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Methodological Framework for Assessing Hydromorphological Conditions of Heavily Modified and Artificial River Water Bodies in Croatia

Katarina Pavlek [1], Mladen Plantak [2], Ivan Martinić [1], Karlo Vinković [2], Ivan Vučković [2] and Ivan Čanjevac [1,*]

[1] Department of Geography, Faculty of Science, University of Zagreb, Marulićev trg 19/II, 10000 Zagreb, Croatia
[2] Elektroprojekt d.d., Civil and Architectural Engineering Department, Section of Ecology, Alexandera von Humboldta 4, 10000 Zagreb, Croatia
* Correspondence: canjevac@geog.pmf.hr

Abstract: Water Framework Directive (WFD) guidance documents from 2019 provide a comprehensive review of methods and guidelines to improve the comparability of heavily modified water bodies (HMWBs) in the European Union. However, there is currently no common, single methodology for monitoring HMWBs and artificial water bodies (AWBs) or for determining maximum (MEP) and good ecological potential (GEP). This study presents the first assessment of hydromorphological conditions of HMWBs and AWBs in Croatia based on type-specific indicators. The typology of HMWBs and AWBs was based on distinct hydromorphological characteristics and modifications in order to be easily related to the uses of the water bodies. The classes of hydromorphological potential were graded from the theoretical MEP, which was determined by the score scale as the tolerated deviation from natural reference conditions, considering potential mitigation measures. The use of the water body and/or the effects on the wider environment were considered while determining MEP and choosing indicators included in monitoring and assessment. In the case of AWBs, the parameters dependent on natural reference conditions, which are non-existent, were omitted from the assessment. Only 27% of HMWBs and 2 out of 51 AWBs achieved good potential for all three hydromorphological elements. The most significant hydromorphological modifications include channelization, straightening, deepening and removal of riparian vegetation due to flood-protection management practices. In order to achieve the environmental objectives set out by the WFD, the Croatian water management system has to start implementing mitigation measures, especially related to natural flood management.

Keywords: hydromorphology; heavily modified water body; artificial water body; channelization; Croatia

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1. Introduction

River systems have been under increasing human pressure due to socioeconomic development since the last century. Although rivers are naturally dynamic environments prone to hydrological and morphological changes, human impacts seem to have caused significant acceleration of these processes [1]. Human interventions on rivers are implemented in order to achieve favourable conditions for numerous uses, such as flood protection, water supply, hydroenergy, navigation and tourism. Consequently, river hydromorphology is being modified by straightening and channelization, armouring, bed and bank revetments, construction of dams and accumulation lakes, construction of weirs to reduce natural incision and sediment mining or removal to ensure depth necessary for navigation [2,3]. These activities have a negative impact on river ecosystems since they disrupt the natural flow of water and sediment and reduce the heterogeneity of freshwater habitats [4]. Hydromorphological modifications may also affect the connection between surface water and groundwater. Channel reinforcements that use hard, impermeable materials (e.g., concrete) can completely disrupt the connection between the surface water and groundwater, especially in the hyporheic zone, causing changes in groundwater levels, nutrient exchange and water quality [5]. Furthermore, channel incision caused by dam construction or river straightening is often followed by the lowering of average surface water levels, which affects the lowering of groundwater levels connected to the river [6,7].

In order to improve the ecological conditions of European water bodies, the European Union issued the Water Framework Directive [8]. The main goal of the Directive was to achieve good qualitative and quantitative status of all water bodies by 2015. One of the important steps in reaching this common goal is the monitoring and assessment of ecological status, which consists of three main quality elements: biological, hydromorphological and physico-chemical. Hydromorphology is a term introduced to describe physical river characteristics, i.e., hydrological regime, longitudinal connectivity and morphology, as important components of river ecosystem conditions. Ecological status is primarily assessed based on biological quality elements, while the assessment of hydromorphological conditions represents the supporting element. However, hydromorphological conditions are an important control of the biotic elements of river ecosystems, as they influence species richness [9] and many ecosystem functions [10].

According to the WFD, the hydromorphological quality of a river should be assessed compared to near-natural reference conditions. However, due to numerous physical modifications on rivers as consequences of significant human impacts, many rivers in Europe do not have sufficient hydromorphological quality needed to achieve good ecological status [11]. According to the WFD, such water bodies can be designated as heavily modified. It is important to emphasise that changes to the hydromorphological characteristics of a heavily modified water body (HMWB), which would be necessary for achieving good ecological status, would have significant adverse effects on its use and the wider environment. Since it is essential to preserve the use of the water body for human needs (e.g., flood protection, water supply, navigation), these water bodies cannot be restored to their natural state, which would be in line with the requirements of good ecological status [12].

Another group of water bodies with severe physical differences compared to a natural state are artificial water bodies (AWBs), which have been created in a location where no water body existed before and which have not been created by the direct physical alteration or movement or realignment of an existing water body (i.e., drainage dykes, navigation channels, etc.) [13]. For heavily modified and artificial water bodies, according to the WFD, the goal is to achieve good ecological potential. Similar to ecological status, ecological potential consists of three quality elements: biological, hydromorphological and physico-chemical [12,14]. The reference state for defining ecological potential is called maximum ecological potential (MEP), which is, according to the Water Framework Directive (WFD), defined as follows: "Hydromorphological conditions of heavily modified or artificial water bodies with maximum ecological potential are consistent with the impacts on the surface water body resulting from artificial or heavily modified characteristics of the water body after all mitigation measures have been taken to ensure the best approximation of the ecological continuum, in particular with regard to fauna migration and appropriate hatcheries and farms" [8] (Annex V, 1.2.5).

