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A proposed quantitative method for assessing the impact of river regulation on its hydromorphological status

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Abstract: Changes in river channel morphological parameters are influenced by anthropogenic factors, such as climatic changes, river catchment management changes, and hydrotechnical development of rivers. To assess the intensity of individual pressures and the resulting changes in abiotic and biotic factors in the riverbed, water quality monitoring is conducted, including the assessment of the hydromorphological status. The assessment can be based on the River Habitat Survey (RHS) which is a synthetic method that includes the evaluation of habitat character and river quality based on their morphological structure.

The input data, which characterise any river include physical features of hydrotechnical structures, bed granulation, occurrence of bedforms, visible morphodynamic phenomena, and a sediment transport pattern. The RHS method allows to determine two quantitative indices used to evaluate the hydromorphological status: Habitat Modification Score (*HMS*), which determines the extent of transformation in the morphology of a watercourse, and Habitat Quality Assessment (*HQA*), which is based on the presence and diversity of natural elements in a watercourse and river valley.

The proposed method can be divided into three stages. The first assesses the river section hydromorphological indices, describing the degree of technical modification (*HMS*) and the ecological quality of the reach (*HQA*), using the RHS method. The second stage describes morphological changes resulting from the technical regulation and estimates indices for the regulated reach. Finally, we compare *HQA* and *HMS* indices before and after the regulation. This comparison is described by numerical indicators and related to reference values.

Keywords: habitat modification score, habitat quality assessment, hydraulic structures, river regulation, water management

INTRODUCTION

Rivers in their natural state, unaffected by technical treatments, are characterised by long-term invariability of basic channel parameters, such as width, depth, or bed inclination, which is referred to as the state of dynamic equilibrium. Natural channels left without engineering intervention can preserve stable conditions defined by a stable profile, cross-sections, and plan that depends on a normally established distribution of discharges and sediment transport, bed and bank material, scrubs and riparian forests, and valley slopes (Friedrichs, Armbrust and deSwart, 1998; Bilal, Xie and Zhai, 2020). The state of dynamic equilibrium does not exclude the occurrence of short-term morphological changes in the river channel resulting from a natural hydrological cycle, i.e. seasonal variations of water and sediment outflow from the river catchment during a year. These changes are usually small and oscillate around multi-year averages. Much larger morphological changes of the river channel are most often a consequence of extreme flood events, after which new conditions of dynamic equilibrium are directly established (Graf, 1998).

In the past, the lack of knowledge about the river regime, especially its morphology, led to imperfect technical solutions and hydraulic structures. Therefore, it is necessary to develop methodical guidelines to examine the morphological regime (Naprawa, 2017). The classification of hydromorphological river characteristics and hydrological regime are increasingly often perceived as principal integrating components for interdisciplinary examinations that helo to understand river behavior (Kondolf, 1995; Rinaldi *et al*., 2016). If a river hydrological regime does not undergo significant changes, then after some time the river will restore parameters of a stable channel. On the other hand, contemporary permanent changes of morphological river channel parameters are mainly influenced by anthropogenic factors, such as:

- climatic changes (Marchi *et al.,* 2010; Macklin, Lewin and Woodward, 2012);
- changes in river catchment management, which change the characteristics of water outflow and sediment transport from the catchment (change in hydrological regime of river) (Mosley and Jowett, 1999; Overeem, Kettner and Syvitski, 2013; Recking *et al*., 2016);
- river regulation (Djekovic *et al*., 2013; Salit *et al*., 2015; Korpak, 2020);
- construction of flood banks in river valleys (Bujakowski and Falkowski, 2019);
- hydrotechnical development of rivers (retention reservoirs, damming structures), which result in the loss of dynamic stability of a riverbed. It also changes local conditions for water flow and transport of bedload and suspended load (Liaghat, Adib and Gafouri, 2017; Biswas and Pani, 2021).

