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# Linking Hydromorphological Degradation with Environmental Status of Riparian Ecosystems: A Case Study in the Stropnice River Basin, Czech Republic

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**Abstract:** Recently, increasing attention has been paid to the anthropogenic degradation of the riverbed and its relationship to the ecological status of the adjacent river landscape. The key objective of this research was to determine the extent of the disturbance of the selected small streams and their riparian zone in a study area located in a forest and forest-agricultural landscape in the Czech Republic. The next step was to analyze the mutual relationships between the ecological status of the riparian vegetation and the hydromorphological status of the riverbed. The main working hypothesis considered the good hydromorphological status of the river as reflected in the favorable environmental status of the surrounding riparian habitats and vice versa. It was found in more than 90% of the total length of studied watercourses that the character of linkages between channel morphology and the ecological status of riparian vegetation is directly influenced by anthropogenic activities. An interesting finding is that the degraded streams in lowland sites are often encompassed by natural or close-to-natural habitats. On the contrary, the natural status of the riverbed was found in a significantly forested headwater area, but the riparian habitats did not reach even a close-to-natural status. This paper contributes to clarifying the significance of human impact on the river morphology, reflected in the reduction of connectivity between the terrestrial and fluvial parts of the river landscape. It helps to explore the most important disturbances affecting mutual interactions between the river and the riparian habitats.

**Keywords:** hydromorphological status; small stream; floodplain; riparian ecosystem; habitat assessment; Stropnice River; Czech Republic

## 1. Introduction

Hydromorphological characteristics represent one of the indicators in the assessment of the overall ecological status of rivers [1]. These features reflect the character of natural processes and human influence occurring throughout the river basin. The nature of mutual influence between a river and its floodplain is dependent on the order in which these two parts of river landscape are transformed by human activities. The order in which these parts were regulated varied in the past; however, significant changes in almost the entire length of the rivers started to occur around the beginning of the 20th century [2]. During this period, it was typical to modify the watercourse initially and then to begin with intensive floodplain exploitation [3]. In this way, a large number of floodplain ecosystems have been degraded along large rivers [4], as well as small watercourses over the last century, usually in favor of agriculture. Primarily in the case of smaller watercourses, an area of their floodplain ecosystems

was reduced to the level of strip-like riparian stands [5]. Most floodplains have been hydrologically disconnected from the river or smaller stream by the construction of dykes, and it is an agriculture, settlements or traffic routes which currently dominate in the floodplains [6]. These activities are the most common especially in Europe, according to Nilsson et al. [7]. Regarding to the fact that floodplain ecosystems in optimal conditions supply multiple ecosystem services and represent biodiversity hotspots, efforts should be made to improve the management of these ecosystems. According to Schindler et al. [8], multifunctionality is more successful where a broad range of stakeholders with diverse expertise and interests are involved in all stages of planning and implementation.

The importance of analyzing hydromorphological conditions, processes, and trends has recently increased with the integration of these issues into an assessment process that is based on the Water Framework Directive 2000/60/EC [9], part of the current European legislation on water management. The assessment of hydromorphological status is a component of the complex ecological evaluation of surface water bodies. Part of the evaluation process defined by the Water Framework Directive (WFD) is the analysis of the chemical and ecological status, the ecological status being composed of biological, physico-chemical and hydromorphological components. The achievement of very good ecological status of each component is evaluated against the so-called “type-specific reference conditions”. Several studies have already dealt with the issue of defining the geomorphic reference conditions of streams (e.g., [10–13]). Since the vast majority of watercourses have been affected by humans (e.g., [14,15]), many authors conclude that referring to a “pristine” stream condition is neither feasible nor worthwhile (e.g., [12,16,17]). The reference conditions are defined by looking at the present and future conditions and constraints, aiming to identify the least degraded and most ecologically dynamic status that could exist at a given river segment [11]. Brierley et al. [10] state that reference conditions are framed in terms of an “expected status”, which represents the best conditions that can be attained by a river, given the prevailing conditions in a catchment.

In the case of heavily modified water bodies (HMWB) or artificial water bodies, instead of ecological status, the so-called “ecological potential” is assessed. Ecological potential is determined on the basis of individual quality components (i.e., biological, hydromorphological and physico-chemical components) defined by the WFD. An important aspect of the whole evaluation mechanism is that the hydromorphological components enter the described evaluation process only if, within the evaluation of biological and physicochemical components, the stream (or the river segment thereof) has been classified as “very good”. In addition to the conditions defined by the WFD, there are many other reasons supporting the hydromorphological assessment of streams required by sustainable land use practices. These reasons include the need to monitor selected characteristics of water bodies important for the protection of nature and landscapes, as well as for a more efficient flood risk management and restoration process leading to the implementation of close-to-natural flood control measures [18].

The need for more extensive studies on the relationships between hydromorphology and the ecology of river ecosystems is emphasized, for example, by Vaughan et al. [19], Elozegi and Sabater [20], Grabowski and Gurnell [21] and Jakubínský and Cudlín [22], who consider the understanding and quantification of that relationship one of the most important objectives for effective management. The issues of interactions between the biotic and physical status of the river landscape solves several scientific concepts, from which “hydroecology” (from “ecohydrology”) [23,24] or, more frequently, also “eco-hydromorphology” [25] has been developed as a new scientific discipline. An essential phenomenon of ecology–hydromorphology linkages are also numerous signs of climate change, which affect the hydrological regime and increase the total water consumption [26]. Durance and Ormerod [27] suggest that, although the riverine environment seems to be very sensitive to the impacts of climate change, its considerable potential to mitigate the impact and improve ecological resilience has not been taken sufficiently into consideration.

The character of the interactions between the terrestrial and fluvial part of the river landscape has been largely influenced by anthropogenic activities, both indirectly (globally—the urbanization of floodplains increased flood risk while deforestation for agricultural purposes caused an enormous

increase in the erosion processes) and directly (by regulating the watercourses and changing the geometric parameters of riverbeds). The specific impact of floodplain regulation on hydromorphological parameters is dependent upon (i) the natural conditions of the watershed and (ii) the land-use type of floodplain; this means that the impact is “site-specific” [28]. In both cases, the development of human activities in the floodplain usually causes a decrease in the naturalness of the habitats within that area [29], leading to an increase of the flood risk level [30,31]. This can be caused directly by the presence of people in the inundation area or indirectly by the reduction of the water retention ability of the floodplain ecosystem. For these reasons, river restoration and renaturalization should consider the environmental consequences related to the entire area of the river landscape respective to the whole watershed area [32].

