The impact of the geographical environment on the hydromorphological conditions of watercourses in southern Poland

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Abstract: Hydromorphological assessment of watercourses provides much valuable information about the riverbed and its immediate surroundings, including the influence of geographical environmental factors along with anthropogenic pressures in the catchment area. This paper presents diversity of hydromorphological conditions of 77 sections located on 39 watercourses in southern Poland in three European ecoregions: Eastern Plains, Central Plains and the Carpathians. The study was based on the Hydromorphological Index for Rivers (HIR) method and two sub-indices: Hydromorphological Diversity Score (HDS) and Hydromorphological Modification Score (HMS). Basic and multi-dimensional statistical analyses were performed to identify the main gradients of the geographical environment and the variables that contribute most to the total variability of HIR. The highest mean HIR values were recorded in the Carpathians ecoregion, then in the Central Plains and the lowest in the Eastern Plains, 0.70, 0.67 and 0.58, respectively. Significant differences were found between the Carpathians and Eastern Plains ecoregions in HIR values obtained. Hydromorphological differentiation is most influenced by altitude and geological type. The cluster analysis enabled two main groups of watercourses to be distinguished – the first one was dominated by variables showing HMS > HDS relationship, while the second one was dominated by HDS > HMS relationship. Multi-dimensional analysis provided additional information on the relationships between the variables and the sections studied. The greatest positive impact on the formation of the final HIR value had the variation of the riverbed slope and natural morphological elements of the bed bottom, while the greatest negative impact on HIR had the transformations observed in spot-check.

Keywords: surface water, landscape, regionalisation, ecoregion, multi-dimensional analyses

INTRODUCTION

The existing hydrological and morphological conditions of watercourses are determined primarily by the geographical environment that exerts a fundamental influence on water (hydrological and morphological) phenomena and processes, as well as by human activities capable of altering, to some extent, the interrelationships of the elements of this environment established by nature. Thus, the geographical environment is the natural one considered collectively with man and the material manifestations of human activity (Rinaldi et al. 2016, Maaß et al. 2021, Abbas et al. 2022). Hydromorphological assessment of watercourses is an important element of water policy in the European Union and worldwide, as it provides an important background for biological and physicochemical analyses of the aquatic environment (Pavlek et al. 2023).

Environmental variability is mainly described by altitude elevation, substrate type and, in the case of watercourses, also by catchment size. The geomorphology of the region is also important here due to the influence of the structure of the Earth's surface on various processes occurring in watercourses. River valley morphogenesis and slope processes provide the basic material for the hydromorphological activities taking place in river channels. Erosion and denudation phenomena are the result of atmospheric and hydrographic factors (Graniczny 2006). These phenomena are important in hydromorphology, as they influence the development of sedimentation processes leading to the formation of landforms, islands and wild rivers and streams.

Surface waters form an element of the geographical environment that influences formation of a specific landscape in a region. Depending on the altitude at which the watercourse section is located, it takes on the nature of a mountain river (mountain landscape), an upland river or a lowland river (lowland landscape). The type of river is related to the natural and anthropogenic processes taking place in river catchment areas, which are functional geographical areas that integrate a variety of environmental processes and human influences on landscapes (Aspinall & Pearson 2000).

Watercourses are the most dynamic element of the geographical environment. It is also necessary to examine relationships between variables within both catchment areas and between the distinct physico-geographic regions through which watercourses flow. Interest in the regionalisation of aquatic ecosystems has increased with the introduction of the Water Framework Directive (WFD) (Directive 2000/60/EC 2000), which introduced an environmental criteria approach to surface water characterisation. Proposed by Illies & Botosaneanu (1963), Europe is divided into ecoregions classifying rivers and lakes based on two systems (A and B). System A differentiates waterbodies based on classes included in three typologies: altitude typology, size typology based on catchment area, and geology. System B considers alternative characteristics – physical and chemical factors that determine the characteristics of a river or river section and, consequently, the biological population structure and composition. These include obligatory factors (altitude, latitude, longitude, geology, size) and optional factors (e.g. distance from river source, mean water width, depth and slope, valley shape and others) (Sánchez-Montoya et al. 2007).

River valleys, due to their different natural character (depressions and terrain indentations) and the different role they play in natural systems, cause some trouble in physico-geographic regionalisation (Garbowski et al. 2023). Hydromorphological assessments of watercourses can vary depending on the assessment methods used (Belletti et al. 2015), but such a parameter seems to be most differentiated by spatial and environmental variables. The division into ecoregions combines spatial and environmental variability by belonging to specific regional units. In order to facilitate the analysis of the impact of geographical environmental factors on aquatic ecosystems, regionalisation was introduced as a classification tool (Munné & Prat 2004, Zogaris & Economou 2017).

River hydromorphology assessed by direct measurement is a time-consuming and costly procedure, yet the most accurate one (Akstinas et al. 2022). There are multiple methods for hydromorphological assessment. In Poland, a commonly used and WFD-compliant method is the Hydromorphological Index for Rivers (HIR). The HIR value is derived from the calculation of two indices: Hydromorphological Diversity Score (HDS) and Hydromorphological Modyfication Score (HMS) (Szoszkiewicz et al. 2017, 2020). Field inventories provide a lot of valuable information but can make it difficult to comprehensively capture certain relationships. A hydromorphological assessment is formulated on more than one variable. The complexity of the geographical environment requires the use of statistical methods of multidimensional analysis, which make it possible to simplify large sets of observations and make them comprehensible (Misztal 2018).

Four significant ecoregions (WFDs) are distinguished within Poland, and these units reflect the structure and spatial relationships of a given region. As a case study, the area of southern

Poland located in the Upper Vistula River Basin within the boundaries of the Lesser Poland (Małopolskie) Voivodeship, which is very diverse in terms of physico-geographical, was selected. The number of physical-geographical units (ecoregions) is three (the Carpathians, Eastern Plains and Central Plains). The diverse substrate, climatic conditions and land use of this region favour the emergence of various processes shaping the hydrology and morphology of watercourse channels.

The aim of this study is to demonstrate the influence of individual elements of the geographic environment, taken as an ecoregion, on the hydromorphological conditions of watercourses in southern Poland. It was assumed that there are differences in the hydromorphology of watercourses between the analysed ecoregions, and this is influenced, among other things, by the features of the geographical environment (such as altitude location, substrate) and human activity.

METHODS

Study area and date source

The research sections where studies of the hydromorphological conditions of watercourses were carried out were located in the Lesser Poland (Małopolskie) Voivodeship, in southern Poland (Fig. 1). Data in the form of in-camera and field protocols were obtained/purchased from the Provincial Inspectorate for Environmental Protection in Krakow (WIOŚ) – the body having responsibility for conducting environmental monitoring. Surveys carried out in 2017 on 77 research sections representing 52 surface water bodies and located on 39 watercourses (rivers, streams and canals) were analysed (Fig. 1).