The first step in defining MEP involves the determination of reference conditions for relevant quality elements according to the appropriate category and type of the closest comparable natural water body (NWB). Then, it is necessary to establish the best possible hydromorphological conditions, i.e., to establish such hydromorphological conditions that would exist if all mitigation measures (with no impact on the use of the water body or the wider environment) had been implemented in order to achieve an ecological continuum [14].

MEP is a basis for defining good ecological potential (GEP), which is an ecological target for heavily modified and artificial water bodies. It is defined as a condition characterised by "small changes in the values of the relevant biological quality elements compared to the values established for maximum ecological potential" [8] (Annex V, 1.2.5). There are currently two approaches which are used in the EU Member States for determining GEP.

According to the reference approach, GEP is determined based on "minor changes" in the values of biological quality elements derived from MEP, while the hydromorphological conditions of GEP must be such to support the achievement of GEP biological values [13]. On the other hand, the mitigation approach is based on the GEP definition through the identification of mitigation measures. Starting from all measures that do not have a significant adverse impact on the use of the water body (which represents MEP), measures that are expected to bring only small environmental improvements are excluded. The GEP is then defined using the biological values expected from implementation of the remaining identified mitigation measures [15].

The WFD prescribes operational monitoring of hydromorphological elements in order to determine the ecological potential of HMWBs and AWBs, assess the effects of mitigation measures after implementation and support water management. Since there is no common methodology for assessing MEP or GEP in the European Union [15], Member States use various methodologies to assess the hydromorphological conditions of their water bodies [16–19], e.g., the River Habitat Survey [20] or the CEN standard [21], which are primarily developed for natural water bodies. However, these methods are mainly used only to assess hydromorphological alterations, not to define MEP (e.g., [22,23]).

In this study, we present a methodological framework for assessing the hydromorphological conditions of HMWBs and AWBs in Croatia based on type-specific indicators which were selected according to the use of the water body and the wider environmental effects. This research represents the first national assessment which was further paired with biological quality elements and used in the classification of ecological potential [24,25].

2. Study Area

Located contact of the Pannonian basin, the Dinaric mountain belt and the Adriatic Sea in the south of Central Europe, Croatia is a country with heterogeneous physical–geographical characteristics. Water resources in Croatia can be divided according to two main drainage basins: around 62% of the Croatian territory is drained as a part of the Danube river basin towards the Black Sea (Figure 1), while the western and southwestern part of the state drains to the Adriatic Sea. The Danube river basin in Croatia is located in the Pannonian plain, which is mostly characterised by lowlands and impermeable lithology, therefore providing the development of a dense surface drainage network [26]. The major tributaries of the Danube crossing Croatia are the Sava and Drava rivers (Figure 1). According to the Köppen–Geiger classification, the climate is classified as a warm temperate humid climate with warm summers (Cfb), with mean annual precipitation of around 1000 mm. On the other hand, coastal and Dinaric Croatia (in total around 38% of the national territory) belongs to the Adriatic Sea basin. This is a predominantly karst area with a poorly developed surface drainage network but with rich underground flow and water resources. In addition, it contains classic karst river phenomena such as strong karst springs, ponors, canyons, sinking and intermittent rivers. The interior of the Adriatic Sea drainage basin is mostly characterised by a humid subtropical climate with warm or hot summers (Cfb or Cfa), the coastal part has a Mediterranean climate (Cs), while the highest mountains have a humid continental climate (Df) [26].

According to different geological, geomorphological and climatological characteristics of these two drainage basins, the two main ecoregions in Croatia are divided into the Pannonian ecoregion and Dinaric ecoregion (which is further subdivided into continental and Mediterranean Dinaric ecoregions).