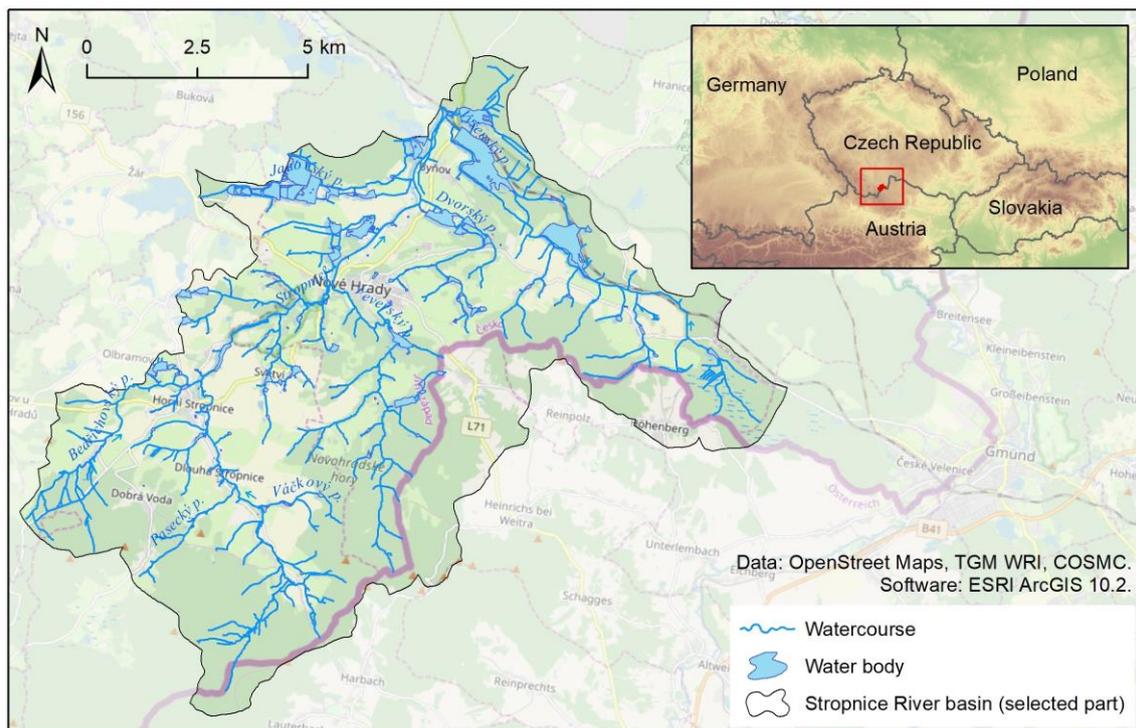
Hydromorphological parameters may be the result of recent activities and of the former development of the surroundings. Several authors (e.g., [33–35]) state that the slope, shape and spatio-temporal variability of natural, seminatural and modified rivers are a response to the amount and character of inputs of water and sediment into the riverbed, which are the consequences of geological factors, climate change and anthropogenic impacts. The quantity and quality of a specified input into the river system is the result of short-term “pulse” disturbances (e.g., the flood event) or of long-term “press changes”, such as changes in land use [36]. Understanding the ecological responses to selected disturbances of the riverine environment can help local stakeholders to estimate the impact of the measures taken and to set the critical limits for potentially dangerous activities in the landscape and its spatial extent [37].

In this study, we focus on the issue of inconsistency between the ecological status of the riverbed and the status of the surrounding landscape, usually caused by uncoordinated landscape management practices, which is subsequently reflected in the secondary degradation of the environmental values. The uncoordinated approach to river landscape management has in the past been caused by efforts to increase the intensity of land use during the socialist period; at present, it is the result of different management practices of private land within the river landscape and watercourse management. As a consequence, the connectivity between the riverbed and its riparian zone or the whole floodplain area is interrupted, which encourages a positive feedback—limited or nonexistent connectivity of the watercourse with the surrounding area, for example, results in a higher susceptibility to hydrometeorological extremes, a loss of biodiversity and a lower ability of the landscape to perform basic ecosystem functions and services. The objective of this study is to answer the following questions: (i) What is the extent of disruption of a watercourse and its floodplain in the model sites? (ii) Is there a direct relationship between stream regulation and the ecological status of the surrounding area, especially within the riparian zone?

## 2. Materials and Methods

### 2.1. Study Area

This study covered the upper part of the Stropnice River watershed in the southern part of the Czech Republic that takes up roughly 25% of the total catchment area. This is an area of approximately 100 km<sup>2</sup>, extending from the headwater area of the Stropnice River in the Novohradské Mountains (spring at 813 m a.s.l.), partly adjacent to the national border with Austria, to the river segment in the wider floodplain near Nové Hradky Town (river kilometrage 58.3–40.9). The selected watershed is representative of the small- to medium-sized watercourses of lowlands and uplands in the Czech Republic. The upper part of the studied area is characterized by the dissected relief of the Novohradské Mountains, formed by erosion or weathering resistant crystalline rocks covered in loamy, sandy or gravelly Quaternary age sediments in some places of the valley bottoms [38]. The river network is characterized by a highly variable hydromorphological status, with the best values only in its mountainous parts near the border with Austria (Figure 1). The lower-course river features are highly degraded by human activities.



**Figure 1.** Location of the case study area—the upper part of the Stropnice River catchment in Southern Bohemia on the Czech-Austrian border.

The middle part of the Stropnice River flows through the foothills of the Novohradské Mountains, consisting of forested uplands and highlands disaggregated by numerous depressions. It is an area with a relatively easily identifiable extent of floodplain with a width of about 100 m. In this area, the Stropnice River typically consists of alternating segments of bends and meanders, which (together with hydromorphological properties) indicate a relatively low anthropogenic influence, and shorter segments of straightened channels (often occurring along roads) significantly influenced by human activities. The lowest river segments are located in the lowland area of the southern edge of the Třeboň Basin (roughly from river 43.9 km), where the floodplain, formed mainly by Gleysols and Fluvisols [38], reaches up to 500 m in width. The overall ecological status of the river network in this area was significantly degraded by human activities, which culminated in the straightening of the Stropnice riverbed and its reinforcement with shaped grass concrete, cemented bricks or concrete embankments from the 1970s to the 1990s. Ploughing of the whole floodplain and exploitation of the adjacent land up to the edges of the newly constructed channel has led to the destruction of the floodplain ecosystem and to the loss of its natural ecological functions. However, since the late 1990s, a considerable part of the floodplain has been transformed into meadows and pastures; this transformation can be considered a positive change in terms of ecological stability of the floodplain in the given area. On the other hand, it should be noted that even this type of land use is not optimal, as pastures can have a negative effect on freshwaters' chemical conditions. The actual channel of the Stropnice River, nonetheless, remains in an unsatisfactory status—it has been artificially straightened and provided with embankments, which prevent the natural biological and geomorphological evolution of the stream. Figure 1 shows the location of the study area.

## 2.2. Data Sources for Floodplain and Riparian Area Delineation

The results of a field mapping conducted in the period 2009–2014 (and extended in 2019) within the selected catchment area represent an important source of data for a large part of our analyses. Since the object of our study was the fluvial ecosystem, we needed to delineate the floodplain lining

the analyzed streams before performing our own field survey. For the floodplain delineation, we used selected thematic data (soil and geological maps) and other data related to the morphometric properties of the relief. Maps of soil ecological units (SEUs) in the scale of 1:5000 represent the most detailed source of data on the soil cover of the Czech Republic. This is the data on characteristics of agricultural areas, assessed according to climatic conditions, the status of the soil and terrain configuration. One major disadvantage of the SEUs is that they are available only for an area belonging to agricultural land resources. For the purpose of floodplain delineation within forested areas, forest typological maps (1:10,000) were used; these maps also show the basic soil and moisture conditions of the studied sites. Possibilities of spatial delineations of floodplains and ecosystems of river landscapes in the conditions of the Czech Republic, with particular regard to small watercourses, are outlined in more detail by Jakubínský et al. [39].