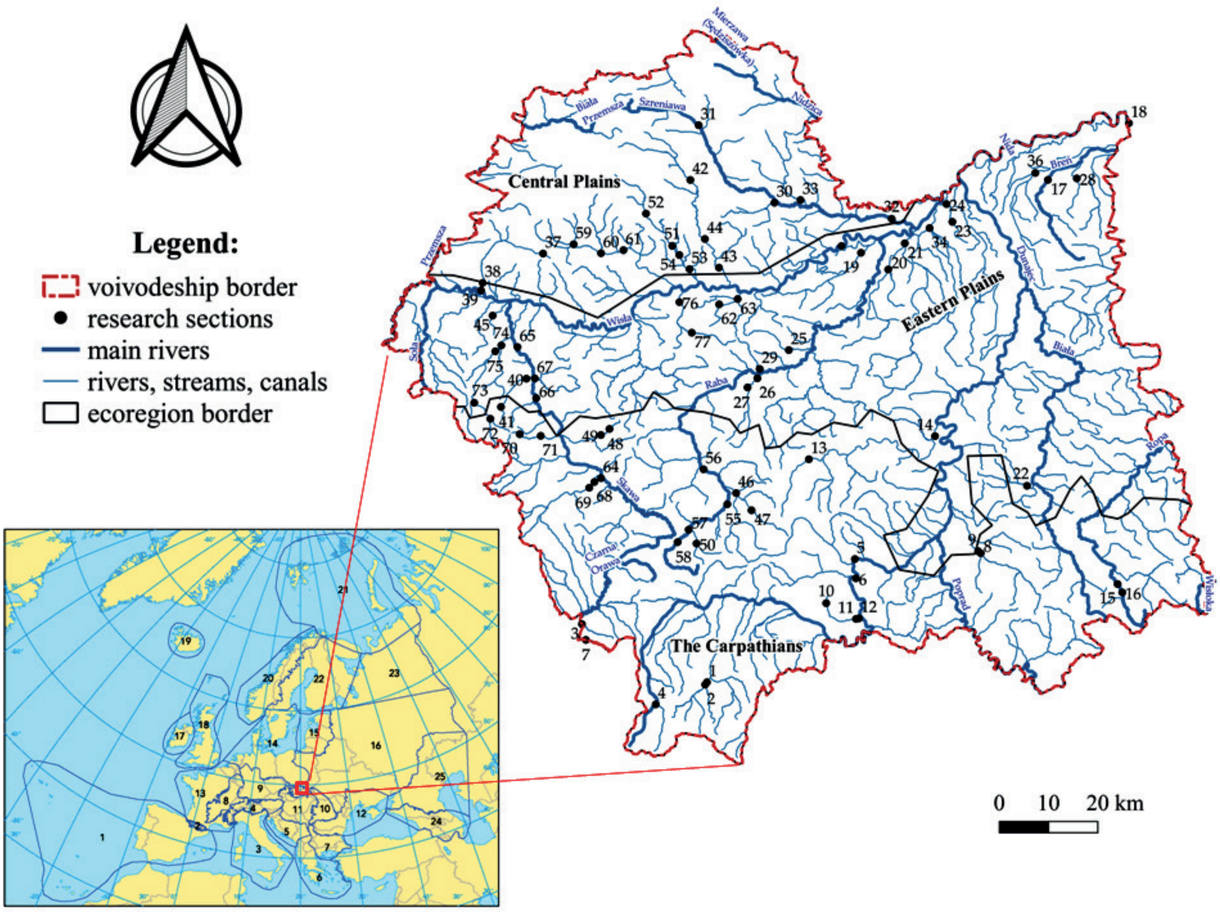


Fig. 1. Map with the location of the 77 studied sections against the background of ecoregions

Physical landscape features

As a result of the long-term activity of natural factors such as tectonic forces and weathering processes, the area of southern Poland has acquired diverse geological deposits. Three geological units typical of the whole of Europe converge here, formed in three successive cycles: Paleozoic, Mesozoic and Cenozoic (Aleksandrowski & Mazur 2017). Figure 2 shows the surface geological deposits of the analysed region of southern Poland. There is a great variety of geological forms here.

The region under consideration is located within three ecoregions (Illies & Botosaneanu 1963): the Carpathians (10), Central Plains (14), and Eastern Plains (16) (Fig. 1). Based on these physicogeographical units, a comprehensive hydromorphological assessment of the watercourses was carried out. Each site was categorised to types according to the WFD river typology based on 'system A':

- altitude typology (<200 m a.s.l. as a lowland, 200–800 m a.s.l. as mid-altitude/upland and >800 m a.s.l. as high/mountain);
- catchment size (10–100 km^2 as small, 100–1,000 km^2 as medium, 1,000–10,000 km^2 as large, and >10,000 km^2 as very large. Due to the occurrence of catchments with an area of less than 10 km^2, the 'very small' category was added);
- geological type (calcareous, siliceous, organic) – no organic substrate was recorded in these studies and this group was excluded from the analyses.

In addition, watercourses were characterised based on channel width (>30 m or ≤30 m), land use types (as semi-natural, agricultural and urbanised) and surface water body types (as natural, heavily modified, artificial). Finally, the differentiation between ecoregions was checked based on the HIR classification.

The hypsometric differentiation of the analysed region is shown in Figure 3. More than 30% of the voivodeship's area consists of mountain and foothill areas located above 500 m a.s.l. and only 9% of the area is occupied by lowland areas located below 200 m a.s.l.

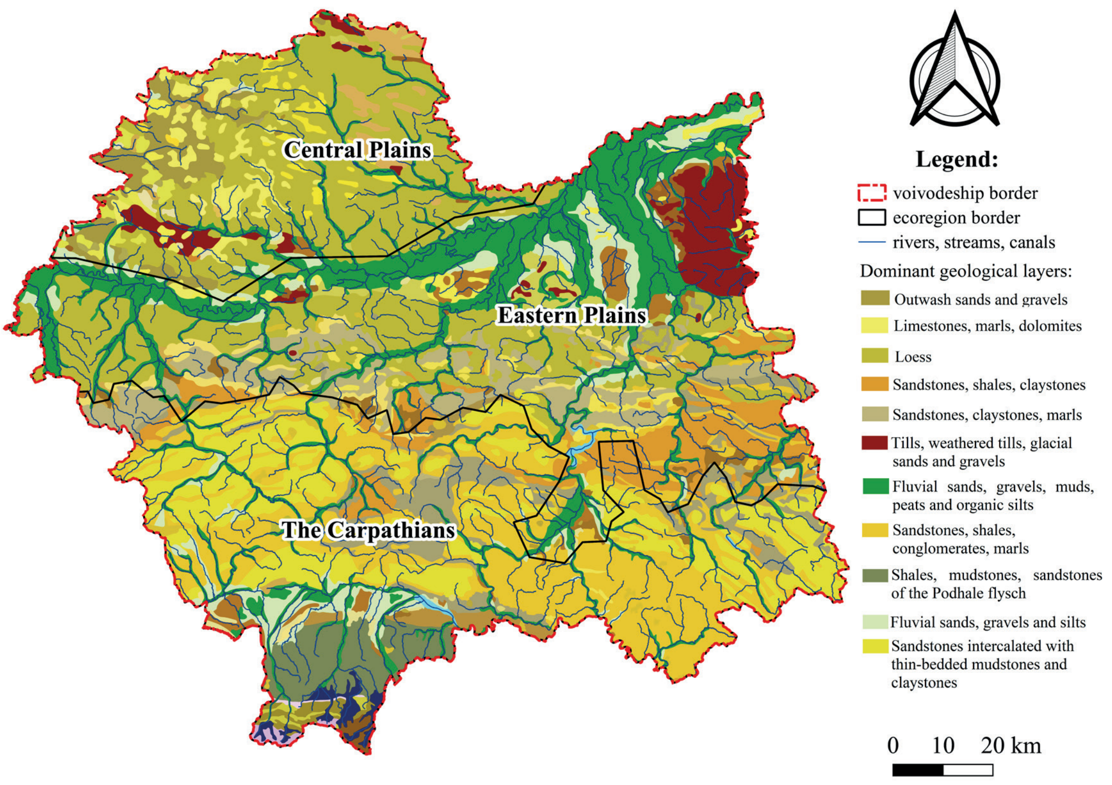


Fig. 2. *Diversity of geological (lithological) deposits against the background of ecoregions*

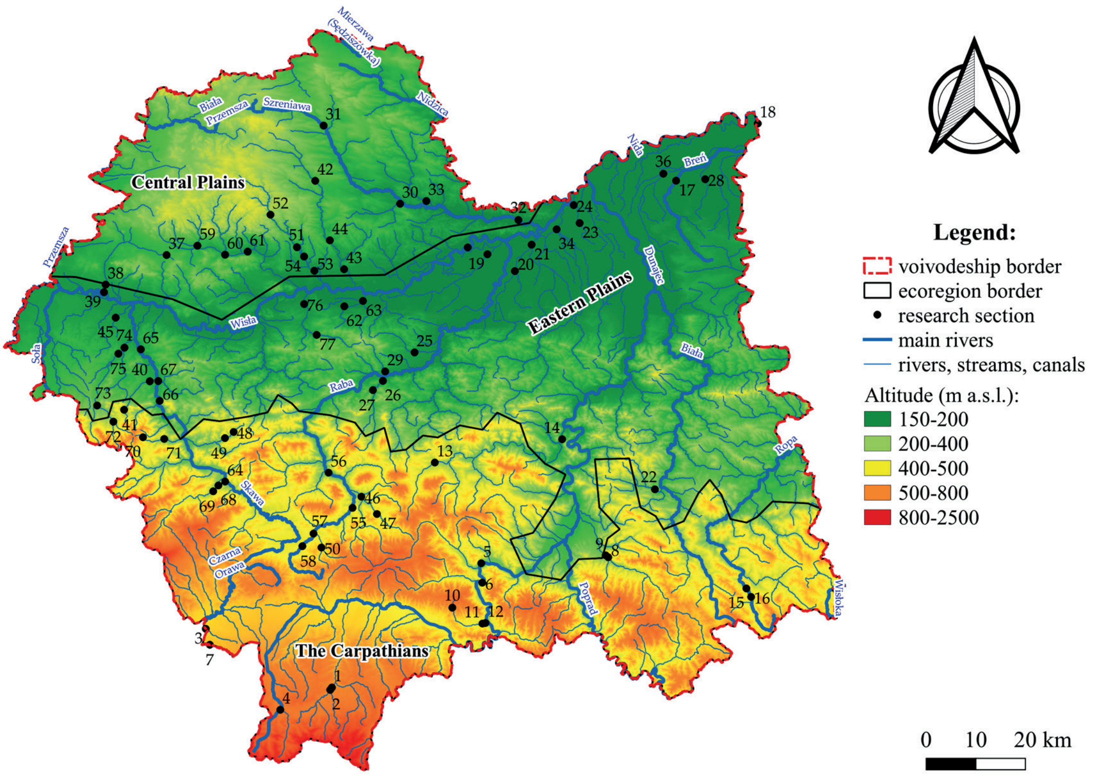


Fig. 3. *Hypsometric map of the analysed region*

Land use characteristics

The area of the voivodeship is characterised by agricultural and forest land use (Fig. 4). More than 50% of the region's area is covered by agricultural land, concentrated mainly in the Eastern Plains and Central Plains ecoregions. Forests cover over 30% of the voivodeship's area, and the Carpathian ecoregion has the largest forest cover. Urbanised areas constitute about 10% of the area. Detailed information about land use forms in ecoregions is shown in Figure 4.