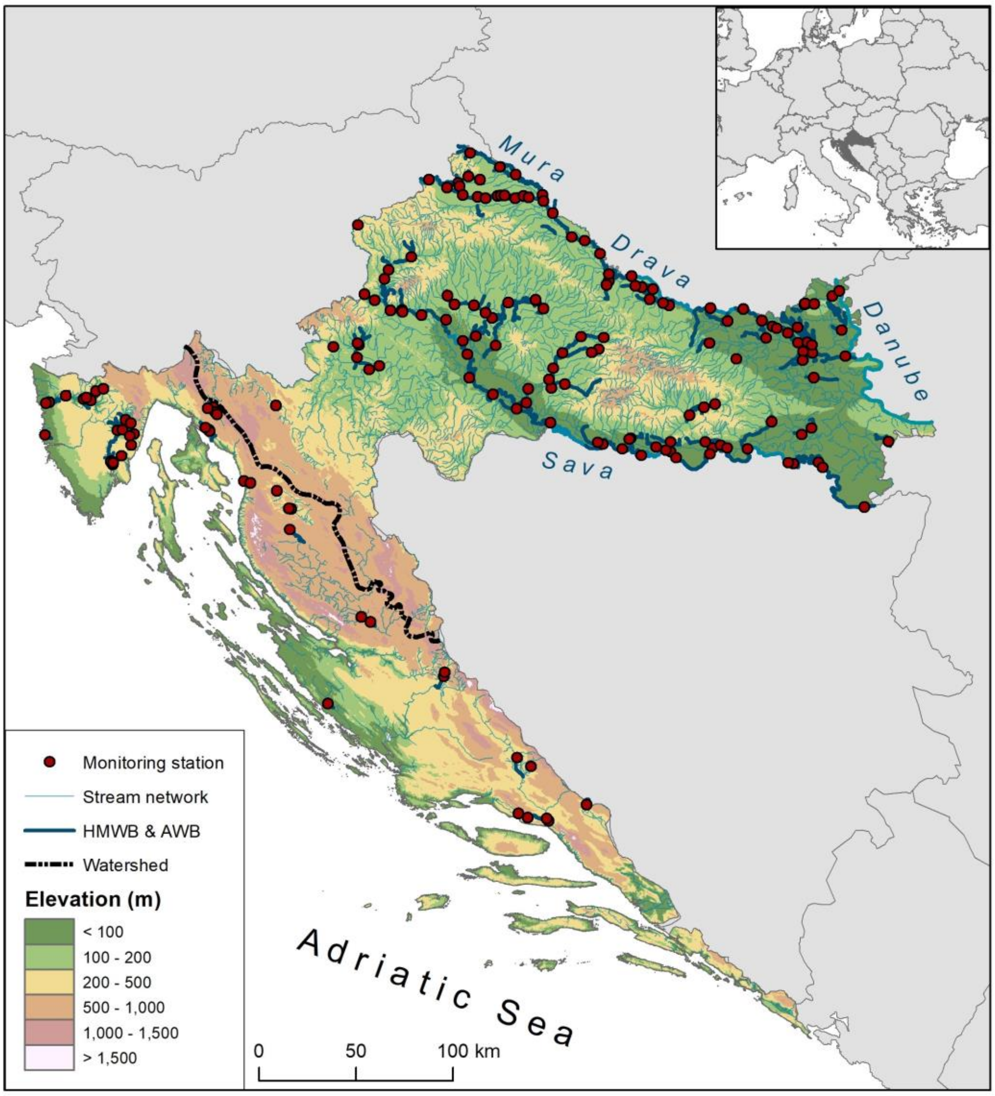

Figure 1. Study area with locations of monitoring stations.

3. Materials and Methods

A typology of heavily modified and artificial water bodies has been defined in order to develop a type-specific methodology for monitoring and assessment of the ecological potential of water bodies in the Republic of Croatia. A total of 22 types of heavily modified and artificial water bodies were defined (Table 1) [24,25]. The typology of heavily modified water bodies was developed according to several criteria, including ecoregion type, catchment area, flow intermittency and the dominantly modified hydromorphological feature: hydrology, longitudinal continuity or morphology. Artificial water bodies were divided into a total of 5 types considering their most distinct features which can be easily related to their uses. Artificial streams with large daily changes in flow represent inflow and outflow channels of hydropower plants, artificial streams with disturbed groundwater–surface water interactions represent drainage ditches of hydropower plants (only in the Pannonian ecoregion - hydropower plants on the Drava River) and artificial streams with large seasonal flow changes include drainage and amelioration canals in the Pannonian and Dinaric ecoregion.

Table 1. Typology of HMWBs and AWBs developed for Croatian rivers.

Pannonian Ecoregion	Dinaric and Adriatic Ecoregion	Description of the River Type
HR-K_1A	HR-K_7A	Small, heavily modified rivers with modified morphology (catchment area 5–100 km^2)
HR-K_1B	HR-K_7B	Small, heavily modified rivers with modified morphology and longitudinal connectivity (catchment area 5–100 km^2)
HR-K_2A	HR-K_8A	Medium-sized, heavily modified rivers with modified morphology (catchment area 100–1000 km^2)
HR-K_2B	HR-K_8B	Medium-sized, heavily modified rivers with modified morphology and longitudinal connectivity (catchment area 100–1000 km^2)
HR-K_3A	HR-K_9A	Large, heavily modified rivers with modified morphology (catchment area 1000–10,000 km^2)
HR-K_3B	HR-K_9B	Large, heavily modified rivers with modified morphology and longitudinal connectivity (catchment area 1000–10,000 km^2)
HR-K_4		Very large, heavily modified rivers with modified morphology (catchment area larger than 10,000 km^2)
HR-K_5	HR-K_12	Heavily modified rivers with large changes in discharge
HR-K_6A	HR-K_13A	Artificial streams with large daily changes in flow
HR-K_6B		Artificial streams with disturbed groundwater–surface water interactions
HR-K_6C	HR-K_13B	Artificial streams with large seasonal flow changes
	HR-K_10 and HR-K_11	Heavily modified ephemeral streams with changed morphology

It is important to note that at the time of this research, assessments according to Articles 4.3 to 4.7 of the WFD were not resolved. Therefore, there are certainly cases where the implementation of mitigation measures could return the water body to the category of a natural water body.

In this study, the MEP was determined as a deviation from the reference conditions of a comparable natural water body, considering the use of the water body and the wider environment. As a starting point, we incorporated the following principles [27] representing mitigation measures:

- To ensure ecological continuum and ecological flow of watercourses according to CIS guidance documents.
- To ensure a minimum amount of water in melioration lowland canals.
- To ensure the necessary flow and energy drop to produce electricity at existing facilities.
- To ensure the required volume in reservoirs and water intake facilities for the supply of drinking water, operation of existing hydropower plants and irrigation.
- To allow moderate seasonal changes in the runoff regime associated with the above functions.
- To allow minor changes in the channel planform and cross-section.
- To ensure optimal drainage of agricultural land while respecting the minimum environmentally friendly depth and/or flow of water in the channel throughout the year and leaving woody riparian vegetation (preferably on the south or west bank of the stream) in a way that creates a high percentage of shading and reduces the input of organic material and fine sediment. The other shore can be covered with herbaceous vegetation and individual trees that allow access for machines to periodically maintain the channel (e.g., prevention of blockages).
- To ensure a narrow line of flood defense in dense urban areas.
- To allow moving of a small amount of sediment inside the channel for flood protection in compliance with the environmental protection acts and other related laws and directives.
- To reduce the risk of floods on natural watercourses while respecting the minimum environmentally friendly depth and/or water flow in the channel throughout the year and leaving woody riparian vegetation in a way that creates a high percentage of shading and reduces the input of organic material and fine sediment.

- The relationship between surface- and groundwater must not be disturbed in order to preserve ecosystems dependent on groundwater and in compliance with the provisions of the environmental protection acts and other related laws and directives.
- To ensure the minimum depth of water for inland navigation and mooring of ships on the legally defined waterway and the related regularly prescribed maintenance of the waterway.