Water quality monitoring is used to evaluate individual pressures and resulting changes in the abiotic and biotic characteristics of a riverbed. The development of a water monitoring programm covers physical, chemical, hydromorphological and biological properties of waters, types of habitats, as well as pressures and impacts on water bodies. A competent body is the Inspection of Environmental Protection which conducts observations of hydromorphological elements to assess ecological status and ecological potential (Directive, 2000). Additionally, a regional legal framework is needed, e.g. the Polish Water Law (Ustawa, 2017). A hydromorphological status can be determined by, among other things, River Habitat Survey (RHS), which is a synthetic method that includes the assessment of habitat character and river quality based on their morphological structure. The main features of the method are precision and reproducibility of measurements. It provides an objective evaluation of the environment; the method generates low cost and simultaneously it is relatively simple in application. A structured system of test profiles provides a wide range of possibilities for the application of different statistical techniques.

The objective of the study was to check the possibility to use on a wider scale the hydromorphological state evaluation method in predicting the effects of engineering activities. These can be limited to technical but also to restoration measures. This issue is therefore adressed since there is no unambiguous methodology for describing the impact of planned modifications on the hydromorphological status. The proposed method can constitute a innovative supporting tool in planning and implementation of hydrotechnical investment projects. In uncertain situations it can be an argument supporting (or suggesting abandonment) of a given engineering task.

MATERIALS AND METHODS

RIVER HABITAT SURVEY METHOD

The hydromorphological status evaluation is considered one of the supplementary criteria in recognising the ecological quality of river channels, as well as the physicochemical quality of water (Armitage and Pardo, 1995; Kemp, Harper and Crosa, 2000; Szoszkiewicz *et al*., 2008; Kiraga and Popek, 2014). It is evaluated considering physical structure of a river and its valley (Szoszkiewicz *et al*., 2008). The hydromorphological quality of the habitat is predicted based on the occurrence of specific features and their diversity, including the presence of wildlife, both fauna and flora. When used for the evaluation of a hydromorphological status, the River Habitat Survey method (RHS) assumes a systematic data collection to describe the physical structure of watercourses within 500 m of a river reach based on both river channel and its valley characteristics, and the land-use of river corridor, such as slope, geological and geometrical properties of the site, and distance from the source. Input data may refer to hydraulic structures (Photo 1a, c, f), bedload granulation with the occurrence of bottom forms (Photo 1b), visible morphodynamic phenomena, flow regime pattern distribution (Photo 1d, e), and sediment transport conditions. The survey allows to determine about 400 parameters describing hydromorphological conditions of a river section. Another advantage of the RHS is a comprehensive description of a watercourse including its valley which extends to a distance of 50 m from the channel.

The method includes 11 spot-checks every 50 m within a reach. At the spot-check, the survey is performed, including data collection, connected with the cross-section and visible site features, and the assessment of river values as a natural ecosystem (Fig. 1). Then, survey data are introduced into a dedicated software. The RHS method is based on two numerical indices, reflecting a number of individual basic parameters:

- Habitat Modification Score (*HMS*), which quantifies the extent of transformation in a river's morphology;
- Habitat Quality Assessment (*HQA*), which is based on the presence and diversity of natural elements in a watercourse and river valley.

HQA and *HMS* indices related to reference conditions enable to determine the hydromorphological status class of the river reach in line with the national legislation and Water Framework Directive (Tab. 1).