Hydromorphological evaluation

The hydromorphological evaluation of watercourses was carried out in accordance with the HIR methodology applicable in Poland (Szoszkiewicz et al. 2017, 2020). According to the methodology, the first step was to carry out an assessment related to the analysis of land cover maps (Geoportal GUGIK 2022), on the basis of which the selection of sites and the number of research sections (from 1 to 3, related to the form of land use) was made. Then, field inventories were carried out in the field in 2017. In the case of watercourses with a riverbed width of ≤30 m, the researchers were carried out on a 500-metre section, where 10 control profiles were selected at intervals of 50 m. In turn, for watercourses with a width of riverbeds >30 m, the researches were carried out over a 1,000 m long section at 100 m intervals. In each control profile, the physical attributes of the river bed (bed bottom, slopes) were assessed in a transect of 1 m width, and in a transect of 10 m width, the types of vegetation in the riverbed and land use along with the vegetation structure were recorded. Finally, a synthetic assessment of the entire inventoried section was carried out in order to precisely characterize the natural and anthropogenic elements affecting the hydromorphological quality of the watercourse. The data collected in this way was used to calculate the HIR (Eq. (1)), which consists of two indicators: the Hydromorphological Diversity Score (HDS) and the Habitat Modification Score (HMS).

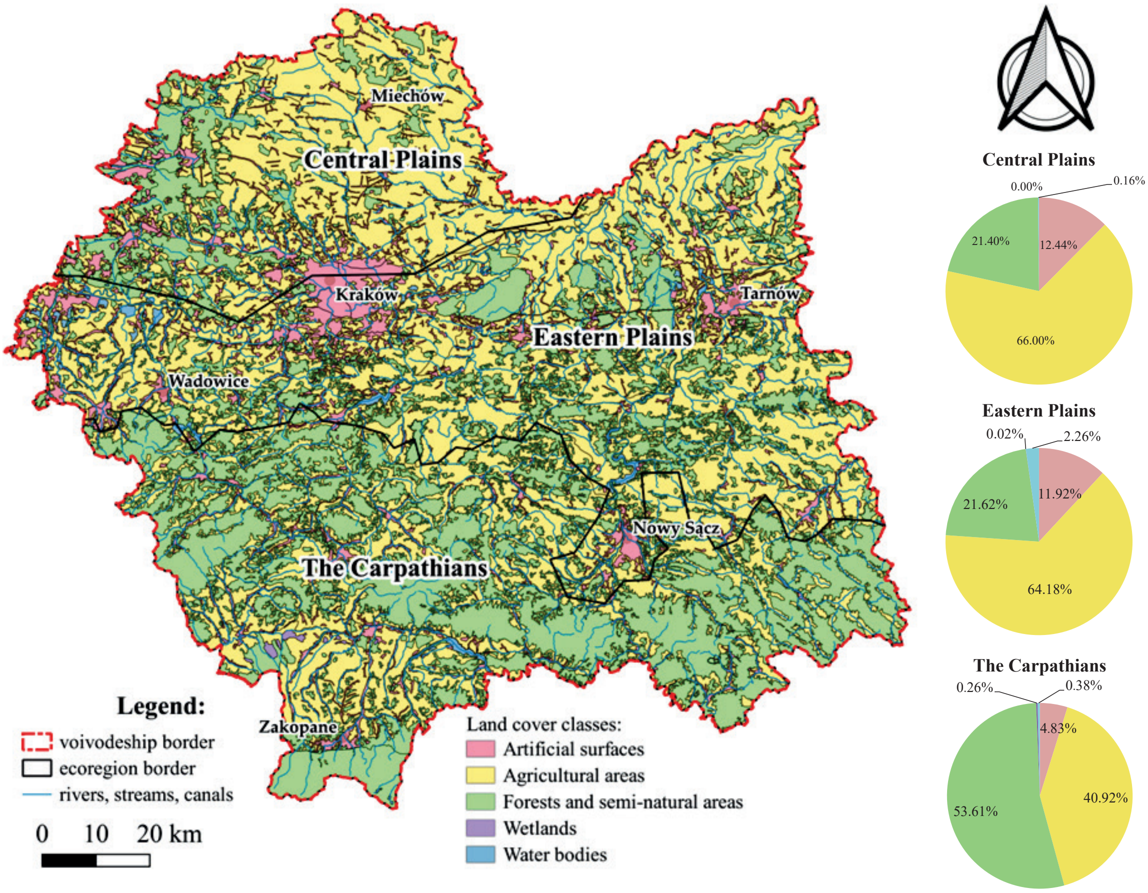


Fig. 4. *Land use forms in the analysed ecoregions*

The HDS considers 13 parameters and provides information on:

1. the stream channel zone – riverbed, including: variation of the river line (1.1), variation of the riverbed slope (1.2), heterogeneity of water flow (1.3), bed material heterogeneity (1.4), natural morphological elements of the bed bottom (1.5), natural morphological elements of the slopes (1.6), and vegetation diversity in the bed (1.7);
2. the stream channel zone – bank face, including: vegetation structure on the slopes (2.1) and diversity of elements accompanying the trees (2.2);
3. the stream valley adjacent to the banktop zone, including: structure of bank-top vegetation (3.1) and not-managed bank-top zone (3.2);
4. the stream valley zone, including: natural land use of the valley (4.1) and connection between the stream and the valley (4.2).

Each of the HDS attributes delivered a range of points, enabling the calculation of the HDS of the river section. The HMS considers five parameters and provides information on:

1. transformed transverse section of the stream channel,
2. hydroengineering structures,
3. transformations observed in spot-checks,
4. disturbance of the connectivity with the river valley,
5. other types of human degradation.

On the basis of parameters collected during field inventories, the HDS and HMS index are calculated. Each parameter is awarded the appropriate number of points resulting from observations. The rule is as follows: the greater the heterogeneity of a watercourse and its valley, the higher the value of the HDS index, which has a positive effect on the final HIR value. In turn, the greater the degree of anthropogenic changes in the watercourse and its valley was registered, the higher the value of the HMS index, which has an unfavorable effect on the final HIR value. The summed HDS and HMS points are included in the calculation of the HIR according to Equation (1). The detailed procedure of scoring is presented in the HIR method manual (Szoszkiewicz et al. 2017, 2020).

$$HIR = \frac{\left(\frac{HDS - HMS}{100}\right) + 0.85}{1.8} \quad (1)$$

The hydromorphological class (from I to V) is determined based on the number of sections examined (Rozporządzenie 2021). In the case of more than 1 section, the hydromorphological classification is determined based on the weighted mean (2):

$$HIR_{mean} = \frac{(HIR_U \cdot wU) + (HIR_A \cdot wA) + (HIR_S \cdot wS)}{100} \quad (2)$$

where:

- HIR_{mean} – mean HIR value for the entire uniform surface water body,
- HIR_U – HIR value calculated for the urbanised section,
- wU – weighting factor for the urbanised areas calculated on the basis of their percentage share in the buffer,
- HIR_A – HIR value calculated for the agricultural section,
- wA – weighting factor for the agricultural areas calculated on the basis of their percentage share in the buffer,
- HIR_S – HIR value calculated for the semi-natural section,
- wS – weighting factor for the semi-natural areas calculated on the basis of their percentage share in the buffer.

Map visualisation and statistical analysis

The maps in this article were generated using QGIS software (QGIS 3.4). The hydrographic division map comes from the Web Map Service (WMS) provided by the National Water Management Holding Polish Waters and the administrative boundaries from the State Border Register (SBR) (Hydroportal ISOK 2015, MPHP 2021, Geoportal GUGiK 2022). The map with river and lake ecoregions comes from the website of the European Environment Agency (EEA 2012). The geological map comes from the website of the Polish Geological Institute – National Research Institute (PIG-PIB 2022). The land use/land cover (LULC) was developed using the CORINE Land Cover (CLC) database (EEA 2000). For this study used 2018 CLC data. Five categories of land use have been distinguished (artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands, waters).