Since the closest link between the stream and the surrounding landscape is achieved in the area adjacent to the banks of the stream, and the intensity of interactions decreases with increasing distance, the quality of mutual interactions was solved mainly within the so-called “riparian zone”, which is the transitional area between the aquatic and terrestrial part of the floodplain (e.g., [40–42]). Mostly, the riparian zone includes a steep bank sites whose vegetation extends to the edge of the riverbed, depending on the character of land use in the surrounding landscape. The riparian zone has a minimum width of 5–10 m, and this measurement does not usually depend on the riverbed width [43,44]. According to Erftverband (non-profit organization operates in the river Erft region, Germany) [45], the maximum width of the riparian zone should not exceed 15 m. Matoušková [46] suggested that the minimum width of the riparian zone for small- and medium-sized streams should be 10 m.

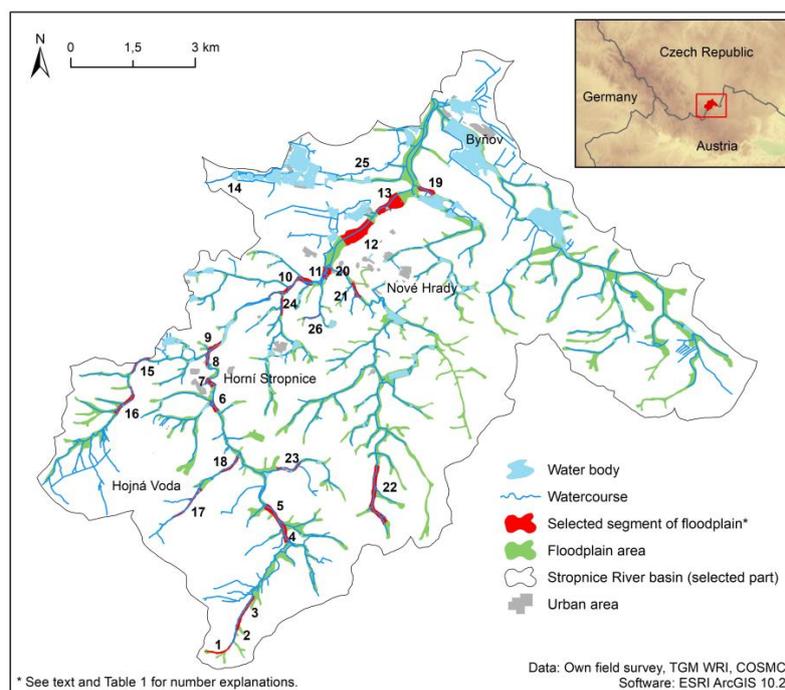
Considering the local conditions of the study catchment, a width of 5 m was selected as the optimal size of the riparian zone. As a further step, we chose 26 floodplain segments in various parts of the catchment representing the specific conditions forming the current status of the river network (a list of the segments selected is given in Table 1). All individual segments are homogeneous in terms of the current hydromorphological status and the prevailing erosion and aggradational processes. The exact position of boundaries between the individual watercourse (and riparian area) segments were determined on the basis of a change in the character of the riverbed’s hydromorphological features, especially the channel forming material (e.g., at the boundary between an anthropogenically modified channel and a relatively natural channel). Figure 2 shows the locations of the defined segments. The main reason for selecting the given segments is the effort to capture the typical conditions prevailing in the selected river basin—i.e., to select an approximately equal number of segments in the upper; middle and lower parts of the catchment (sediment source, transfer and accumulation zone of the river), which, at the same time, will be homogeneous throughout their length in terms of the riverbed hydromorphological characteristics and the use of the surrounding landscape. The individual segments were numbered in the direction from the headwater area towards the lower parts of the basin, with the main watercourse (i.e., the Stropnice River) being numbered first.

The above-described areas (floodplain segments) were used to determine the environmental status of the floodplain. Geometrical parameters of the riverbed (i.e., the channel and riverbed width and degree of channel incision) were measured using a laser distance meter (Toolcraft LDM 70, Toolcraft Inc., Marion, NC, USA) and manual inclinometer during the field survey. The determination of the quality elements of the hydromorphological status was carried out based on an expert estimate according to the approach used (i.e., the hydro-ecological monitoring (HEM) methodology described in more detail in Section 2.3.1.). The GIS (Geographic Information System) layer of the habitat valuation method [47] was used to calculate the habitat values in the riparian zone and in the entire floodplain. The forest typology base (specialized maps of forest types) and geobiocenological procedures (e.g., [48]) were also used to clarify the interaction of watercourses and vegetation cover. The basic data characterizing the individual segments of streams (i.e., their length, the location within the catchment, the floodplain area, various habitats within the given river segment, etc.) were identified by applying GIS tools (basic

geoprocessing tools such as “clip”, “intersect”, “dissolve”, etc.) to the data freely provided by the Czech Office for Surveying, Mapping and Cadastre and by the T. G. Masaryk Water Research Institute (within the Digital Database of Water Management Information [49]).

**Table 1.** List of selected floodplain segments in the Stropnice River catchment.

Segment Number	Stream Name	Length (m)	Fluvial Process Zone
1	Stropnice River	598	Source
2		678	Source
3		840	Source
4		647	Transfer
5		599	Transfer
6		321	Transfer
7		383	Transfer
8		324	Accumulation
9		503	Accumulation
10		1425	Accumulation
11		347	Accumulation
12		793	Accumulation
13		671	Accumulation
14	Janovský Stream	386	Transfer
15	Bedřichovský Stream	678	Accumulation
16		880	Transfer
17	Pasecký Stream	1011	Source
18		689	Transfer
19	Dvorský Stream	577	Accumulation
20	Veveřský Stream	205	Accumulation
21		433	Accumulation
22		1582	Source
23	Váčkový Stream	695	Accumulation
24	Nameless stream (near Světví Village)	459	Accumulation
25	Millrace from Janovský Stream	212	Accumulation
26	Nameless stream (left-bank tributary)	473	Transfer



**Figure 2.** Floodplain area and selected study segments in the Stropnice River catchment.

### 2.3. Approaches Used

#### 2.3.1. Determining the Hydromorphological Status

In order to analyze the current hydromorphological status, the methodology for monitoring hydromorphological indicators related to the ecological quality of watercourses (“hydro-ecological monitoring” (HEM)), continuously being developed at Charles University in Prague [50] within the implementation activities of the WFD, was applied to the field survey data. Based on the classification of hydromorphological assessment methods developed during the REFORM project (Restoring Rivers for Effective Catchment Management [51]), the HEM method belongs to the category of “morphological assessment”. Other categories defined include (1) physical habitat assessment—e.g., RHS (River Habitat Survey) in England [52], LAWA (Verfahrensempfehlung zur Gewässerstruktur-kartierung) in Germany [53] or RBP (Rapid Bioassessment Protocol) in the USA [1]; (2) riparian habitat assessment—e.g., Riparian Quality Index (RQI) in Spain [54]; (3) hydrological regime assessment—e.g., IARI (Indice di Alterazione del Regime Idrologico) in Italy [55] and (4) fish longitudinal continuity assessment—e.g., QSS (Guidance on hydromorphological assessment of rivers) in Austria [56]. According to the authors of [51], methods for a morphological assessment differ from other categories of assessment methods, defined as they have a broader geomorphological perspective and give a greater consideration to physical processes (e.g., hydrological and sediment continuity, sediment transport, erosion and channel adjustments) and alterations derived from human pressures.