The HQA describes the diversity of natural morphological elements of a river reach. Its numerical value depends on hydraulic, granulometric, and vegetation parameters of the site. High values show the high diversity of natural elements. The *HMS* indicates a total degree of anthropogenic changes of a river reach. It has a low value in the case the habitat has undergone limited anthropological alteration. *HMS* and *HQA* are inversely proportional. The *HQA* value is determined by granulometric and hydraulic parameters, such as bedload granulation, flow regime, bank and bottom naturally occurring morphological elements, and the diversity of water and riparian vegetation. High *HQA* values indicate a high diversity of natural elements in a river channel and its surrounding area. The *HMS* value is affected by such elements as the presence and size of water structures (piers, dams, culverts, abutments, etc.), bank profiles transformations (embanking, reinforcing, devastation, resectioning, plants mowing), and

Photo 1. River valley morphological elements included in the River Habitat Survey method: a) bridge piers (the Bystrzyca River), b) visible bottom granulation (the Bystrzyca River), c) concrete weir (the Piława River), d) hydraulic jump visible downstream the stone weir (the Bystrzyca River), e) transition from smooth to turbulent forms of water movement (the Kłodnica River), f) devastated bed and riparian concrete reinforcement (the Czarna River) (phot.: *M. Kiraga*)

bottom modifications (resectioning, reinforcing, outer materials introduction, dredging, etc.). The low *HMS* value indicates a relatively low level of anthropogenic impact on the reach.

It has to be mentioned that two ecologically similar river sections could be exposed to different anthropogenic influences. Human intervention may lead the section to gain natural features, for example reintroduction of fauna and flora native species, or oxbow lakes inclusion in the main channel course. Anthropogenic transformations of the habitat do not necessarily deteriorate the river hydromorphological status. If it was so, any modifications would be forbidden (Kiraga and Popek, 2014; Kiraga, 2020). The higher *HMS* value, the stronger transformation of the habitat. However, human efforts could also enhance the natural status of the habitat.

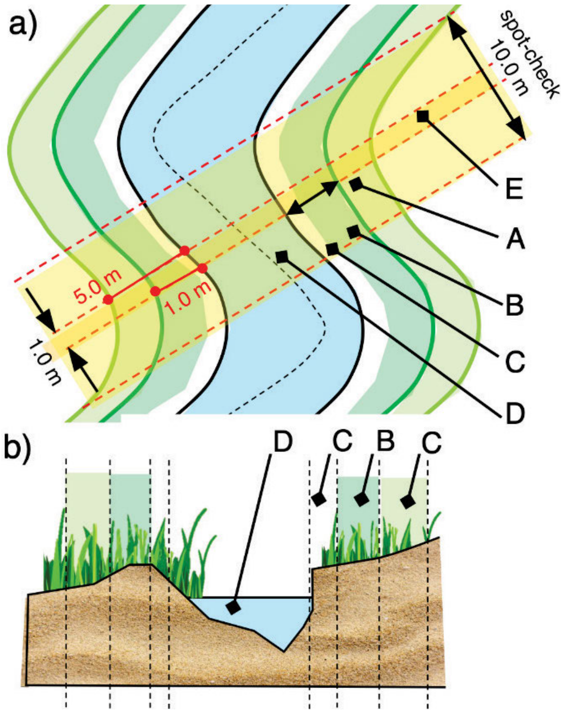

Fig. 1. Dimensions of sections examined using the River Habitat Survey method: a) plan view, b) cross-section; *A* = land use within 5 m of banktop, *B* = vegetation structure within 1 m of banktop, *C* = vegetation structure on the bank slope, *D* = channel vegetation, *E* = physical attributes; source: own elaboration

many instances, the introduction of technical facilities is indispensable for the development of a region.

The main factor reducing the ecological quality is the overall watercourse modification resulting from such activities as:

– straightening of river channels (Brooker, 1985; Gualtieri *et al.*, 2020; Zhou and Endreny, 2020);
– standardisation of cross-section dimensions and shape (Żelazo, 2006);
– elimination of irregularities along river bed and banks (Żelazo, 2006);
– devastation of ecotone vegetation (Gholami and Khaleghi, 2013);
– limiting the extent of flooding (Grizzetti *et al.*, 2017; O'Hare and White, 2018).

