0,24                     | 0,87                      | 0,09                      | 0,22                      |
| Absolute height                | 0,77                     | 0,24                      | -0,04                     | -0,23                     |
| Spring yield                   | -0,33                    | 0,06                      | 0,88                      | 0,14                      |
| The degree of use              | -0,22                    | 0,84                      | -0,26                     | -0,16                     |
| Water temperature              | 0,89                     | -0,08                     | 0,02                      | 0,10                      |
| Water mineralization           | 0,20                     | -0,20                     | -0,09                     | -0,87                     |
| pH                             | 0,38                     | -0,21                     | 0,83                      | -0,19                     |
| Expl.Var                       | 1,96                     | 1,71                      | 1,60                      | 1,42                      |
| Prp.Totl                       | 0,24                     | 0,21                      | 0,20                      | 0,18                      |
According to the results of the mathematical and statistical analysis, four main factors were identified, which determine the peculiarities of the distribution of springs in the territory of the Voronenkovsky NPSD of the Carpathian NNP: 1) 19.6% of information; 2) 17.1%; 3) 16.0%; 4) 14.2% of the information.

The first factor (19.6% of information) – shows that with the height of the springs temperature slightly increases and the role of precipitation in the formation of water temperature in the springs increases, so it can be identified as climatic.

The second factor (17.1% of information) indicates the connection between the distance of springs from roads, settlements (Vorokhta township) and tourist routes passing through relatively “stable” territories; so this factor can be defined as geomorphological.

The third factor (16.0% of information) – can reflect the conditions of supply (in the water of springs with high flow rate higher pH values are noted) and complement one of the aspects of the manifestation of the first factor – climatic.

The fourth factor (14.2% of information) – shows the relationship of total salt content in water with geographical coordinates, so it may be an indicator of the influence of regional geological and tectonic conditions on the formation of the chemical composition of local springs.

3.3 Spatial analysis of the background patterns of the chemical composition of the study area waters

By mathematical processing of results of analyses of surface water quality the complex index of quality potential (CIQP) within studded area was calculated [23]. The CIQP calculations summarize the stock ratios of organoleptic, physical, chemical, biological, toxicological and other indicators (relative amount of reserve power), which is an excess of permissible values over the actual and subtracted the ratio of reserve deficits, which are concentrations (or other measurements). The result is divided by the number of metrics used:

$$CIQP = \frac{1}{n}\sum_{i=1}^{n} x_i; \quad x_i = \begin{cases} \frac{WQ_i}{C_i} - 1, & if \frac{WQ}{C_i} > 1 \\ \frac{WQ}{C_i} - 1, & if \frac{WQ}{C_i} < 1 \end{cases}$$

where $WQ_i$ – water quality standard for the i-th indicator – limit values (allowable) of water status indicators and their properties that meet the requirements of different consumers; $C_i$ – the actual value of water quality for the i-th indicator; $n$ – number of metrics.

This indicator, according to the authors [24], is the basis of qualitative component of safety of hydro-ecosystems because it allows to quantify the magnitudes of critical anthropogenic loads.

In this case, the hydro-ecological norm is considered to be the sweep of stochastic oscillations of indicators of components of hydro-ecosystems, which do not go beyond the reactions of the device to maintain homeostasis. Environmental regulation involves taking into account the so-called maximum permissible load on the ecosystem. Permissible is the load, "under the influence of which the deviation from the normal state of the system does not exceed natural changes and, therefore, does not cause undesirable effects in living organisms and does not lead to deterioration of the quality of the environment" [24]. Any load not exceeding the limit (that is, the normative) is considered permissible, which in turn is equal to the critical load multiplied by the reserve factor (depending on the degree of "confidence" and the potential for cumulative action, this factor usually ranges from 0.2 to 0.5) [25].

The spatial variability modelling of the qualitative component of the safety of hydro ecosystems of the Danube basin on the northeastern slopes of the Carpathian Mountains was first tested for the upper part of the Prut hydro-ecosystem to Yaremche (catchment area - 602.0 km²), which is almost completely covered by the nature conservation area of the CNNP. Mid-term values of the Quality Scores were analyzed for their relationship to the altitude and length of the river. According to the obtained results, regularities of changes in the concentrations of the natural components of the qualitative composition of the hydro-ecosystem depending on the altitude of the terrain were found (Figure 3). Similar data were obtained during the analysis of the relation between the change of the
geometric mean components \( F(x) = \ln x \) of the chemical composition of natural waters with the length of the river (Fig. 4).

Thus, trend lines and equations are obtained, which allow us to determine the rate of natural water components by river length and terrain altitude, for individual seasons and water phases. As a result of the performed researches, the functional regularities \((r^2 - \text{the value of the approximation reliability})\) of the spatial distribution of \(CIQP\) in the investigated territory with altitude \((H)\) of terrain \((10)\) and length \((L)\) of the river were established:

\[
CIQP = 6.6734 \ln (H) - 38.731; r^2 = 0.90 
\]

\[
CIQP = 0.0008L^2 - 0.16L + 9.19; r^2 = 0.92 
\]

For the hydro-ecological standard (background indicator) we take the range of stochastic oscillations of indicators of components of hydro-ecosystems, which do not go beyond the reactions of the device to maintain homeostasis.

For the study area, the maximum permissible load on the hydro-ecosystem may be one in which the content of water quality constituents does not decrease below those calculated by model equations.

4. Conclusions

The study solves the problem of analyzing the background spatial-factorial patterns of the distribution of quantitative and qualitative indicators of groundwater sources and surface waters within the upper part of the Prut River - tributaries of the Danube in the Carpathian National Nature Park, located in the northeast Carpathian Mountains. The basic regularities and peculiarities of the distribution of springs in the studied territory were studied by means of factor analysis of the set of estimation parameters and the relationships between them. Patterns of changes in the concentrations of the natural components of the qualitative composition of the hydro-ecosystem have been found, depending on the altitude of the terrain. Similar data were obtained in the analysis of the relationship between the average geometric components of the chemical composition of natural waters and the length of the river. Trend lines and equations were obtained, which can be used to determine the background normative values of natural water components along the length of the stream and the altitude of the basin for individual seasons and phases of water.

Therefore, as a result of the performed researches an electronic database of qualitative and quantitative component of safety indicators of hydro-ecosystems of the studied territory has been created. The patterns of spatial-factorial distribution of environmental safety indicators have been identified. Mathematical models of background indicators of the basin system have been created. The results obtained will allow to determine scientifically sound ecologically safe values of the impact of economic activity on the hydro-ecosystem. For the conservation area of the Carpathian National
Nature Park, the maximum permissible load on the hydro-ecosystem should be such that the quality index does not decrease below that calculated by model equations. In this paper, for the first time, the functional natural pattern of hydro-ecosystems of the upper part of the Danube basin within the northeastern slopes of the Ukrainian Carpathians is shown to increase its qualitative potential with increasing absolute altitude above sea level for nature conservation territory.

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