Using the Statistica package (13.3), basic descriptive statistics were calculated for each ecoregion and the normality of distribution was checked using the Shapiro–Wilk test, at the 5% significance level. To check the differences between variables in three ecoregions, the non-parametric Kruskal–Wallis ANOVA test was used. The presence of significant differences in HIR values between environmental variables (altitude typology, size of the catchment area and geology typology) was checked using the U Mann–Whitney test ($\alpha = 0.05$). The variability of each data set (CV) was determined as follows: CV ≤ 15% – low variability; 15% < CV ≤ 35% – moderate variability and CV > 35% – high variability (Wilding & Drees 1983). In order to examine the complex impact of geographical environment factors on the final values of the HIR, multivariate cluster analyses using the Ward method and principal component analysis (PCA) were used. The applicability of PCA analysis was checked using the Kaiser–Mayer–Olkin (KMO) criterion and the Bartlett test (StatSoft 2023). A helpful tool in analysing variables was MS Excel 2007 with the PivotTables function.

RESULTS

Out of 77 sections located in three divergent ecoregions of southern Poland, 31 sections (40.26%) fell to the Carpathians and Eastern Plains each, while 15 sections (19.48%) fell to the Central Plains. HIR covered a wide range of values from 0.11 to 0.90, with a mean of 0.64 (Table 1). Statistical analyses revealed that the obtained values of HIR and its components (HDS and HMS) differed by ecoregion (Table 1), with significant differences in HIR values found only between the Carpathians and Eastern Plains ($P < 0.05$). The highest HIR values were recorded in the study sections located in the Carpathians ecoregion (0.70) and the lowest in the Eastern Plains (0.58). HIR was marked by moderate variability (CV) of values in the analysed ecoregions. A relatively large range of values (min.–max.) was observed in the Carpathians ecoregion, while the smallest spread of values was in the Central Plains.

Considering the locations (altitude) of the surveyed sections, a majority of them – 63 (82%) were located in the altitude range of 200–800 m a.s.l. (as mid-altitude), 13 (17%) <200 m a.s.l. (as lowland) and only 1 (1%) at an altitude >800 m a.s.l. (as high/mountain) (Figs. 5, 6). The highest hydromorphological diversity (HDS > HMS), influencing the high value of HIR, is found in sections belonging to the category of mountain and upland watercourses, and the lowest in lowland sections, in which various types of bed and slope modifications predominate (HMS > HDS).

Overall and without dividing into ecoregions, the statistical analysis showed that there is a significant ($P < 0.05$) variation in hydromorphological conditions between upland and lowland sections. Due to the low representativeness of mountain watercourses, this category was not included in the analysis.

Table 1
Statistical characteristics of the HDS, HMS and HIR for the analysed ecoregions

Parameters		**Ecoregion**								
		the Carpathians *N* **= 31**			**Central Plains** *N* **= 15**			**Eastern Plains** *N* **= 15**		
		min. - max. / mean / median	**SD**	**CV [%]**	**min. - max. / mean / median**	**SD**	**CV [%]**	**min. - max. / mean / median**	**SD**	**CV [%]**
		ANOVA Kruskal–Wallis test probability (*P*)								
HDS:		14.0 – 78.0 / 57.81/58.00	12.89	22.3	22.5 – 73.0 / 47.67/47.00	12.79	26.8	17.5 – 71.5 / 38.81/34.50	15.85	40.8
Ecoregion	The Carpathians	–			**0.044872***			**0.000014**		
	Central Plains	**0.044872**			–			0.613850		
	Eastern Plains	**0.000014**			0.613850			–		
HMS:		0.0 – 95.5 / 17.06/7.50	25.83	151.3	0.0 – 74.5 / 12.53/0.00	21.59	172.3	0.0 – 77.5 / 20.29/15.50	19.23	94.8
Ecoregion	The Carpathians	–			0.528887			0.445592		
	Central Plains	0.528887			–			**0.035308**		
	Eastern Plains	0.445592			**0.035308**			–		
HIR:		0.11 – 0.90 / 0.70/0.76	0.20	29.3	0.21 – 0.88 / 0.67/0.73	0.17	26.0	0.14 – 0.87 / 0.58/0.57	0.17	29.4
Ecoregion	The Carpathians	–			0.797593			**0.001190**		
	Central Plains	0.797593			0.241373			–		
	Eastern Plains	**0.001190**			–			0.241373		

* Bold values indicate statistical significance ($P < 0.05$).

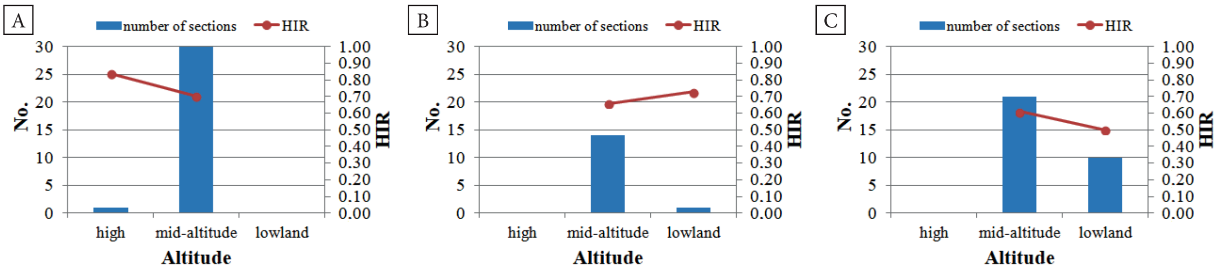


Fig. 5. *Altitude typology: A) the Carpathians; B) Central Plains; C) Eastern Plains. High >800 m a.s.l.; mid-altitude 200–800 m a.s.l.; lowland <200 m a.s.l.*

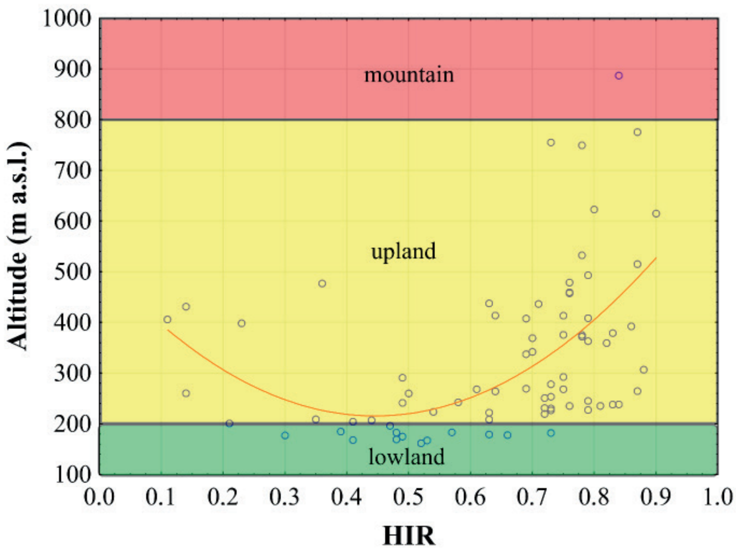


Fig. 6. *The effect of altitude [m a.s.l.] on HIR values*

It is observed that HIR values increase with altitude (Fig. 6). It can be seen from the graph that the lowland watercourses were characterised by HIR values in the range 0.21–0.73, with HIR values of most of the analysed sections oscillating close to 0.50, while the upland watercourses were characterised by a wider range of data 0.11–0.90, with most of the analysed sections obtaining HIR values >0.50. A few upland sections with HIR values <0.50 were dominated by anthropogenic pressures (HMS > HDS).

Considering the type of catchment area size, it can be clearly stated that all ecoregions were dominated by small catchments areas with a size range of 10–100 km^2 which represents 57% of all analysed sections (Fig. 7). Very small (≤10 km^2) and very large (>10,000 km^2) catchment areas were the least frequently recorded. For the sections located in the Carpathians ecoregion, the highest HIR values were recorded in the catchment areas ≤10 km^2 (0.85).

Overall, and without division into ecoregions, the statistical analysis performed showed that there were no significant differences ($P > 0.05$) in hydromorphological conditions between sections located in small and medium catchment areas.

The study was conducted on two different geological substrates, i.e. calcareous and siliceous. Of the 77 research sections/sites, 42 (55%) of which are in calcareous rivers and 35 (45%) in siliceous rivers. Larger mean HIR values were obtained by watercourses flowing in silicate (0.70) than in limestone (0.62) substrates. There were no watercourses associated with organic substrate among the analysed sections (Fig. 8).

Overall and without division into ecoregions, the statistical analysis performed showed that there is a significant ($P < 0.05$) variation in hydromorphological conditions between sections with carbonate and silicate substrates.