Water discharges and surface level volatility are crucial conditions that promote biodiversity and, consequently, the high ecological status of waters. The extensive sediment accumulation upstream of the hydraulic structures has unfavourable consequences for reaches affected by backwater afflux. It is then necessary to provide dredging. The most dangerous for the environment are the consequences arising downstream of structures due to local scouring (Graf, 1998; Kiraga, 2020). This process could result in the deepening of the river bottom, subsequent lowering of water level within the riverbed and its valley (Graf, 1998; Urbański, 2008), as well as degradation of its morphological structure (Wang *et al.*, 2018; Dias, Fael and Núñez-González, 2019; Liang *et al.*, 2020), and disturbance of ecotone zones (Kang *et al.*, 2011). The introduction of transverse

Table 1. Five classes of hydromorphological status based on index values: Habitat Quality Assessment (*HQA*) and Habitat Modification Score (*HMS*)

HMS: indicator value category	*HQA*: Indicator value category				
	very natural (*HQA* ≥ 57)	natural (*HQA* = 50–56)	moderately natural (*HQA* = 37–49)	weakly natural (*HQA* = 30–36)	slightly natural (*HQA* < 30)
Pristine/semi-natural (*HMS* = 0–2)	I	II	II	III	III
Predominantly unmodified (*HMS* = 3–8)	II	II	III	III	IV
Obviously modified (*HMS* = 9–20)	III	III	III	IV	IV
Significantly modified (*HMS* = 21–44)	III	IV	IV	IV	V
Severely modified (*HMS* ≥ 45)	IV	IV	V	V	V

Source: own elaboration based on Directive (2000).

ANTROPOGENIC IMPACT ON RIVER HYDROMORPHOLOGICAL STATUS

Water regulation includes longitudinal and transverse channel modifications and should ensure the maintenance of a dynamic equilibrium in the reach. Regulatory works, which have continued for centuries, caused the degradation of many large and small watercourses. Dredging and straightening of the riverbed, banks reinforcement, and cutting off the channel from the valley with dikes are processes that serve to improve water use and flood control or drought protection but they are perceived as highly destructive to both the environment of the river itself and its valley. Riverbeds are developed to promote economic growth, protect against flood, improve transportation, etc. Therefore, in structures, such as weirs or dams, prevents free migration of fish and other aquatic organisms,. This leads to a decrease in the hydrofauna diversity. The loss of valuable features of a valley is often caused by too frequent or largely unnecessary maintenance works, including extensive bank mowing, elimination of islands and other natural bedforms that result from sediment transport patterns varied in time, banks unification, and removal of native plant species. However, maintenance works carried out on an insufficient scale lead to an intensive erosion process, channel overgrowing, as well as to dangerously low river capacity. An example of inappropriate regulation of river channels and their valleys could be the elimination of ponds, oxbow lakes, and wetlands by covering them with soil, deforestation of riparian and valley areas, and planting of tree species unsuitable for valley conditions.

The construction process itself carries the risk of losing ecologically valuable features of river ecosystems (Ametepey and Ansah, 2014; Enshassi, Kochendoerfer and Rizq, 2014). The main causes of the loss of naturalness associated with the construction process include:

– excessive ground compaction by construction machines and vehicles movement, the storage of soil, construction materials, and equipment;
– additive erosion occurring downstream the construction site, often not included in hydraulic model studies;
– works related to the drainage, leading to excessive drying or a collapse of an area;
– tree and shrub removal to organise the construction site.

Human intervention can, however, help to improve the ecological quality of river sections, and restoration projects are a good example of this. In general, restoration is a long-term process that includes various technical operations and intrinsic river transformation, i.e. carried out by nature itself. Technical undertakings may include:

– conversion of erosion-inhibiting dams into ramps, allowing for aquatic organisms migration, as well as the removal of impermeable fortifications;
– works that do not form a finished element of a restored watercourse, but start a natural process of restoring the natural state, e.g. plants introduction;
– sustainable maintenance works, which consist of minor corrections of the natural transformation of the river reach (e.g. replenishment of dead or damaged trees and shrubs) (Jędryka and Kamińska, 2004);
– abandoning redundant activities in water maintenance and leaving the habitat to the influence of nature itself. This promotes morphodynamic processes, animal activity (e.g. beavers), and vegetation expansion to proceed freely (Wohl *et al.*, 2005; Żelazo, 2006).