Once the MEP was established, we proceeded with the assessment of the hydromorphological conditions.

The basis of the assessment methodology for the hydromorphological potential was the methodology for the assessment of hydromorphological status in Croatia HYMO_HR, which relies on a five-point scale scoring system, where 1 represents high status with the lowest degree of modification and 5 designates a bad status with the highest degree of modification [28,29]. The overall status is established based on the principle one out, all out, meaning the worst status for one of the three hydromorphological elements categories defined by the WFD (hydrological regime, longitudinal continuity and morphology). For each category, an average score is calculated based on the scores of several indicators. Good status is achieved with a score of less than 2.5. The scoring system uses both quantitative and qualitative scores, depending on the availability of data.

For the assessment of hydromorphological conditions for HMWBs and AWBs, the methodology of HYMO_HR was modified in accordance with the definition of reference conditions, i.e., the MEP. The criteria for the class boundary of every indicator was lessened compared to the assessment scale for natural water bodies. Hydromorphological conditions at MEP for most indicators represented 75% of the natural reference conditions. In addition, some indicators directly related to the use of the water body or the wider environment were omitted from the monitoring and assessment process. For example, an indicator related to land-use in the floodplain, which is otherwise assessed in the case of natural water bodies, was omitted since it is directly related to the wider environment of the water body (Table 2). Furthermore, in the case of water body types related to hydropower use (heavily modified rivers with considerable changes in discharge), only daily oscillations in water levels and discharge were assessed since they represent important indicators of hydropeaking, which has been shown to be a significant environmental threat for river ecosystems [30]. Seasonal changes in flow were assessed but not included in the final score in the case of HMWBs used for hydropower since their flows highly depend on the operation of hydropower plants and cannot be mitigated.

Table 2. Indicators for the assessment of hydromorphological potential for different river types.

	Indicator Description	**1A, 1B, 7A, 7B**	**2A, 2B, 8A, 8B**	**3A, 3B, 9A, 9B**	**4**	**5, 12**	**10, 11**	**6A, 13A**	**6B, 6C, 13B**
Hydrology	Changes in mean seasonal discharge (or water level)	✔	✔	✔	✔	✘	✔	✘	✘
	Daily changes in water level during average water levels	✔	✔	✔	✔	✔	✘	✔	✘
	Daily changes in discharge	✘	✘	✘	✘	✔	✘	✘	✘
	Days without flow in the channel	✔	✔	✔	✘	✘	✘	✔	✔
Longitudinal connectivity considering biota migration (fish, etc.)		✔	✔	✔	✔	✔	✔	✔	✔
Morphology	Changes in the channel planform	✔	✔	✔	✔	✔	✔	✘	✘
	Changes in the channel cross-section	✔	✔	✔	✔	✔	✔	✘	✘
	The amount of artificial hard materials below the water level	✔	✔	✔	✔	✔	✔	✔	✔
	Artificiality of the bed sediment	✔	✔	✔	✔	✔	✔	✘	✘
	Bank structure	✔	✔	✔	✔	✔	✔	✘	✔
	Bank slope	✔	✔	✔	✔	✔	✔	✘	✔
	Length of the riparian corridor	✔	✔	✔	✔	✔	✔	✔	✔
	Lateral connectivity with the floodplain	✘	✘	✘	✔	✔ *	✘	✘	✘
	Lateral channel movement	✔	✔	✔	✔	✔	✔	✘	✘

Notes: * only type 5.

In the case of AWBs, the number of indicators was diminished to five for inlet and outlet channels of HPPs, and six in the case of HPPs and flood-protection drainage ditches. Hydrological parameters include daily oscillations in water levels and days without flow in the channel, while morphological parameters include channel bed substrate, bank structure, bank slope and length of the riparian zone. Therefore, indicators closely related to the use of the water body, such as lateral movement or connectivity with the floodplain, as well as indicators assessed based on a natural reference state, which does not exist for the AWB (e.g., channel geometry, seasonal or daily flows), were omitted.

The hydromorphological monitoring and assessment was carried out by desk research and fieldwork (Figure 2). Representative reaches of each water body were investigated in the field during early spring of 2020 (Figure 3A). Investigated length of the reaches was 200, 500 or 1000 m, depending on the channel width of the water body (less than 10 m, 10–30 m, more than 30 m).