In most cases, the analysis included watercourses with a channel width of ≤30 m (87%). In the Central Plains ecoregion, studies were only conducted on watercourses with a channel width of ≤30 m. In the Carpathians and Eastern Plains ecoregions, higher HIR values were recorded in channels >30 m wide (Fig. 9).

The hydromorphological classification allows the study sections to be assigned an appropriate hydromorphological quality class ranging from I (best) to V (worst). All HIR classes were recorded in the Central Plains and Eastern Plains ecoregions. Most sections in the Central Plains ecoregion obtained class 2, while class 3 dominated in the Eastern Plains ecoregion. In the Carpathians ecoregion, no class 4 was recorded, and stretches/sections in class 2 predominated (Fig. 10).

The influence of catchment area use on the hydromorphology of watercourses is clearly visible (Fig. 11). In all ecoregions, the highest HIR values were observed in the seminatural area and the lowest in the urbanised areas. The dominant land use type in the Carpathians ecoregion was seminatural, while in the Central Plains and Eastern Plains ecoregions, agricultural land predominated.

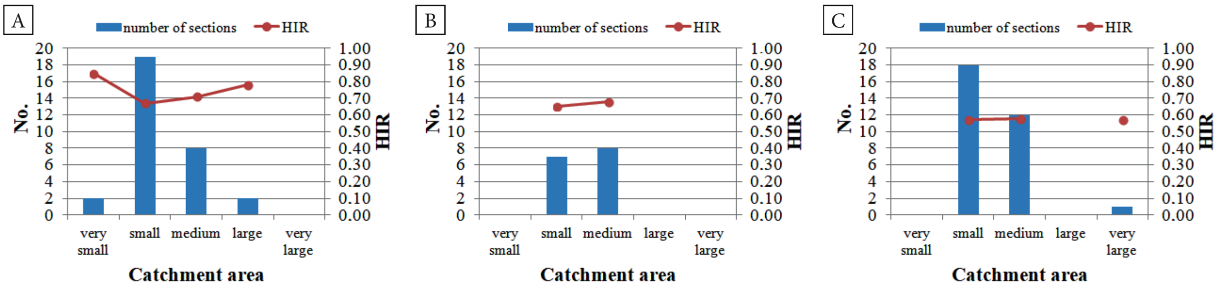


Fig. 7. Size typology based on catchment area: A) the Carpathians; B) Central Plains; C) Eastern Plains. Very small ≤10 km²; small 10–100 km²; medium 100–1,000 km²; large 1,000–10,000 km²; very large >10,000 km²

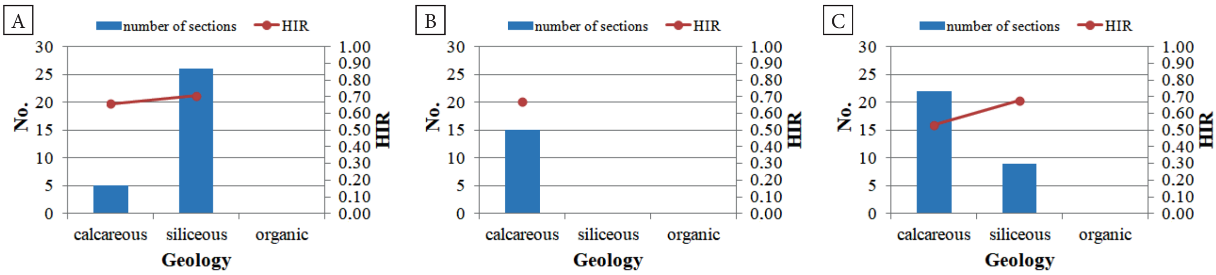


Fig. 8. Geological characteristics: A) the Carpathians; B) Central Plains; C) Eastern Plains

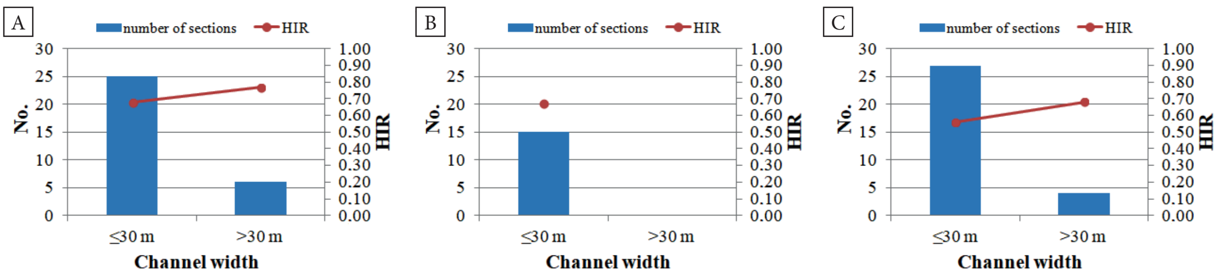


Fig. 9. Channel width characteristics: A) the Carpathians; B) Central Plains; C) Eastern Plains

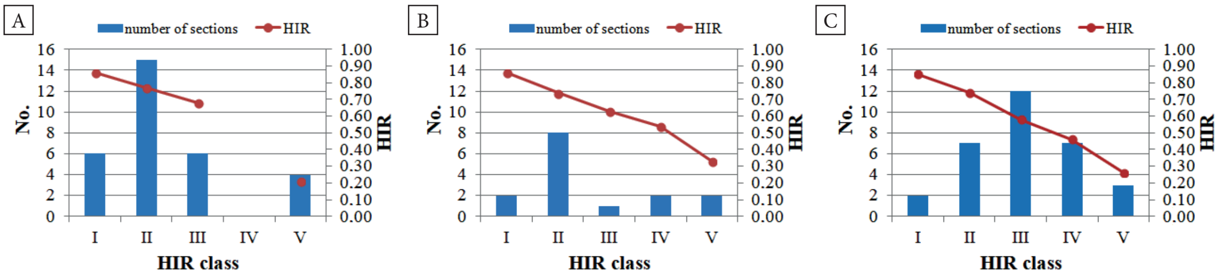


Fig. 10. Hydromorphological quality: A) the Carpathians; B) Central Plains; C) Eastern Plains

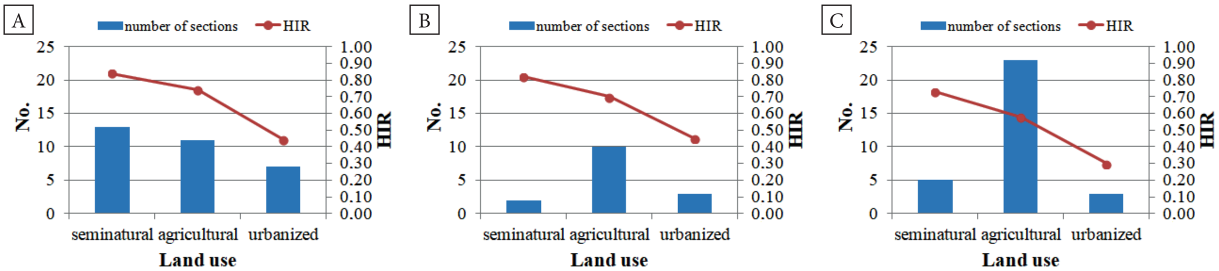


Fig. 11. Land use characteristics: A) the Carpathians; B) Central Plains; C) Eastern Plains