Technical water regulation should respect the need to achieve good water quality and specific environmental objectives. Thus, it can be stated that river regulation should be a compromise between economic objectives of a project and non-deterioration of relative hydromorphological quality. However, there are no unambiguous tools to assess the change in the hydromorphological status of rivers due to their regulation. This paper aims to fill this research gap by proposing a method, which may provide a quantitative description of changes in the hydromorphological status of a river section due to its regulation.

RESULTS AND DISCUSSION

A PROPOSAL OF QUANTITATIVE INDICATORS FOR THE HYDROMORPHOLOGICAL STATUS CHANGES RESULTING FROM THE RIVER SECTION REGULATION

The proposed method of quantitative evaluation of changes in the hydromorphological status that result from the planned reach regulation can be divided into three stages. The first one is to perform the RHS within the chosen river reach in the form of field studies according to a spot-check key, and *HQA* and *HMS* evaluation using the River Habitat Survey Toolbox by Riverdene Consultancy. Then HQA_* and HMS_* indices are obtained for the reach where regulation works are planned. The second stage is to develop a regulation design plan, which could be compared with the natural river morphology (Fig. 2). Then the River Habitat Survey is performed at the modified site. The algorithm of the method is shown in Figure 3. Table S1 (https://www.jwld.pl/files/Supplementary-material-Kiraga-Markiewicz.pdf) summarises expected changes in cross-sections and along the entire section length. It should be emphasised, however, that the second stage, meaning the hydromorphological status assessment of the regulated reach, is only a prediction, a prognosis of the researcher, based on his/her knowledge of environmental and natural phenomena following various modifications of the river channel morphology. For this reason, it is important to involve experts in predicting such changes. The last stage is the comparison of the *HQA* and *HMS* indices based on the RHS survey and prediction, i.e. before and after regulation. This comparison is described by numerical indices (Fig. 4). The proposed diagram can serve as a supporting tool for an engineer evaluating the potential impact of river regulation on the hydromorphological condition of the channel and valley.

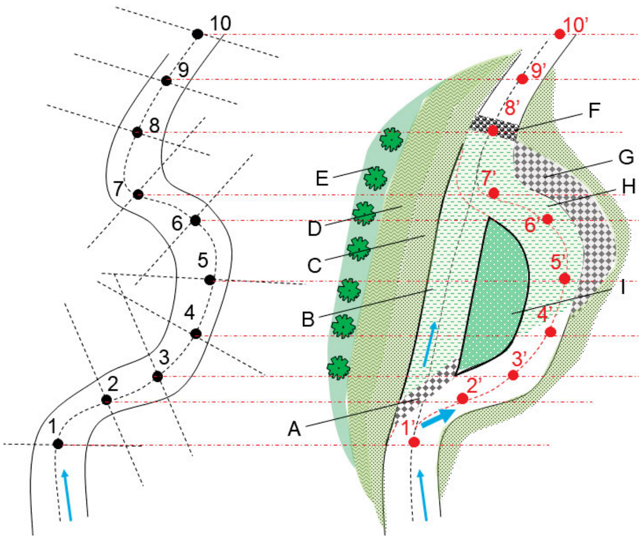

Fig. 2. Diagram based on the quantitative assessment method to asses the river section regulation impact on its hydromorphological status; *1–10* = River Habitat Survey cross-sections, evaluated according to RHS method assumptions (1st stage of the method); *1'–10'* = the assumed cross-sections, which consider channel and valley changes resulting from the regulation; *A* = gabion weir, *B* = secondary channel for the flood discharges, *C* = rough turf zone, *D* = shrubs zone, *E* = tree zone, *F* = stone weir, *G* = lateral stone embankment, *H* = biofilter vegetation zone (free water surface and emergent macrophytes), *I* = hydrophytic filtration island on stone bedding, reinforced with wooden piles; source: own elaboration