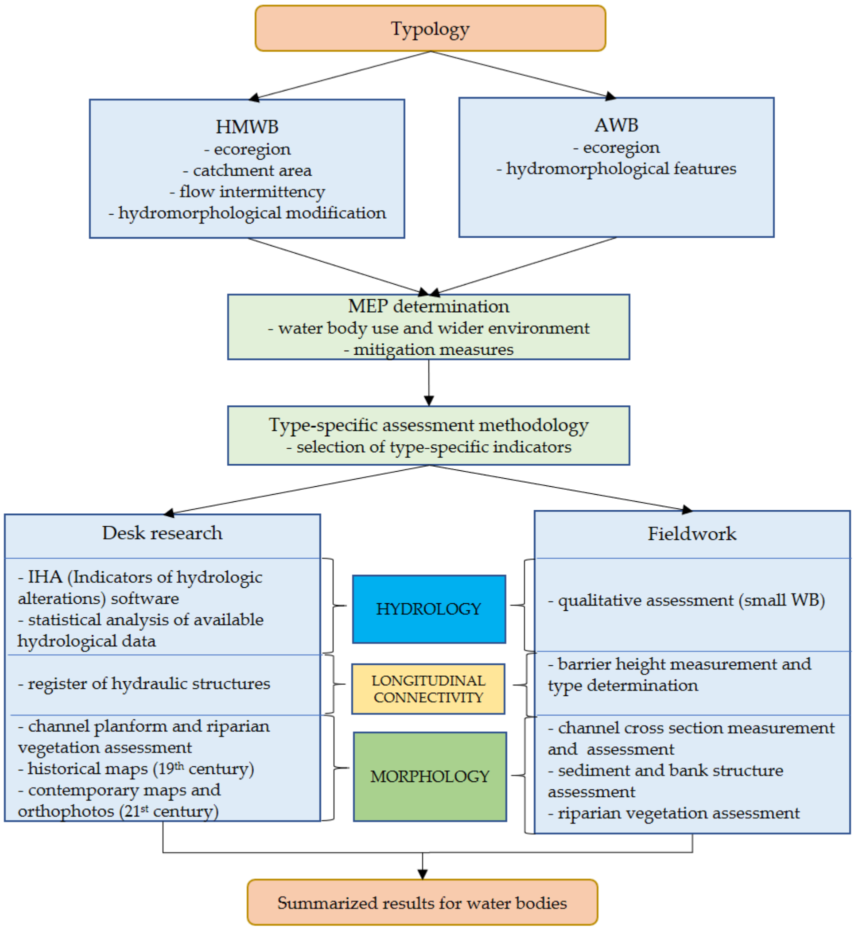

Figure 2. Research workflow.

Hydrological parameters were assessed based on the data from the Croatian Hydrological and Meteorological Service and Croatian Waters. Data series were processed using standard statistical tools in MS Excel and IHA (Indicators of Hydrological Alteration). If data were not available, which was often the case for small rivers and artificial streams, the hydrological parameters were assessed qualitatively using data obtained in the field and through analyses of hydrological pressures in the catchment.

Longitudinal connectivity was assessed using the spatial database (register) of hydraulic structures in Croatia provided by Croatian Waters and through field research. This database consists of several thousand individual structures such as dams, weirs, sluices, embankments, groynes, ports, etc. The height of barriers located in the investigated reaches was measured in the field (Figure 3B).

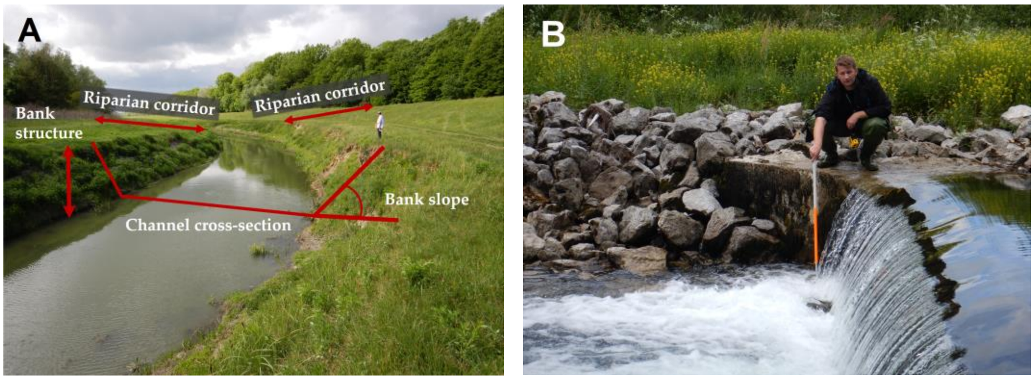

Figure 3. Channel morphology assessment in the field (**A**), barrier height measurement (**B**).

Topographic maps of the Third Military Survey of the Habsburg Empire at a scale of 1: 25,000, made in the period 1869–1887, were used to assess the changes in channel planform. These maps represent the key source for determining the reference conditions for this hydromorphological indicator because most middle-sized rivers in the Pannonian ecoregion have been straightened and channelized since the 1950s [28,31]. Older military surveys (the First, made in the period 1774–1784, and the Second, made in the period 1851–1869) were also used as an additional source of data. All historical maps were accessed via the online portal Arcanum Maps [32]. The current state of the channel planform was analysed based on contemporary topographic maps at a scale of 1: 25,000 and orthophotos at a scale of 1: 5000 from the late 2010s, provided by the Croatian Geodetic Administration.

Channel cross-section, sediment structure, changes in bank structure and slope and the type and structure of riparian vegetation in a 10 m wide buffer zone were assessed based on field observations (Figure 3A) and orthophotos. Lateral movement and connectivity with the floodplain were assessed using orthophotos, the spatial register of hydraulic structures and field data.

In this study, we summarized results for the water bodies since they provide a more general and larger-scale picture of the hydromorphological conditions than the data on representative reaches.

4. Results

In total, we analysed 152 water bodies, from which (101) 66% were designated as heavily modified and 51 (34%) as artificial. Only 29 (19%) water bodies achieved good potential for all 3 hydromorphological elements (score less than 2.5). A majority of those water bodies (24) are located on very large rivers: the Sava, the Drava or the Mura. Only 2 out of 51 artificial water bodies achieved good scores for all three hydromorphological elements, although 10 had good hydrology, 32 had good longitudinal connectivity and 13 had good morphology scores. Looking at the lengths of water bodies, 28% of lengths have achieved hydromorphological conditions sufficient for good potential.

Morphology in general had the lowest scores; 62% of water bodies did not have sufficient morphological conditions to achieve good potential (Figure 4A). On the other hand, 55% of water bodies were assessed to have good hydrological conditions. In the case of longitudinal connectivity, 57% of water bodies achieved good conditions.

Comparing the results for the lengths of water bodies (Figure 4B), it was found that a larger percentage of river lengths achieved good potential in morphology (48%) but this was still not enough to surpass the amount of water body lengths in bad morphological condition (52%). Regarding hydrology, 58% of water body lengths had good conditions and 67% had sufficient conditions of longitudinal connectivity. Therefore, shorter water bodies have, on average, worse scores for morphology and longitudinal connectivity.