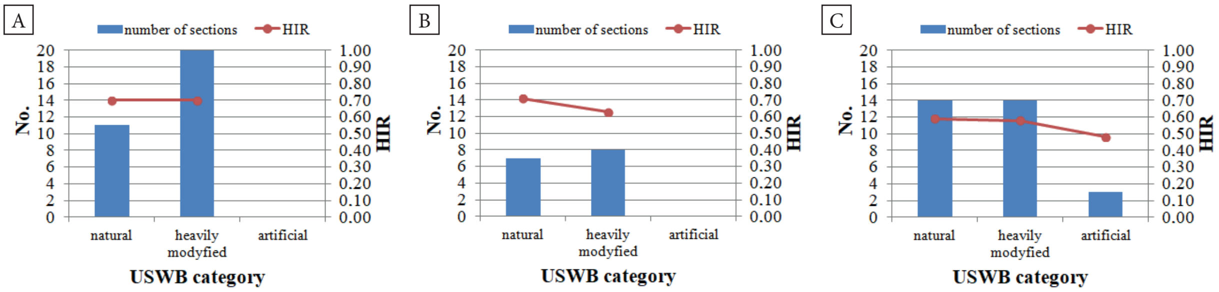
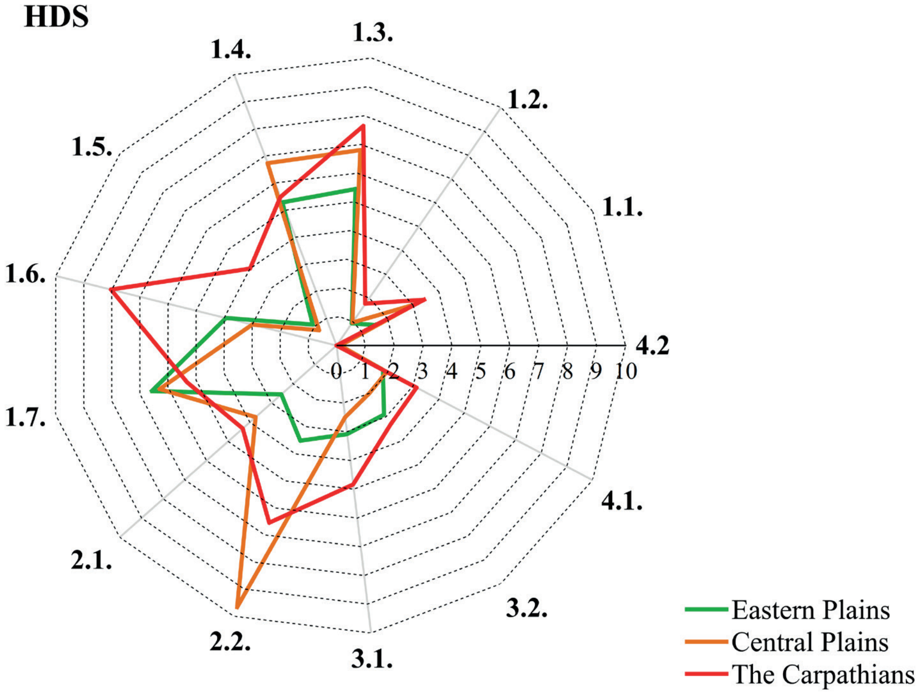


Fig. 12. The surface water bodies characteristics: A) the Carpathians; B) Central Plains; C) Eastern Plains

Figure 12 shows USWB category. Heavily modified watercourses dominated (54.5%), followed by natural (41.6%) and artificial (3.9%). The highest HIR values were recorded in natural watercourses (0.67), with the exception of sections in the Carpathians ecoregion, where similar mean HIR values were obtained for heavily modified and natural watercourses (0.70). Artificial watercourses were the worst in terms of hydromorphological quality, occurring only in the Eastern Plains ecoregion (0.48).

The highest total HDS values were observed in the Carpathians ecoregion and the lowest in Central Plains areas (Fig. 13A). HDS values for the Carpathians ecoregion are mainly influenced by natural morphological elements of the slopes (1.6), heterogeneity of water flow (1.3), and diversity of elements accompanying the trees (2.2). The final value of the HDS for sections located in the Central Plains was significantly influenced by diversity of elements accompanying the trees (2.2), heterogeneity of water flow (1.3), bed material heterogeneity (1.4) and vegetation diversity in the bed (1.7). In the Eastern Plains, the highest values of HDS occur in vegetation diversity in the bed (1.7), heterogeneity of water flow (1.3) and bed material heterogeneity (1.4).

A



B

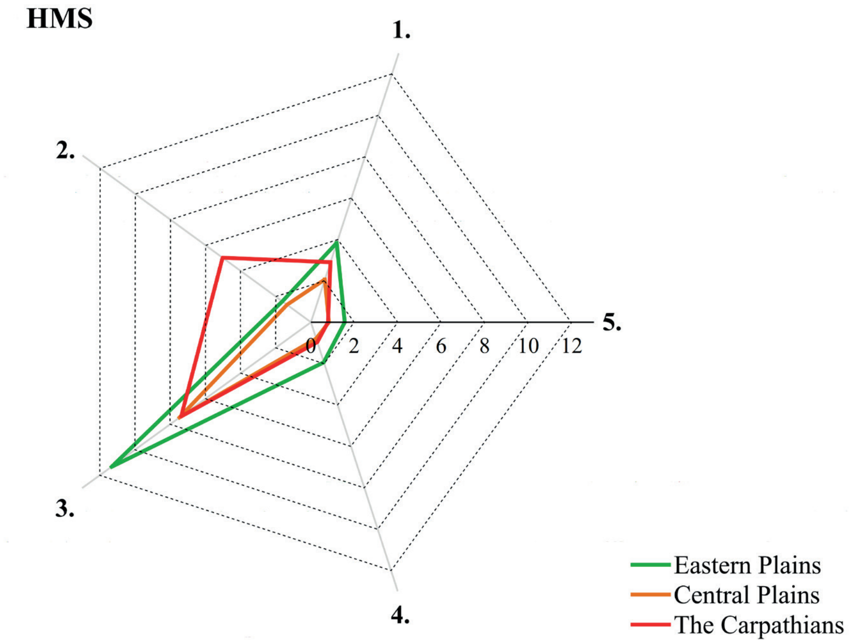


Fig. 13. *Radar plots showing the diversity and impact of variables on the HDS and HMS index in the three analysed ecoregions. The variables were characterized by the mean value*

The largest anthropogenic changes in the hydromorphology of streams and rivers, expressed using the HMS indicator, were recorded in sections of the Eastern Plains, and the lowest in the Central Plains (Fig. 13B). In the case of the Carpathians and Central Plains ecoregions, the main influence on the obtained HMS values was three out of five analysed parameters such as: transformed transverse section of the stream channel (1), hydroengineering structures (2) and transformations observed in spot-checks (3), while in the case of the Eastern Plains ecoregion, two of five analysed parameters such as: transformed transverse section of the stream channel (1) and transformations observed in spot-checks (3). In all three ecoregions, the negative impact of transformations in spot-checks on the hydromorphological condition of watercourses is visible.

By far the most important direct influence on the HDS index was for the Carpathians ecoregion conditions related to natural morphological elements of the slopes (13.9%), in the Central Plains region conditions related to diversity of elements accompanying the trees (20.3%), and in the Eastern Plains ecoregion conditions related to vegetation diversity in the bed (17.0%). By far the most important direct influence on the HMS index was for the three ecoregions conditions related to transformations observed in spot-checks (43.2%, 59.6%, and 55.8% respectively).

Multi-dimensional analyses were performed to further characterise the variables. The similarity of hydromorphological parameters of watercourses was presented using a dendrogram (Fig. 14). In this study, two main groups of watercourses (cluster I and II) were observed, which are homogeneous in terms of hydromorphological conditions. Within each group, two subgroups can be distinguished (I.a, I.b, II.a and II.b). The average HIR value for 77 sections is 0.64. Closer characterisation of the groups was obtained by using cross-sectional statistics and simple ANOVA analysis. It shows that most of the analysed variables influenced the formation of clusters, especially transformations observed in spot-checks (3), variation of the riverbed slope (1.2), natural morphological elements of the slopes (1.6), structure of bank-top vegetation (3.1), and other types of human degradation (5). The variable 4.2 – connection between the stream and the valley – had no significant impact on the formation of clusters.

Comparing the mean values, the resulting cluster groups can be characterised as follows:

The first group (I.a) consisted of 11 sections of rivers, located mainly in the Eastern Plains (10) and Central Plains (1). In this group, the HMS (variables no. 3 and 1) and HDS (variables no. 1.7, 1.4 and 1.3) values are similar, and the mean HIR value is 0.47. The mean location of the research sections is 185.22 m a.s.l., with slope 2.4‰. This includes watercourses with a calcareous substrate (100%) with a riverbed width of ≤30 m (100%). Medium-sized catchments are dominant (100–1,000 km²).

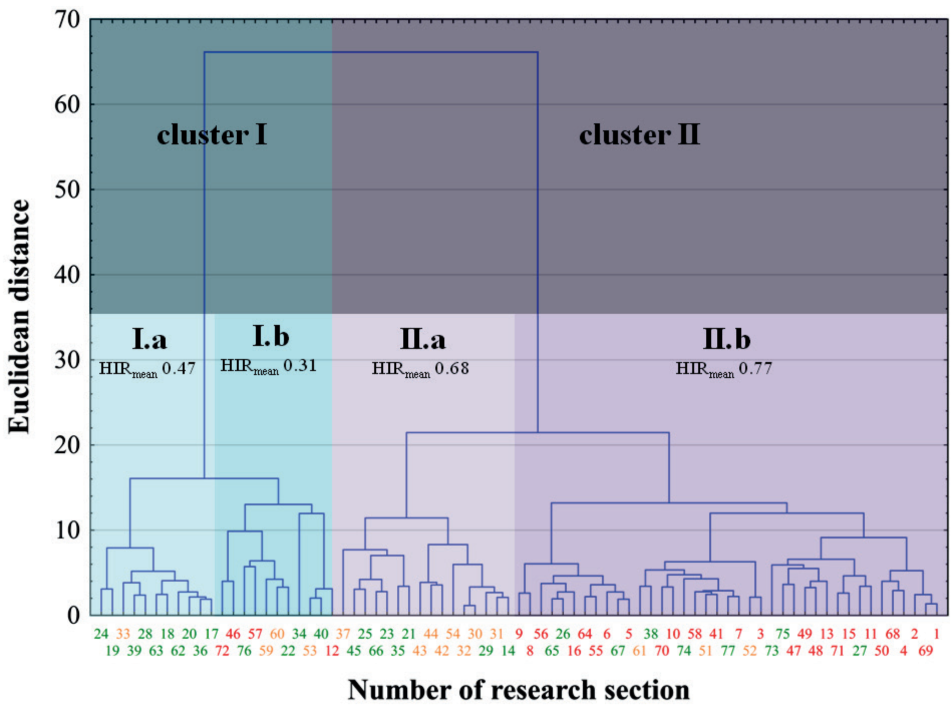


Fig. 14. *Dendrogram based on Ward's method considering evaluated Hydromorphological Index for Rivers (HIR). On the horizontal axis, affiliation to ecoregions is marked with colours: red – the Carpathians, green – Eastern Plains, orange – Central Plains*