This methodology is the national evaluation approach recognized by the Ministry of Environment of the Czech Republic. Monitoring of the hydromorphological status of the streams is carried out in the form of field mapping of selected hydromorphological characteristics of the riverbed, riparian zone and the floodplain. The assessment is based on the principle of scoring the individual indicators that are analyzed in terms of their impact on the hydromorphological quality. The result represents an arithmetic average of the values for all zones. The value obtained is then classified into one of the five levels of the hydromorphological status defined by the WFD requirements. In accordance with the requirements of the Water Framework Directive 2000/60/EC, the individual parameters of the HEM methodology were further classified into three hydromorphological quality elements: hydrological regime, flow continuity and morphological conditions. A list of all indicators is given in Table 2.

**Table 2.** List of indicators entering the hydromorphological evaluation according to the hydro-ecological monitoring (HEM) methodology [50]. WFD: Water Framework Directive.

Indicator Used	WFD Hydromorphological Quality Component
Nature of flow (NTF) Influence of hydrological regime (IHR)	Hydrological regime
Longitudinal profile capacity (LPC) Throughput of the inundation area (TIN)	River continuity
Channel pattern adjustment (CHA) Channel width variability (CHV) Longitudinal profile depth variability (LDV) Cross section depth variability (CDV) Riverbed modifications (RBM) Large woody debris in the river (LWD) Riverbed structures (RBS) Riverbed material (RBL) Bank modifications (BKM) Bank (riparian zone) vegetation (BKV) Usage of riparian zone (URZ) Usage of the river floodplain (UFL) Bank stability and lateral channel migration (BST)	Hydromorphological features

A score is determined for each indicator listed in Table 2, based on the classification procedures given for each indicator, either universal or type-specific. Individual indicators are scored on a scale of 1–5, with 1 representing the best and 5 the worst status. The scoring principle reflects the basic requirements of the WFD, where the highest hydromorphological quality is achieved when the status of the river corresponds to potentially natural conditions with the highest variability corresponding to the characteristics of the environment. For each evaluated parameter, the methodology HEM describes the source data needed for the determination, the principle of evaluation, the scoring procedure and gives the scoring matrices needed to determine the final score. The hydromorphological quality of a segment is calculated as a weighted average of the scores calculated for each indicator based on the scoring tables valid for each indicator [50]. The classification of the hydromorphological status is done by assigning the calculated value of the hydromorphological quality of the segment to one of the five hydromorphological status classes according to the limit values corresponding to the intervals defined by the CNS (Czech National Standard) based on European Standard EN 15843 (see Table 3). Own calculation of the hydromorphological status (HMS) of watercourses is based on the following equation:

$$\text{HMS} = (\text{CHA} \times W_{\text{CHA}} + \text{CHV} \times W_{\text{CHV}} + \text{LDV} \times W_{\text{LDV}} + \text{CDV} \times W_{\text{CDV}} + \text{RBL} \times W_{\text{RBL}} + \text{RBM} \times W_{\text{RBM}} + \text{LWD} \times W_{\text{LWD}} + \text{RBS} \times W_{\text{RBS}} + \text{NTF} \times W_{\text{NTF}} + \text{IHR} \times W_{\text{IHR}} + \text{LPC} \times W_{\text{LPC}} + \text{BKM} \times W_{\text{BKM}} + \text{BKV} \times W_{\text{BKV}} + \text{URZ} \times W_{\text{URZ}} + \text{UFL} \times W_{\text{UFL}} + \text{TIN} \times W_{\text{TIN}} + \text{BST} \times W_{\text{BST}}) / 4 \quad (1)$$

where in all indicators abbreviations are listed in Table 2, and “W” denotes the weight assigned to the given indicator (i.e., “ $W_{\text{CHA}}$ ” means the weight determined for indicator of channel pattern adjustments in the relevant category of watercourses, grouped on the basis of prevailing natural conditions). The weights are not used to express the hierarchy of indicators but to capture the type-specific differences in their importance for the hydromorphological quality of the watercourse in different natural conditions. The procedure for determining the weights and their list is given in [47].

**Table 3.** Classification of hydromorphological status based on the hydromorphological quality computed according to the European Standard EN 14614 [50].

Score Value	Class	Hydromorphological Status
1.00–1.49	1	Near to natural
1.50–2.49	2	Slightly modified
2.50–3.49	3	Moderately modified
3.50–4.49	4	Considerably modified
4.50–5.00	5	Heavily modified

According to Kampa and Bussetini [57], the HEM methodology is relatively well-suited to the demands of the WFD and standards for assessing the hydromorphological status, particularly in the field of hydromorphological parameters. However, on the contrary, the method less reflects the monitoring and evaluation of the hydrological regime. Although an instruction manual is provided, field survey is partially subjective, especially in the estimate of the areal characteristics. The methodology is described in more detail in, e.g., [57,58]. The complete methodology was published by the Ministry of the Environment of the Czech Republic.

### 2.3.2. Evaluating the Landscape Environmental Status

The biotope valuation method (BVM) [44] was used to evaluate the environmental conditions of the landscape within the study area. This method is based on the interdisciplinary assessment of all habitat types occurring in the Czech Republic (192 habitats in total). The complete list of habitat types is based on the 139 natural and close-to-natural habitats of the Habitat Catalogue of the Czech Republic [59] and on the 53 man-made habitats defined by Seják et al. [47]. To each habitat type

belongs a specific value obtained by analyzing eight environmental characteristics using metrics listed in Table 4. The acquired point value (score) of that habitat type (related to 1 m<sup>2</sup> area) shows the relative ecological importance in comparison with other habitat types. Through combining the ecological functions and the restoration costs of respective biotopes, an approach has been developed in the Hessian federal state of Germany and modified in the Czech Republic for the assessment and economic evaluation of environmental assets and their life-supporting quality. This so-called Hessian method was recommended in 2000 for dissemination by the EU White Paper on Environmental Liability that preceded Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability. The Hessian method is based on interdisciplinary expert valuations of all the types of habitats that exist in the respective national territory. In order to identify and protect biodiversity and ecosystem functions and services [60,61], a complete list of habitat types for the Czech Republic was drawn up. Each habitat type has been valued by an interdisciplinary team of ecologists from different scientific backgrounds using points according to eight ecological characteristics, each of them with a potential score ranging from one to six points.