If the ratio of the Habitat Quality Assessment for the river reach after (HQA_*) and before regulation (*HQA*) is >1, it means an improvement of naturalness as a result of a technical measure. This in practice is impossible. The maximum value of this ratio would be 1.00, indicating no change in the habitat naturalness degree. Such a value would be achievable if regulatory works were limited to, for example, only local interference in riparian or channel vegetation structure. A HQA_*/HQA ratio of ⟨0.81; 1.00) represents a slight reduction in the Habitat Quality Assessment index. This usually translates reduction by a one-class hydro-

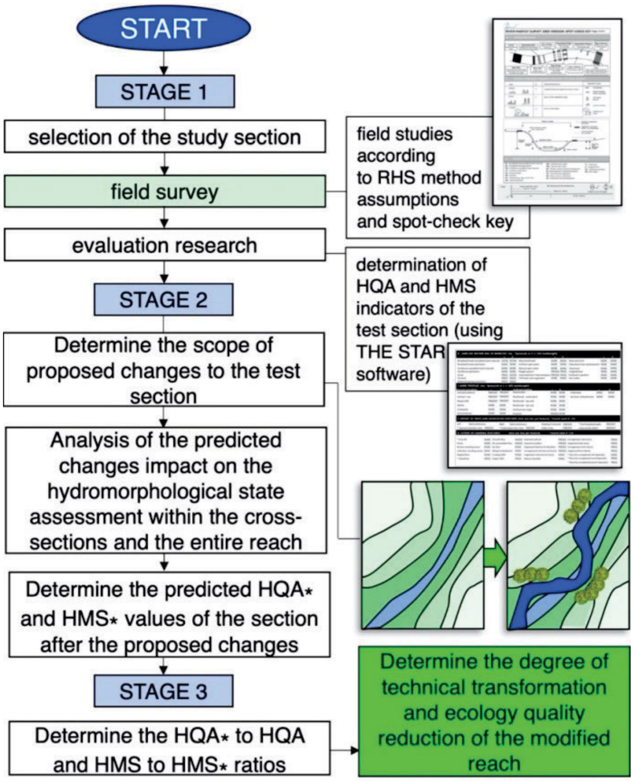

Fig. 3. The algorithm for the River Habitat Survey's application in the evaluation of planned engineering tasks; RHS = River Habitat Survey, *HQA* = Habitat Quality Assessment before regulation, HQA_* = Habitat Quality Assessment after regulation, *HMS* = Habitat Modification Score before regulation, HMS_* = Habitat Modification Score after regulation; source: own elaboration

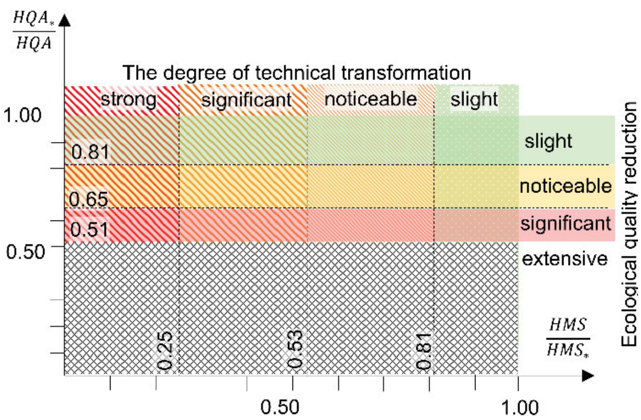

Fig. 4. Diagram for assessing the impact of the river section regulation on its hydromorphological status; *HQA*, HQA_*, *HMS*, HMS_* as in Fig. 3; source: own elaboration