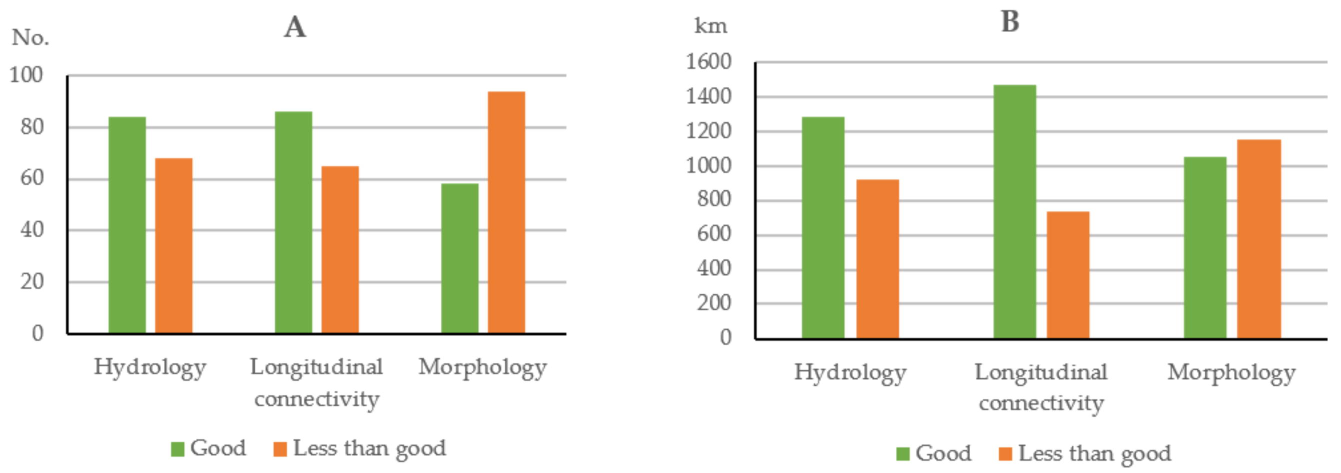

Figure 4. Number (**A**) and lengths (**B**) of water bodies with good or less than good hydromorphological potential.

Looking at average scores for specific hydrological parameters (Table 3), it was found that the parameter describing seasonal changes in discharge proved to have the worst scores. On the other hand, daily discharge and low-flow discharge (days without flow), which are assessed for water bodies with modified hydrology, turned out to have better scores on average. However, it is important to note that several water bodies with significant hydropeaking were not included in this study since they are not officially designated as heavily modified (e.g., the Dobra River). Regarding morphology, substrate and bank slope were on average mostly satisfactory and in line with the heavily modified nature of the water bodies. However, the most problematic parameters were channel geometry (planform and cross-section), lateral movement and length of the riparian corridor.

Table 3. Central tendencies of scores for every indicator (green stands for good potential, orange for less than good potential; threshold is 2.5).

Indicator Description	Average Score	Median Score
Changes in mean seasonal discharge (or water level)	2.48	3
Daily changes in water level during average water levels	2.24	2
Daily changes in discharge	2.33	2
Days without flow in the channel	2.34	2
Longitudinal connectivity considering biota migration (fish, etc.)	2.47	1
Changes in the channel planform	2.75	2
Changes in the channel cross-section	3.45	4
The amount of artificial hard materials below the water level	1.14	1
Artificiality of the bed sediment	2.41	3
Bank structure	2.46	3
Bank slope	2.13	2
Length of the riparian corridor	3.14	3
Lateral connectivity with the floodplain	2.72	3
Lateral movement	3.42	4

A large percentage of small and medium-sized rivers in the Pannonian ecoregion are straightened and channelized due to flood protection. These interventions are mostly implemented on rivers in lowland regions which are characterised by agricultural activities and/or dense population (types 1 and 2). River channels are often deepened in order to accommodate high discharges and to ensure good drainage from the surrounding agricultural areas. Channel straightening and channelization turns the natural heterogeneity of the channel cross-section into a uniform V-shaped pattern. Since agricultural areas are in most cases located very close to river banks, lateral movement of the channel is restricted and the floodplain is practically non-existent. River banks are in most cases made from soil and covered by grass (Figure 5A). Although uniform and engineered, bank slope is on average satisfactory for the growth of riparian vegetation. However, riparian vegetation is mostly removed from the river banks and the investigated buffer zone of 10 m on both sides of the channel to prevent blockages during floods. In cases where channel slope is managed by the construction of weirs, banks are armoured by hard materials (rocks, boulders, cement) due to erosion, which often occurs downstream of the weir (Figure 5B). Weirs for channel slope levelling represent the most common type of barriers on small and medium-sized rivers.

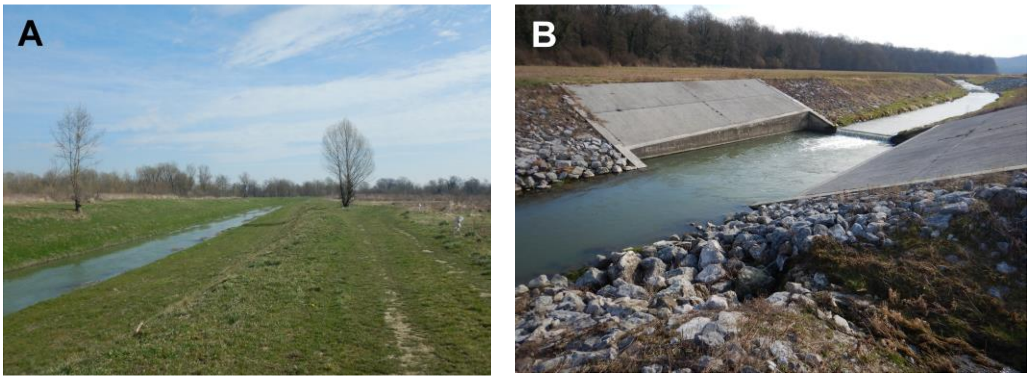

Figure 5. Hard engineering approach in flood-protection management on medium-sized Croatian rivers; types HR-K_2A (**A**) and HR-K_2B (**B**).