**Table 4.** List of characteristics entering the habitat type evaluation according to the biotope valuation method (BVM) methodology and principle of its determination [47].

Ecological Characteristics	Scoring Principle
Habitat maturity (HM)	Phylogenetic age of plant species in plant community
Habitat naturalness (HN)	6 points to natural or semi-natural; 1 point to anthropogenic habitat
Diversity of habitat spatial structure (DSS)	6 points if all possible vegetation floors are present
Diversity of habitat species (DTS)	Number of autochthonous plant species
Rareness of habitat (RH)	Geographical and climatic uniqueness, scarcity, frequency and spatial extent
Rarity of species of habitat (RS)	Number of rare and threatened plant species on the red list (IUCN Red List)
Vulnerability of habitat (VH)	Rate of habitat endangerment through the change of habitat conditions due to land use change
Threat to existence and quality of habitat (TQ)	Unfavorable tendency of development of the given habitat

The sum of points achieved in the first four characteristics in Table 4 (habitat quality) was multiplied by the sum of points achieved in the four remaining characteristics (of rareness and vulnerability). The result obtained was divided by the maximum of points (576) and multiplied by 100.

$$\{[(HM + HN + DSS + DTS) \times (RH + RS + VH + TQ)]/576\} \times 100 = \text{BVM value} \quad (2)$$

The score of a respective habitat type shows its relative ecological significance compared to other habitats. A complete list of habitat types for the territory of the Czech Republic was created (based on NATURA 2000 natural or close-to-natural habitats, extended by underground water habitats and man-made habitats), including their respective scores, showing the ranking of habitats according to their ecological quality (the habitat's life-supporting potential). The BVM methodology is described in more detail in Seják and Cudlín [62]. Data from the analyzed river segments were obtained as the sum of scores of individual habitat types (depending on their area) occurring in the relevant floodplain segment. The information gathered from aerial photographs using GIS analysis and verified by a subsequent field survey was used to determine the exact position of the boundaries of individual habitat types.

The data concerning the hydromorphological status of the river network and environmental conditions of the floodplain were further classified into several categories, depending on the intensity of the analyzed phenomena. The aim of this approach was to simplify the classification of the resulting values and, thus, to facilitate the interpretation of the observed phenomena. We have defined four categories according to the degree of anthropogenic influences (see Table 1) based on the results achieved by applying HEM methodology. The environmental status of the floodplain determined by the BVM was also categorized according to the same principle. Even in this case, the rate of anthropogenic influence of the habitats—from natural to entirely unnatural (man-made) habitats—was used as a key parameter for the five categories (Table 5).

**Table 5.** List of categories defined according to the level of the anthropogenic impact on the hydromorphological status of the stream, with respect to the environmental status of the floodplain.

Category	Hydromorphological Status of Stream Segments
1	Minimally affected by human activities, in an almost natural status
2	Influenced by human activities but with preserved natural parameters (e.g., riverbed dredging)
3	Significantly influenced by man—unnatural (man-made) geometry of the channel and its pattern but with preserved connectivity of stream with its surrounding
4	Entirely degraded segment with unnatural (man-made) channel geometry and pattern, without connectivity with its surrounding (concreted or covered over channels)
Category	Environmental Status of Floodplain
A	Natural habitats
B	Close-to-natural habitats
C	Distant-from-natural habitats
D	Alien-to-natural habitats (mostly man-made habitats performing some natural functions)
E	Unnatural (man-made) habitats

### 3. Results and Discussion

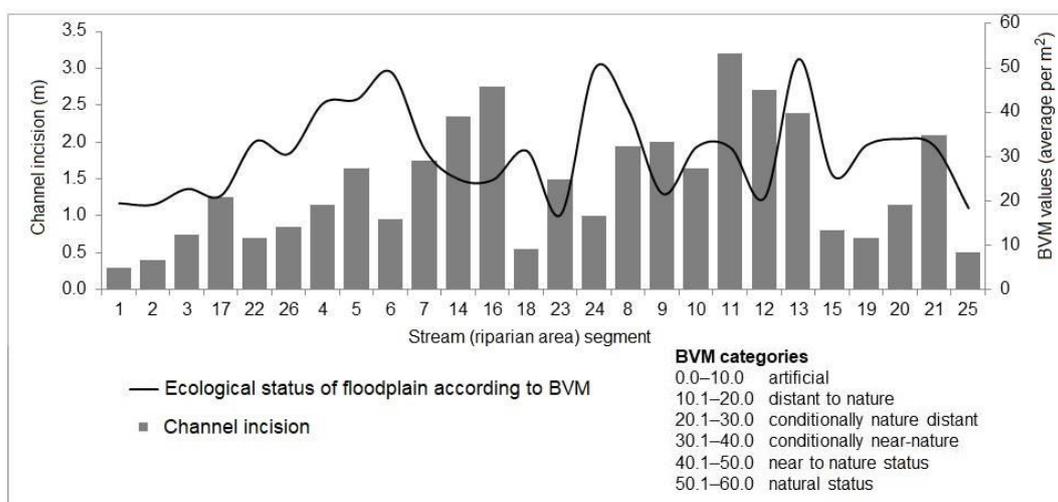
All acquired data described in the methodological part were used for the analysis to understand better the nature of the relationship between the observed variables. This primarily involved the identification of mutual relationships between the hydromorphological status of the river network and the ecological status of land adjacent to the stream.

Generally, a more degraded (distant-from-natural) riverbed status became common in the segments located within a more spacious flat valley floor, often near urban areas (the “hydromorphological quality” parameter surveyed according to the HEM methodology exceeded the value of 2.5, which corresponds to average and worse conditions under the WFD classification). Usually, these are the segments with artificially straightened and, often, unnaturally incised channels, where the riverbed and banks have been fortified with concrete, prefabricated components or vegetation blocks. Conversely, segments in the headwater stream part of the catchment in the Novohradské Mountains have a particularly good hydromorphological status. These segments are located at hard-to-reach locations, which are covered almost exclusively by forest stands. The studied part of the Stropnice River and its tributaries usually reached a hydromorphological quality (HEM) of around 1.5 point. This corresponds to a very good status.