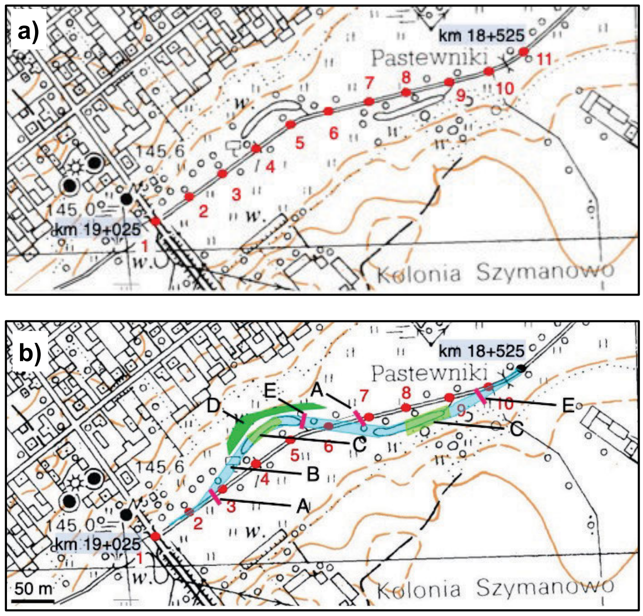

Fig. 5. Researched river reach of the Zielawa River: a) section undergoing River Habitat Survey, b) proposed restoration works; *1–11* = cross-sections; *A* = stream leading stone threshold (20 cm high), *B* = alternative river channel pathway, *C* = biofiltration vegetation, *D* = ecotone vegetation, *E* = low stone threshold (15–20 cm high); source: own elaboration

morphological status according to the classification (Fig. 5) or the class remains unchanged. Values of HQA_*/HQA of ⟨0.65; 0.81) signal a noticeable reduction in the *HQA*, which could be derived from perceptible depletion of biodiversity in the section studied. Such a value usually translates into a decrease in hydromorphological status by 1–2 classes. The HQA_*/HQA ratio of ⟨0.51; 0.65) indicates a significant reduction in the habitat naturalness. In such a case, the regulation would require an expert survey, and its implementation should be preceded by a profit and loss consideration (citizen safety, economic, environmental, etc.). Finally, the predicted decrease of the *HQA* value by more than a half of the initial value ($HQA_*/HQA < 0.50$) should be the reason to abandon regulation activities.

The proposed method also considers a mutual ratio of the Habitat Modification Score values. The relationship of indices describing the degree of habitat modification before (*HMS*) and after the regulation (HMS_*) is calculated. The value of $HMS/HMS_* < 0.25$ indicates a very strong degree of technical influence on the river section. The range of ⟨0.25; 0.53⟩ implies a significant degree of anthropogenic transformation that would require justification in the form of an expert opinion. Higher values of the HMS/HMS_* ratio, up to 0.81, may appear in the case of a noticeable degree of technical interference in the morphology of the reach. However, it should be referred to the fact that channel and valley regulation, including technical transformations, does not mean a decrease in hydromorphological quality. The application of natural materials following ecological engineering rules would maintain a high *HQA* index and a high value of the *HMS* index. A ratio of $HMS/HMS_* = 1.00$ indicates no modification involving engineering measures.

METHOD APPLICATION – EXAMPLE

To verify the proposed methodology, an attempt was made to use it to assess changes occurring as a result of restoration measures on the Zielawa River. The Zielawa River is a right tributary of the Krzna River, and has its source in an artificial reservoir by the village of Mosty. The natural landscape consists of a vast accumulation plain, resulting from, among other things, the influence of river erosion and accumulation processes. The Zielawa valley is characterised by a large variety of plant communities, both eutrophic and wet, as well as dry and mesotrophic conditions. In dryer areas, we can find pine forests, whereas in wetlands, alder riparian forests with black alder are present. Meadow-forest land prevails in the valley, with characteristic peat bogs, marshes, and extensively used meadows.