The second group (I.b) consisted of 11 sections, located in the Carpathians (4), Eastern Plains (4) and Central Plains (3) areas. In this group there are clearly higher values of the HMS index (variables no. 3 and 2) and lower HDS (variables no. 1.3, 1.7 and 1.4) with the lowest mean HIR value of 0.31. The mean altitude of the research sections is 304.93 m a.s.l., with slope 18.0‰. This includes watercourses with a predominantly calcareous (64%) and sometimes siliceous substrate with a riverbed width of ≤30 m (100%). These include small (64%) and medium-sized (36%) catchments.

The third group (II.a) consisted of 16 sections, located in the Central Plains (8) and Eastern Plains (8) areas. In this group there are clearly higher values of the HDS index (variables no. 1.4, 2.2 and 1.7) and lower HMS (variables no. 3 and 2) with a mean HIR value of 0.68. The mean altitude of the research sections is 229.82 m a.s.l., with slope 4.2‰. This includes watercourses with a predominantly calcareous (81%) and sometimes siliceous substrate with a riverbed width of mostly ≤30 m (88%). Small catchments (10–100 km^2) account for 56%, the rest are medium-sized catchments and one very large (>10,000 km^2).

The fourth group (II.b) is the most numerous and consisted of 39 sections, located mainly in the Carpathians ecoregion (27), and to a lesser extent in the Eastern Plains (9) and Central Plains (3) areas. In this group there are clearly higher values of the HDS index (variables no. 1.6, 2.2 and 1.3) and lower HMS (variables no. 3 and 2) with a mean HIR value of 0.77. The mean altitude of the research sections is 417.63 m a.s.l., with slope 16.6‰. This includes watercourses with a predominantly siliceous (72%) and sometimes calcareous substrate with a riverbed width of mostly ≤30 m (79%). In this group there is the greatest diversity in terms of catchment area, from very small (≤10 km^2) to large (1,000–10,000 km^2), especially in the Carpathians ecoregion.

Figure 15 shows a biplot – a scatter plot of factor loadings including the scattered objects (sections) in a space defined by the first two principal components explaining a total of 46.09% of the total variance. Application of principal component analysis (PCA) was facilitated by satisfying assumptions of the method – Bartlett's test and KMO criterion ($P < 0.05$; KMO > 0.5). The analyses show that two bundles of vectors can be distinguished – the first group consists of variables related to HDS indicator, e.g.: 2.2 (diversity of elements accompanying the trees), 1.2 (variation of the riverbed slope), 1.6 (natural morphological elements of the slopes), and the second group of variables mainly related to HMS indicator e.g.: 3 (transformations observed in spot-checks), 5 (other types of human degradation) and 1 (transformed transverse section of the stream channel), and two variables related to HDS such as: 1.7 (vegetation diversity in the bed) and 4.2 (connection between the stream and the valley). The most strongly correlated pairs of variables are 1.5 and 1.3, 1.6 and 3.1, 1.7 and 4.2, 1 and 3, 4 and 5 (positive correlations), as well as 1 and 1.4 and 1.5 and 1.7 (negative correlations). Variables that are uncorrelated or very weakly correlated include: 1.4 and 1.5, 2 and 2.1 as well as 1 and 1.3.

The scatter plot of the study sections (1–77) in the space defined by the first two principal components also provides interesting information and complements the dendrogram (Fig. 14). Four compact clusters of points can be observed: (1) for example 17, 18, 19, 20, 36 and 63, (2) for example 14, 31, 42, 44, 54 and 66, (3) for example 12, 22, 34, 53, 57 and 72, (4) for example 2, 4, 9, 11, 13, 41 and 73. The points distributed on the left are characterised by the highest proportion of parameters describing the HMS index, while the points on the right represent the watercourse sections with the highest proportion of parameters included in the HDS index. The outlier points can be seen – these are e.g. 72, 46 and 57 – watercourses located in the Carpathians ecoregion but strongly modified and influenced by human impact (buildings, fortifications, hydrotechnical structures, etc.). The point depicting section 66 is close to the coordinate system. This means that in this section the values of the studied HDS, HMS and finally the HIR are closest to the average values (arithmetic mean calculated for 77 sections).

The spatial distribution of HIR values in the three ecoregions is shown in Figure 16. The weakest HIR values were recorded in the Eastern Plains, where the dominant form of land use is agricultural activity, followed by urbanised areas. The best HIR values were recorded in the Carpathians, especially where the land cover is dominated by forests, and slightly worse in highly urbanised areas.

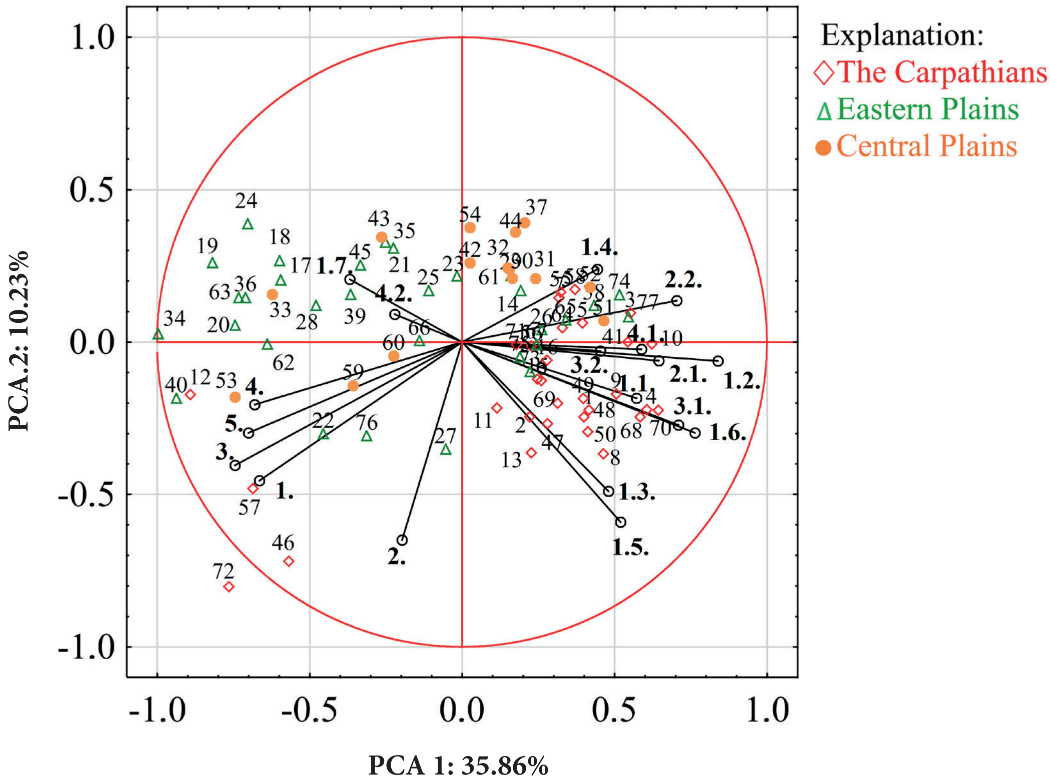


Fig. 15. Biplot – results of PCA analysis for variables describing HIR in relation to the three ecoregions