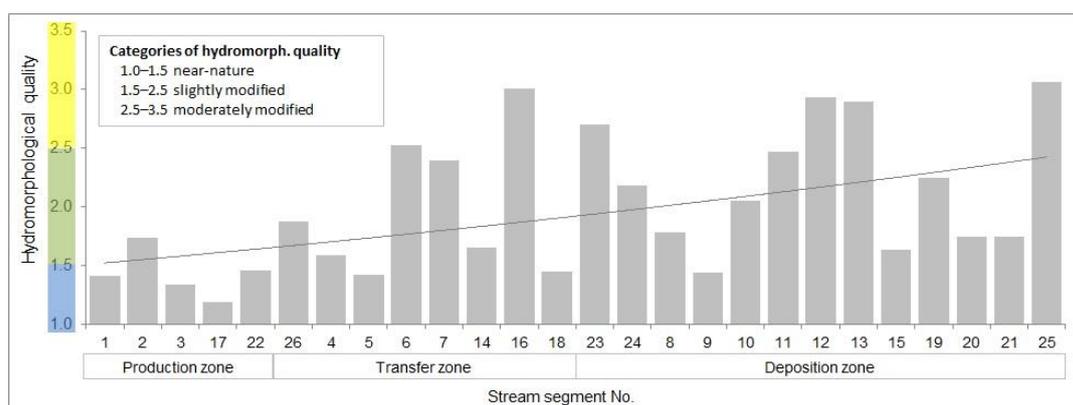
A different situation occurred when evaluating the environmental status of floodplain lining the river network in almost its entire length. When evaluating the habitats in accordance with the BVM method [47], we found that the floodplain reached the highest values at the lower-course stream, marginally also at the middle course, typically in the segments with a more significantly developed alluvial ecosystem in terms of its width dimensions. Despite the fact that these floodplain segments are often intensively used by man, the various habitat types occurring here showed a slightly increased diversity (the BVM values vary around 45.0—i.e., they reach about half of the maximum habitat value identified in the Czech Republic).

In addition, habitat naturalness, one of the most important features in assessing the floodplain environmental status according to the BVM methodology (from a total of eight indicators), was selected and analyzed in detail for each floodplain and bank zone segment. Habitat naturalness assesses the presence of synanthropic species, which is expressed as a percentage of their numerical representation in the relevant vegetation floor in the area of habitat considered (more information about the principle of determining this naturalness is given by Seják et al. [47]). The results of the analysis of naturalness (Figure 3) show that the actual level of naturalness in the various floodplain segments was quite variable, and in some cases, it reached almost the maximum possible value 6 points. Whereas the naturalness values appear to be average in the upper-course transport segments, when elevation decreases (lower-course transport segments and aggrading segments), variability tends to increase, and segments with almost minimal naturalness and segments with close-to-natural habitats occur more frequently.

The second working hypothesis of this study was the existence of a direct link between the degree of riverbed incision, measured as the difference between the lowest reached elevation of the river bottom and an average elevation of bank edge on the two opposite banks, and the environmental status of the bank zone and adjacent floodplain. However, based on the data analysis from the study area, the validity of this hypothesis was not confirmed—the results showed a very low degree of dependence between the riverbed incision and the ecological quality of habitats in the floodplain. This could be due to the presence of significant anthropogenic disturbances in the floodplain area and the riverbed itself, causing frequent discrepancies between the current hydromorphological status of stream, expressed by the level of incision, among others, and the ecological status of the surrounding floodplain. All the above discussed characteristics and their values for the study segments are displayed in the graphs in Figures 4 and 5; individual segments are sorted in descending order from the uppermost locations at the headwater streams to the lowland aggradational areas.



**Figure 3.** Ecological status of floodplain habitats based on the BVM methodology and the average riverbed incision in individual segments.



**Figure 4.** Hydromorphological status of streams (its segments) according to the hydro-ecological monitoring (HEM) methodology [50]; the lower, the better.

This study focused mainly on the analysis of the relations and interactions between the hydromorphological status of the river network and the ecological status of the relevant floodplain segments (shown in Figure 2). This data can be obtained mainly through principal component analysis (PCA), which allow us to identify patterns in data based on the correlation between features and aims to find the directions of maximum variance in high-dimensional data and projects it onto

a new subspace [63]. Data on the hydromorphological status (outputs of the HEM methodology), the naturalness of floodplain and riparian zone (one of the indicators determined within the BVM method), as well as the ecological stability of these areas, were used as input variables for PCA. The ecological stability was determined according to Míchal [64] as a ratio between the area of ecologically stable land-use categories (forests, meadows, pastures and water bodies) and ecologically unstable categories (urban areas and arable land). The outputs show that the first three components explain 88.6% of the total variability, with the largest part being hydromorphological features (1st component, 46.8%), naturalness of the floodplain (2nd component, 24.9%) and ecological stability of the floodplain (3rd component, 16.8%). The outputs of the analysis provided information about the existence of several specific types of interactions between the channel features and the ecological status of the surrounding landscape (outputs of the PCA is shown in Figure 6). According to these parameters, the stream segments, which share similar features and types of interaction between the fluvial and terrestrial parts of the river landscape, can be aggregated into several groups (Table 6 and Figure 6).

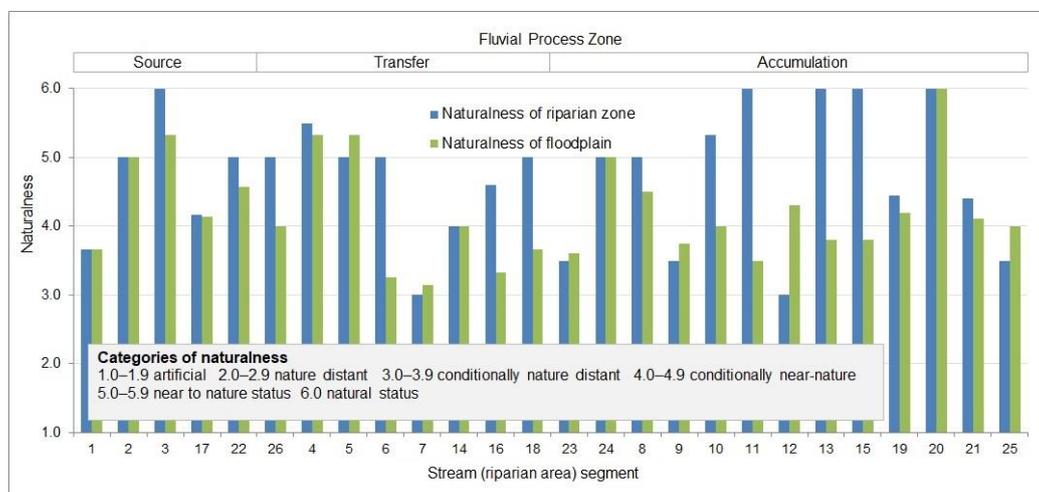


Figure 5. Naturalness of riparian zones (corridor) and floodplain areas of the relevant stream segments based on the biotope valuation method (BVM) [47].