In 2013, a selected section of the river from kilometer 18+525 to 19+025 was assessed (Fig. 5a). The studied section was straight and regulated with a high influence of anthropogenic activities in the form of settlements, vegetation mowing, unification of channel cross-sections, and banks reinforcement. The section was classified as class V (according to Kiraga 2020: weakly natural, severely modified), where the *HQA* was 37 and *HMC* 47.

The restoration works include oxbow lakes integration with the main channel course (sections 4, 5, 7–9), introduction of ecotone vegetation on the left bank, where residential buildings are settled, and the implementation of biofiltration vegetation in the oxbow lakes area combined with a slight water damming by means of stone thresholds (Fig. 5b). The aim of the planned regulation is to increase the retention of the analysed area and to clean the water using the root system of biofiltration plants.

The proposed restoration works changed the *HMS* and *HQA* values within cross-sections 3–10. Table 2 summarises the obtained numerical values of HQA_* and HMS_*. The modification degree of the section increased by five points, while the factor describing the degree of habitat naturalness decreased by eight points. As the planned technical measures involve noticeable technical transformation and slight ecological quality reduction, it can be concluded that this project is acceptable for implementation.

Table 2. Method application example – summary of Habitat Quality Assessment and Habitat Modification Score values

Parameter	Value (–)	HQA_*/HQA	HMS/HMS_*
HQA	37	0.78	0.90
HMS	47	noticeable	slight
*HQA**	29		
*HMS**	52		

Explanations: *HQA* = Habitat Quality Assessment of researched reach, *HMS* = Habitat Modification Score of researched reach, HQA_* = forecasted Habitat Quality Assessment of the reach after engineering development; HMS_* = forecasted Habitat Modification Score of the reach after engineering development.
Source: own study.

CONCLUSIONS

The paper discusses a new method for the evaluation of a hydromorphological status of a river reach. Those changes could result from the river channel development with water structures, reinforcement, as well as changes in the shape of the channel and its profiles modifications. The method can be a supporting tool for environmental impact assessment at a design stage of a project, which in many cases is essential for regional development. Hydraulic engineering projects undertaken, especially in environmentally valuable areas, need to be properly described and their influence on river hydromorphology should be the subject of an independent expert study.

Bank reinforcements stabilise the riverbed, which is subject to gradual degradation due to the loss of dynamic equilibrium and efforts are made to prevent excessive erosion. Therefore, it should be highlighted that river channel technical development could provide ecological advantages for the river valley. A wide range of natural regulation activities is recommended, i.e. implementation of natural materials for all kinds in bank and bed reinforcement, including gabions, stone weirs, wooden piles, and a fascine, as well as the introduction of vegetation that stabilises the banks: extensively rooted trees, turf, shrubs that provide hiding and nesting places for animals. Natural materials easily blend into the terrain and their introduction often allows free water organisms to transfer through the channel. The engineering practice suggests the following design solutions: fascine or stone reinforcements, coverings, wooden sills, small weirs, palisades, and fences, as well as fascine and stone rapids. Water surface level regulatory structures include fascine and stone small dams and weirs, and baffle blocks fixed with piles. The negative impact of river development on ichthyofauna can be mitigated by introducing fish ladders.

The hydrotechnical structures and technical solutions should be minimised, meanwhile measures desigend to recover natural features, including river restoration, should be introduced in as much as possible. According to the Water Framework Directive, their impact on the habitat should be determined at the design stage. Such structures should meet requirements concerning their flow capacity, stability, load bearing capacity, safety, and reliability of operation. Therefore, river regulation ought to be preceded by an in-depth study based on hydrological, hydraulic, and environmental issues.

It is recommended to check the practical application of the method on a larger number of test facilities. Thus, the initial method presented in the article can be verified, expanded and improved. During the verification process, the limitations of the method may be discovered, and its scope of applicability determined. However, it should be emphasised that the initial verification of the method has provided promising results, and the method itself is certainly a useful engineering tool to support decision-making.

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