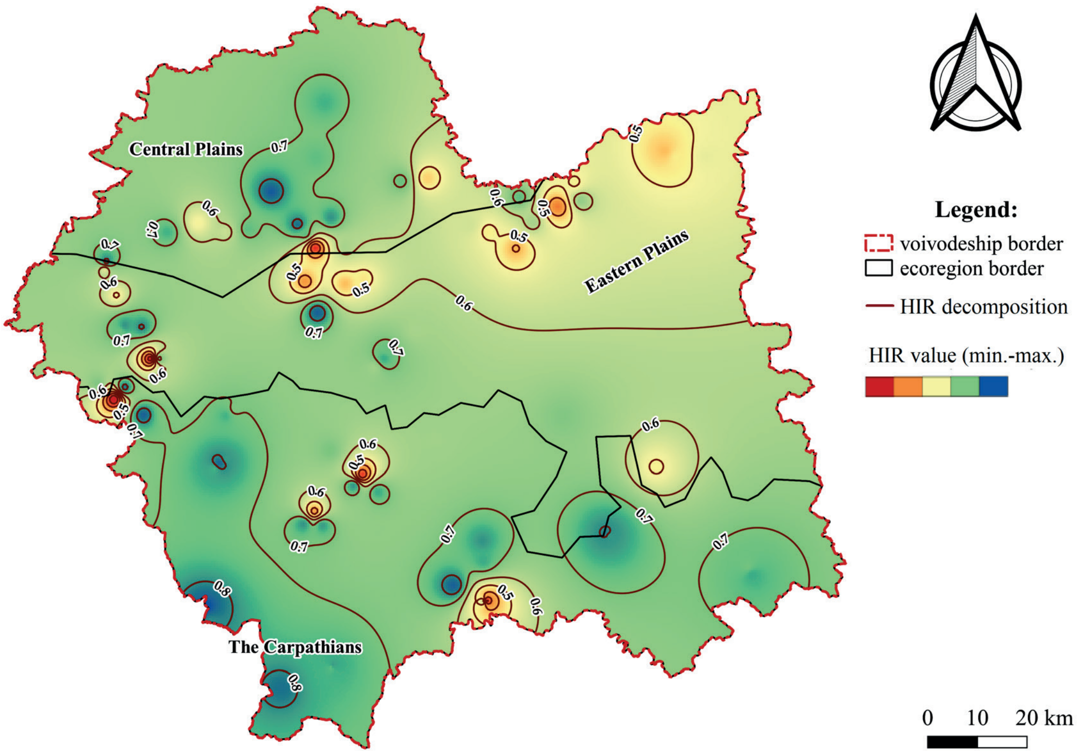


Fig. 16. The spatial distribution of HIR values in the three ecoregions

DISCUSSION

Application of HIR to 77 sections of watercourses located in three ecoregions in southern Poland showed significant hydromorphological differentiation. It is observed in the case of geographical conditions such as altitude, type of geology and anthropogenic conditions, which are manifested by human activity in watercourse catchment areas. Garbowski et al. (2023) showed significant differences between hydromorphological conditions in watercourses across two different regions of central and northern Poland. Both in their study and this one, the variables influencing hydromorphological quality were parameters related to natural morphological elements of banks and the valley.

Halabowski & Lewin (2020) report that the highest HIR indices were obtained for the least anthropogenic river sections, while the lowest values were obtained for river sections under the greatest human pressure. A similar trend can be observed in this study – the sections located in the Eastern Plains tended to have worse hydromorphological parameters related, among other things, to land use form. Here, agricultural land use is predominant, so transformations in spot-checks related to their regulation are observed in great numbers.

A study by El Hourani et al. (2022) showed significant differences between the mountain and lowland ecoregion in the case of the Hase River, Germany. The lowland sections showed a worse hydromorphological class than the mountain sections, which is partly due to natural factors (e.g. location, geology) and secondarily to anthropogenic factors (e.g. land use). As it turns out, vegetation – and especially canopy (afforestation) and its accompanying elements – influence good hydromorphological quality (Turunen et al. 2021), and these in this study were observed in large numbers in stretches located in upland areas, especially in seminatural areas.

A significant number of small and medium-sized rivers in the Eastern Plains ecoregion have straightened and channelised riverbeds, which is related to flood protection. These treatments are most often applied on rivers in lowland regions that are characterised by agricultural activities and/or dense population, as is the case on rivers in Croatia (Pavlek et al. 2023).

Areas adjacent to lowland rivers are generally accessible and fertile, which translates into intensive agricultural activities and high urbanisation. Changes related to modification of riverbeds and banks are observed here, as well as interference with riparian zones affecting biodiversity (Feld et al. 2014, Kałuża et al. 2020, Knehtl et al. 2021, Kupiec et al. 2021, Borek 2023, Denic et al. 2023, Garbowski et al. 2023). In the case of lowland rivers, a dominance of laminar flow is observed and this in turn translates into habitats for macrophytes and macroinvertebrates (Guareschi et al. 2014, Kujanová et al. 2018, Vilenica et al. 2022). The selected river sections were therefore characterised by a relatively high diversity and abundance of hydromorphological units compared to the other sections (Akstinas et al. 2022).

Studies by Dresti et al. (2016) and Licciardello et al. (2021) show that in Italy, the worst hydromorphological conditions prevail in mountain rivers marked by high levels of human housing and dams (hydropower plants). Similar study conclusions are reported by Wiatkowski & Tomczyk (2018), who also noted a negative impact of dams on river ecosystems, altering the environment and disrupting the hydromorphological continuity of watercourses. In this study, it can be noted that, as a rule, sections of upland and mountain areas are distinguished by better hydromorphological conditions, but there are exceptions – some sections especially in the anthropogenic areas are highly modified, which affects the reduction of hydromorphological quality (Fig. 15, section nos. 46, 57 and 72). The reasons for this are partly to be found in the numerous transformations and degradation of Carpathian rivers and their tributaries that took place in the 20th century, which had a negative impact on hydrological processes and habitat conditions of fauna and flora (Nawieśniak 2018, Hajdukiewicz et al. 2019).

As noted by Gündüz & Şimşek (2021), an increase in modification of a riverbed gradually increases with direction of flow, especially when the main river and its tributaries flow through urbanised areas. Profiling and slope reinforcement are evident in this case, and the bed is partially concreted or totally channelised. Negative effects of human activity over many years in the upper reaches of the Dunajec River have also been observed by

Hajdukiewicz & Wyżga (2019), where gravel extraction and channelisation works have caused dramatic changes in the riverbed – its stabilisation, narrowing and elimination of islands (mid-corridor landforms). Transformations in riverbeds, especially transverse structures, can influence the emergence of ecological niches in which previously unseen species will appear (Sługocki et al. 2021). Foothill rivers are also characterised by low macrophyte community abundance due to multiple stressors (Gecheva et al. 2021), of which the change in flow regime caused by hydraulic structures plays a significant role (Papadaki et al. 2017).

The analysis of Müller et al. (2022) shows that restoration/reclamation planning for watercourses should focus on activities aimed at improving the continuity of the river (due to small or large hydraulic structures), which reduce the river space and negatively affect the final hydromorphological quality in many cases.

A type of substrate is mainly important for the purpose of water biological assessment (Rawer-Jost et al. 2004) and less important for hydromorphological assessment. Limestone and siliceous rivers differ in terms of overall nutrient conditions (Krueger & Waters 1983), with siliceous rivers generally being poorer and more sensitive to physico-chemical disturbance (Villeneuve et al. 2018). It is difficult to find information in the literature relating to the influence of substrate type on the hydromorphological quality of watercourses. This study showed that sections located in an area with silicate substrate were characterised by better hydromorphological conditions. Feio et al. (2014) report that catchments <100 km^2 with silicate substrate were more affected by stressors (anthropopressure) than mountain streams with the same substrate.

CONCLUSIONS

The analyses showed that there are differences in hydromorphological conditions between the ecoregions, however significant differences were observed between the Carpathians and Eastern Plains ecoregions. The hydromorphological conditions of watercourses in this region are determined by the conditions of the natural environment, such as altitude and geological substrate, and the anthropogenic environment (transformation observed in spot-checks). Considering hydromorphological quality at spatial scales, such as the regionalisation proposed by the WFD, has a positive effect and can be successfully used to support bioassessment to improve the detection of human impacts on aquatic ecosystems. Through using multivariate analyses, a group of variables were identified that played a significant role on the final HIR. In addition, the analyses carried out on the basis of ecoregions made it possible to identify the elements/attributes influencing the hydromorphological diversity of watercourses. Thus, it can be said that the distinction and detailing of regional units is needed, as we are trying to order geographical space in this way and regionalisation is a very good example of such sorting.

Although anthropogenic activities negatively influenced HIR in most of the ecoregions, natural geographic environmental factors such as substrate, altitude position and catchment area size had a dominant influence. The results underline that the hydromorphological quality of watercourses in all three ecoregions is determined by the co-occurrence and interaction of multiple stressors (natural and anthropogenic), supporting the conclusion that basic/complex management strategies are required to achieve the ambitious goal of good ecological status of surface waters, not only at the catchment but at the whole region scale.

Understanding both the role and importance of linkages between river habitat quality and the ecoregion to which it belongs is of strategic importance for proper management in the catchment area and for conducting potential remedial work (e.g. river restoration). In the future, this will allow the development of recommendations to be included in the river basin management plans and programme of measures to achieve good ecological status in accordance with the objectives of the WFD.

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