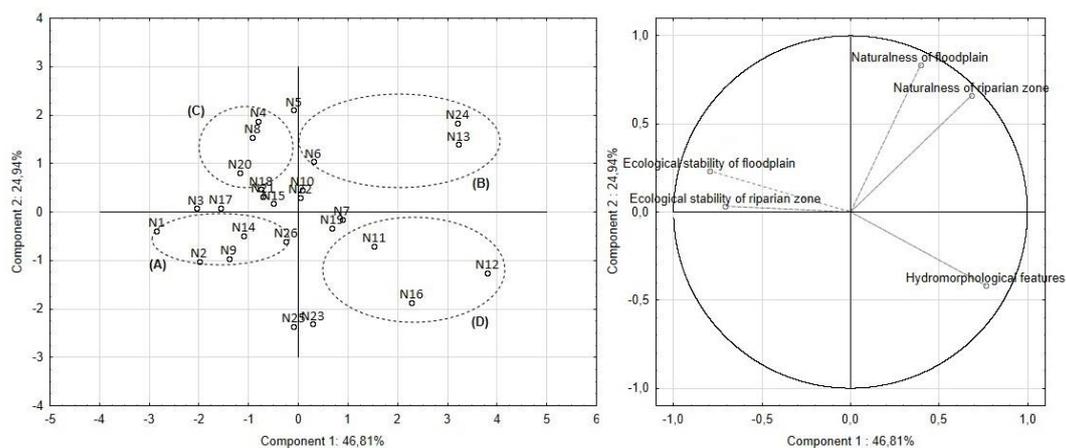


Figure 6. Projections of individual cases (analyzed stream segments N1–N26) into the principle component analysis (PCA) plot, including the four designated sets of identified categories (on the left) and resulting vectors (1st to 5th principal components) of the main parameters considered (on the right).

**Table 6.** Identified categories of the stream segments, grouped on the basis of a combination of qualitative parameters of the floodplain (BVM) and watercourse (HEM) status (1 = good, 2 = moderate and 3 = worse status; the key to determining the values is given below the table).

Segment Category	Hydro-Morphological Status *	Average Value (HEM)	Environmental Status of Floodplain **	Average Value (BVM)	River/Floodplain Segments (No.)
A	1	1.86	3	22.37	1, 2, 9, 14, 26, 25
B	2	2.23	1	43.33	24, 13, 6, 10, 22
C	1	1.55	2	32.52	4, 8, 20, 18, 21, 15, 3, 17, 5
D	3	2.51	3	26.43	12, 16, 11, 23, 19, 7

Note: \* hydromorphological status 1—HEM value < 1.99, 2—HEM = 2.00–2.49 and 3—HEM > 2.50. \*\* environmental status 1—BVM value > 40.0, 2—BVM = 30.0–39.9 and 3—BVM < 29.9.

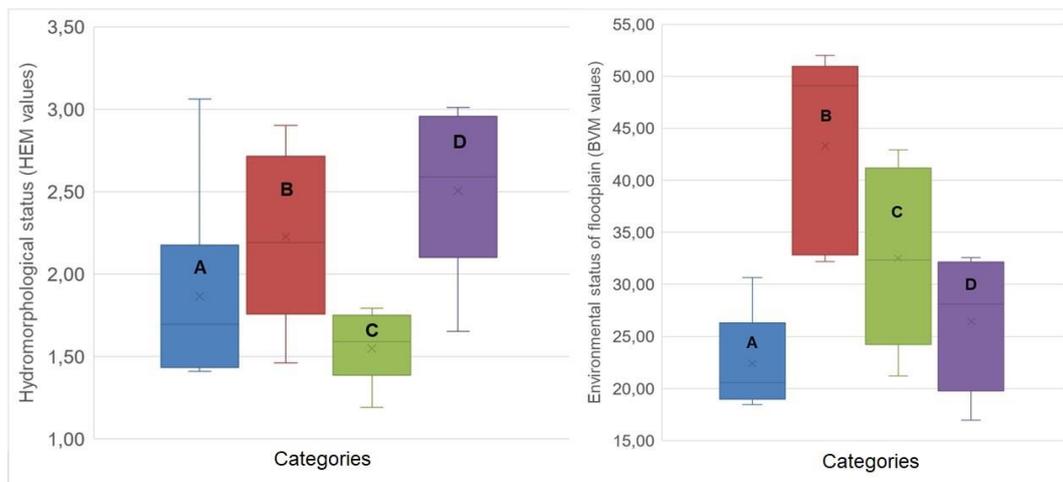
The first group (Type “A”) represents segments with good to very good hydromorphological status of the riverbed (determined by the HEM methodology) and low ecological status of the surrounding landscape (in terms of habitat value based on the BVM methodology). A typical feature of this group is the predominance of continuous forest stands in the floodplain, formed mainly by commercial forests (mostly spruce monocultures). Although these locations are characterized by a low representation of habitats valuable from a biodiversity point of view, a major positive aspect is their essential contribution to the ecological stability of this area.

The second identified group (Type “B”) is represented by floodplain segments characterized by a relatively degraded hydromorphological status of riverbed and a good environmental status of some floodplain habitats (BVM values > 45.0), which are, however, mixed with habitats of lower ecological value. This is due to the partial restoration of the terrestrial part of floodplain, which took place in this area in the 1990s and resulted in the current disjointed status of the floodplain and of the relevant channel segments. Due to the very specific conditions necessary for the above-described relationship, the stream (floodplain) segments of this category are relatively rare.

The third defined category (Type “C”) is represented by stream segments that do not reach the highest values; however, they generally have higher values at all analyzed variables—i.e., the riverbed morphology and the mosaic of valuable habitats in the floodplain are in a relatively good status. At present, this is an ecologically stable part of the landscape. This situation was identified typically in the middle-course stream segments with prevailing aggradational processes within the riverbed, where the floodplain reaches a width of tens of meters. These are commonly foothill locations with a sudden decrease in the entraining ability of the stream (particulate matter movement) due to a lower slope. The typical habitat in this category is a mosaic of alluvial ash-alder meadows with monocultures of ecologically unsuitable stands or degraded forest stands with ruderal communities, sometimes supplemented with wet *Cirsium* meadows. The relatively good hydromorphological status is primarily due to a very limited extent of the valley floor, whose area is additionally reduced due to the belt of a meandering stream that does not provide sufficient space for intensive commercial land use.