On average, larger rivers in the Pannonian ecoregion (types 4 and 5) achieved good potential in all hydromorphological categories. There are three large rivers in the Pannonian ecoregion in Croatia whose reaches are classified as HMWBs: the Sava, Drava and Mura. On the Drava River, there are three hydropower plants in Croatia; therefore, the river's seasonal discharge has been significantly modified due to its use. However, changes in daily discharges were assessed to be satisfying and in line with the heavily modified nature of the river reaches. This is due to the position of the hydrological station (data used for the assessment) being quite far downstream of the HPP, where the effect of hydropeaking is less pronounced. Longitudinal connectivity in the upper sections of the river is disturbed by dams and accumulation lakes of the HPPs, but in downstream sections the longitudinal connectivity is undisturbed, as in the case of the rivers the Sava and Mura. The morphology of the large rivers with changed hydrology (type 5 – 1.90) is assessed as somewhat worse than the morphology of the large rivers with changed morphology (type 4 – 1.53) (Table 4). That difference is primarily because of the Sava River in Zagreb, which is channelized. However, most parts of these large rivers have morphologically good conditions, e.g., unchanged river banks covered in riparian vegetation (Figure 6A). Channel geometry is partly modified compared to the state on the historical maps; however, keeping in mind the changed conditions in discharge and sediment flux as well as human interventions needed for flood management, the channel planform and cross-section of these rivers is satisfactory. Channel migration is locally limited by river bank protection and levees; however, in the case of, e.g., the Drava River, there are quite large areas of natural floodplain that are protected since the river is part of the regional nature park Mura–Drava.

In the Dinaric ecoregion, small rivers are on average under the influence of modifying factors in all three hydromorphological categories. On small streams which usually have a higher slope, complete concrete channelization is common in settlements (Figure 6B). In agricultural areas, the same measures for flood management are being implemented as in the Pannonian region, causing negative effects on morphological conditions (channelization, straightening, restriction of lateral movement, removal of riparian vegetation). However, it is important to notice that the hydropeaking influence is more pronounced on Dinaric rivers with changed hydrology than those in the Pannonian region, since the hydrology score on average does not satisfy the conditions needed for good ecological potential (HR-K_12 - 3.50).

Table 4. Average scores of hydrology, longitudinal connectivity and morphology by HMWB and AWB types (green stands for good potential, orange for less than good potential; threshold is 2.5).

WB Type	Hydrology	Longitudinal Connectivity	Morphology
HR-K_1A	1.83	1.00	3.21
HR-K_1B	2.12	4.43	2.94
HR-K_2A	2.23	1.00	2.95
HR-K_2B	2.15	4.45	3.34
HR-K_3A	2.13	1.00	3.38
HR-K_3B	2.00	5.00	2.25
HR-K_4	2.05	1.00	1.53
HR-K_5	1.56	1.50	1.90
HR-K_6A	2.71	5.00	3.57
HR-K_6B	2.60	1.40	2.75
HR-K_6C	3.41	1.76	2.55
HR-K_7B	2.76	3.86	2.98
HR-K_8A	1.67	1.00	3.69
HR-K_8B	1.78	5.00	2.04
HR-K_10	2.00	4.00	2.58
HR-K_12	3.50	3.00	2.16
HR-K_13A	3.00	5.00	4.00
HR-K_13B	2.78	2.11	2.67
Average	**2.49**	**2.47**	**2.62**

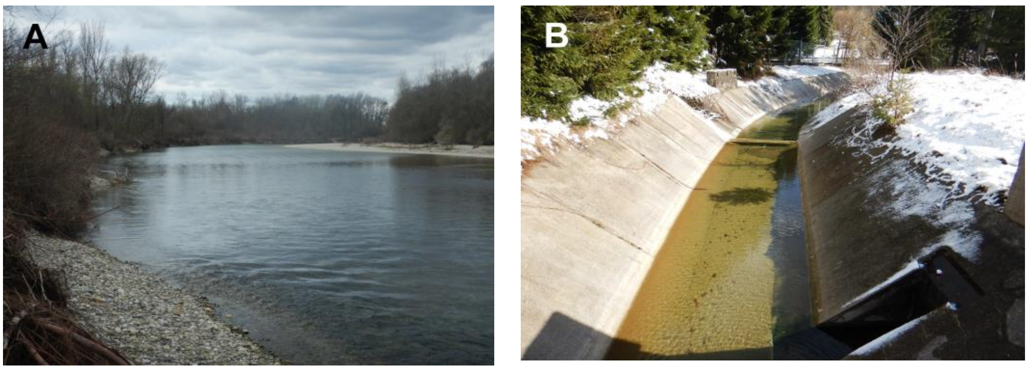

Figure 6. Good morphological conditions of a large river in the Pannonian region, the Drava River (**A**), concrete channelization of a small stream in the Dinaric region (**B**).