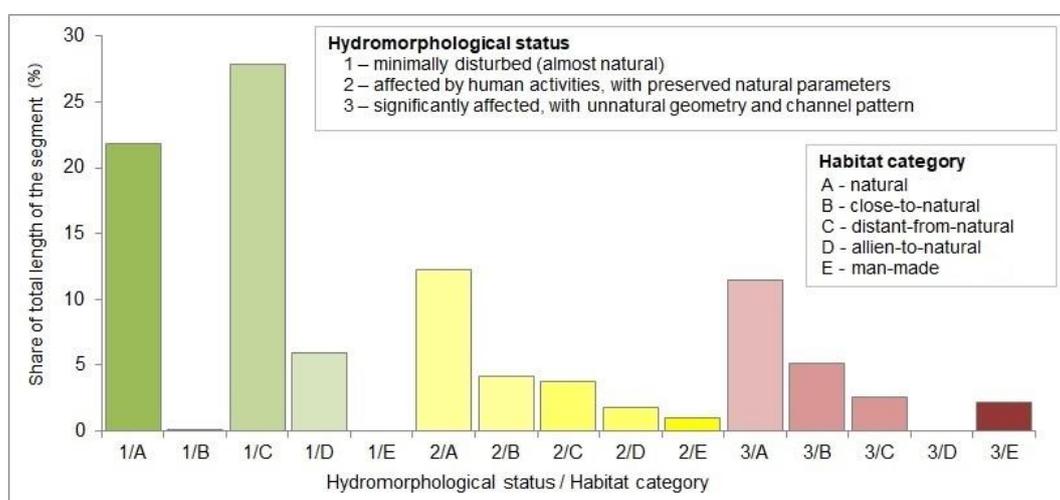
The last, fourth defined category (Type “D”) are segments of floodplain for which the overall degradation of the fluvial environment is typical, both in terms of the hydromorphological status of the streams and the environmental status of the surrounding floodplain. The majority of such segments can be found in the lower and middle course stream, occurring in a wide, intensively exploited floodplain. A typical feature of these segments is an artificially straightened and incised riverbed, lined with a narrow “ecotone” of bankside vegetation that gives way to agricultural crops on arable land covering the vast majority of the floodplain ecosystem. The land cover usually consists of large contiguous blocks of arable land, interrupted only by the axis of a watercourse or transport infrastructure (road embankment) and, to a lesser extent, of pastures or small water bodies. Among the most common habitats within the segments discussed are mainly the annual and perennial cultures on arable land, alluvial ruderal fallows, fallows with scrub growths and trees and urban areas with minimal vegetation cover. Table 6 provides an overview of the observed parameters, including the representation of their quality and the values achieved within the four defined categories (types of

stream segments). The range of values detected for the hydromorphological status of streams and ecological status of the floodplain is shown in the box plots in Figure 7.



**Figure 7.** Descriptive data (box plots) for the four identified groups (categories A–D) of stream segments, differing in terms of the prevailing hydromorphological status of the stream and the environmental status of the floodplain.

Based on the categorization of the hydromorphological status of the stream and the ecological status of the floodplain, the mutual comparison of a pair of the analyzed variables (presented in the graph in Figure 8) was performed. The graph shows that the most prevalent part of the river network in the upper Stropnice River catchment has good hydromorphological conditions (a “close-to-natural” status), only marginally affected by human activities (1st Category—A). The first category mentioned includes stream segments with a total length of approximately 8.53 km. Roughly, an equal proportion belonged to segments affected by man but with preserved natural parameters (2nd Category—B) and to segments significantly degraded by human activities (3rd Category—C). Almost entirely, degraded river segments with unnatural geometry and channel patterns and without any connectivity of the riverbed with its surroundings (concreted or covered over channels, 4th Category—D) were absent in the catchment.



**Figure 8.** Representation of the individual hydromorphological status categories (1–3) and the environmental status of the floodplain (A–E).

The majority of stream segments with minimally influenced environmental values of the surrounding floodplain were represented in the study area—i.e., the category of “natural habitats” (Type A), which generally included nearly 7.00 km of the river network. The segments classified as having “few natural habitats” (Type C) occupied a relatively large scale (roughly 5.24 km of the study river network). Based on a synthesis of the results from both categorizations, we can conclude that the largest share (27.8%) of the total length of the analyzed stream segments was attributable to the floodplain formed by the few natural habitats, where the stream has very good hydromorphological conditions (1/C Category). The natural floodplain habitats with a river network in a very good status (21.8%, 1/A Category) located in the upper part of the Stropnice River catchment represent the largest section of our study area. On the contrary, segments with entirely unnatural floodplain habitats and a stream significantly degraded by human activity (3/E Category) are hardly present (2.2%).

#### 4. Conclusions

Based on the results, we can conclude that the relationship between the morphological status of a river network and the ecological status of the appropriate floodplain area is significantly affected by external factors—mostly by human activity (in the case of the study area, the given linkage is clearly influenced in more than 90% of the total length of studied watercourses). Human activity is a common cause of loss of connectivity between the terrestrial (i.e., the floodplain) and fluvial (i.e., the riverbed) part of the river landscape, and this trend is particularly evident in segments with prevailing aggradational processes of the watercourse (deposition zone). In the segments with intensive sediment transport, where the riverbed is characterized by a greater slope and, thus, a higher entraining ability, it is typical to find minimal anthropogenic pressure on landscape use along the streams, which is indeed evident in the increased ecological stability; in terms of biodiversity values, a rather below average status tends to be typical. A specific development can be observed in the lower part of the reference catchment, characterized by intensive landscape use and a high level of stream degradation. Following our expectations, we found that the best biodiversity values only reach those habitats along the aggradational parts of streams in the intensively exploited landscape of the wider floodplains where the degradation of natural hydromorphological characteristics is typical. Despite the fact that the stream has significantly limited connectivity with its surroundings due to the overall channel profile modifications, it is possible to find a mosaic of ecologically more valuable habitats in the bank zone and in the floodplain. Such habitats have developed after the recent restoration of the terrestrial part of the river landscape.

The results of our study point to the absence of suitable conditions for the interaction of the watercourse with its bank zone. The degradation of the natural status is often caused by disturbances in the riverbed pattern, the hydromorphological features of the stream and the intensive exploitation of the surrounding landscape. Since the morphologic characteristics of rivers also contribute to their hydrological regime, the current hydromorphological status can be considered one of the prerequisites for the occurrence of certain specific alluvial habitats. Moreover, the degraded hydromorphological status may, along with the ongoing impacts of climate change, lead to a complete drying of the watercourse, which is periodically repeated in the most vulnerable stream segments. The phenomenon of intermittent streams is becoming increasingly common in Europe and elsewhere in the world [65,66]. In the Czech Republic, this problem is mainly related to small watercourses, whose hydrological regime however has not been monitored in the long term, and therefore, there is no accurate data on the number of watercourses subjected to this phenomenon. A possible solution is to use a “retrospective bioindication”, which allows identification of ephemeral or intermittent streams based on the presence of specific animal species [67,68].

Since the intensive land exploitation of the floodplain in roughly one-third of the study area has stopped, there is currently a spontaneous development of habitats in the riparian zone, which can be broadly described as a new post-agrarian wilderness. The results of the hydromorphological evaluation allow us to deduce the composition of potential natural habitats, which may exist in the

given hydric conditions and anthropogenic pressures. This information about the hydromorphological status can be used to determine the actual level of habitat naturalness in the river landscape. For the above reasons, the conditions are usually unsuitable for the formation and further development of natural and close-to-natural habitats within the bank zone of the study area.

The quantity and quality of potential interactions between the stream and its bank zone or floodplain are influenced mainly by two factors—the degree of channel incision and the character of channel-forming materials, which can also be used as key evaluation criteria to identify the segments with limited potential of an occurrence of natural habitats in the floodplain. Consequently, an awareness of locations with inadequate values in the above-mentioned factors in water management issues can be used for planning more effective restoration measures.

**Author Contributions:** J.J. wrote the main paper, performed most of the computations and prepared the figures. I.P. delineated the floodplain locations in the area of interest and commented on the manuscript in its initial phase. P.C. discussed the results and commented on the manuscript at all stages. All authors have read and agreed to the published version of the manuscript.

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