Regarding artificial water bodies, it is important to note that inflow and outflow channels from HPPs generally cannot satisfy the needed criteria for good ecological potential. The construction requirements for these channels are quite strict and connected to their use and cannot be mitigated by any measures in order to improve their hydromorphological conditions (Figure 7A). Therefore, these kinds of artificial water bodies are recommended to be assigned as an exemption from the requirements of the WFD according to Article IV(5), as also emphasized by Halleraker et al. [15]. On the other hand, drainage ditches of the HPPs and drainage canals used for agriculture achieved better scores, although still not sufficient to achieve good potential (on average). However, few artificial water bodies did achieve good conditions for some or all hydromorphological elements. These are primarily canals built for flood protection (e.g., Lonja-Strug canal, Figure 7B), with artificial channel geometry but with well-developed riparian and aquatic vegetation and low bank slopes.

Figure 7. Artificial water bodies: outflow from the HPP (**A**) and flood-protection canal with good morphological conditions (**B**).

5. Discussion

5.1. Challenges in Assessing Hydromorphological Conditions of HMWBs and AWBs

Although there are common implementation strategies with comprehensive guidelines regarding the required steps of the assessment [14], implementation of the WFD in the case of HMWBs and AWBs is still not harmonised across the Member States. According to Halleraker et al. [15], it is not possible to precisely define the boundaries of ecological potential categories at the EU level (as in the case of ecological status), mainly because it cannot be separated from the process of designating a HMWB. There is a significant influence of national judgment on the importance and acceptability of adverse effects on the use of water bodies or on the wider environment. In addition, due to the wide range of uses and variations in the nature and extent of hydromorphological changes, it seems necessary to employ a place-based approach, which is customized to the unique hydromorphological conditions of every HMWB or AWB. Furthermore, the ecological impacts of hydromorphological changes have still not been sufficiently investigated [15]. In order to minimise these problems, the newest common implementation strategy guidance [14] presents comprehensive steps for the assessment of MEP and GEP. It also provides a publicly available mitigation measures library in order to achieve comparability of classification results between Member States. The development of national, regional or specific methods for defining the GEP is foreseen, but in line with the guidance recommendations.

Studies of hydromorphological alterations in rivers and/or their impacts on biodiversity are numerous [33–38]; however, few papers explicitly deal with HMWBs and AWBs and use adapted assessment methodologies (e.g., [39]). For example, the Polish hydromorphological assessment methodology presented in Garbowski et al. [23] does have lower score thresholds for AWBs, but it does not determine MEP or take into consideration mitigation measures, as we did in this study. In Croatia, the designation of an HMWB and an AWB is made by Croatian Waters, the main state water management institution and the main decision-maker regarding feasibility of mitigation measures. The national library of measures is still not developed. However, since financial feasibility should not be analysed while determining MEP according to the WFD, MEP in this study was defined based on the presumed effect of mitigation measures that are feasible according to the use of the water body and the wider environment.

Furthermore, some studies have noted inconsistencies in assessing hydromorphological quality due to inadequate adaptation of the methodology to the regional hydromorphological characteristics of the rivers [40]. In this study, the applied indicators are generally in line with the indicators used in other hydromorphological assessment methodologies [34,35] but they are type-specific, i.e., their inclusion and score ranges are differentiated according to the established typology of the water bodies.

Limitations of this study are related to the use of qualitative data for assessing the hydrology of small streams; however, data scarcity in such conditions is often challenging. Moreover, in the future, more processed-based indicators should be added to the assessment according to the newest guidelines at the European Union level [19,33].

A large number of water bodies with hydromorphological conditions classified as less than good in Croatia are under the influence of flood-protection measures. Since the 19th century, the amelioration of former marshlands by improving drainage was an important activity in the lowland regions of Croatia [41]. Many river and stream segments have been straightened, channelized and deepened, with riparian vegetation removed from the river banks in order to provide better flow conditions during high discharges [31]. However, this "hard engineering approach" today prevents numerous water bodies from achieving good ecological status or potential [28]. Flood-protection measures are a common issue across Europe; e.g., in Poland, a large proportion of medium-sized watercourses are influenced by reduction or total elimination of the riparian zone, while larger rivers often have wide and long riparian corridors [42]. Regarding Mediterranean river basins, a study in Greece found that channel resectioning, realignment and reinforcement, which are common flood-protection measures in agricultural catchments, are the main cause of longitudinal cross-sectional hydromorphological changes in rivers [20]. Therefore, there is a need for application of mitigation measures for the improvement of hydromorphological conditions, especially regarding natural flood-management techniques.

Results of the hydromorphological assessments show the current state of the river channel and, paired with analyses of past states and changes, can allow future projections [43]. In this way, it is possible to identify potential problem areas, i.e., river sections with increased flood or bank erosion risk as well as sections with a need for restoration or different management practices [23,38].

5.2. Selection of Indicators for the Assessment of Hydromorphological Conditions and MEP

Hydrological indicators for HMWBs should be optimally assessed based on environmental flow conditions. The definition of environmental flow requires long-term analysis of biological and hydrological data, while its successful implementation depends on legal regulations and good cooperation with water managers. However, research on environmental flow in Croatia is scarce and regulations are not well developed. For example, in the Adriatic Sea basin, particularly strong changes in seasonal and total flows are being recorded on the Cetina River due to the construction of five hydropower plants after the 1950s [44]. In some river segments, discharge has been decreased by as much as 90% due to water diversion, leading to channel narrowing by about 50% of the former width [45]. Although some considerations of environmental flow have been made, strict regulations have not been put into force and the prescribed biological minimum (usually practiced as a 10% of mean discharge) is not always respected [44]. Since these changes in discharge are a direct consequence of the water body's use (the HPPs could not work without the water diversion), the assessment of seasonal discharges did not seem to be sensible in defining hydromorphological potential. However, in this methodological framework, we kept the assessment of daily discharges and water levels for water bodies under the influence of HPPs since the issue of hydropeaking, which is also evident on these rivers (e.g., the Drava and the Cetina), should be mitigated by the implementation of certain measures (e.g., compensation reservoirs, bypass channels and adjusted operation).

The construction of dams generally presents one of the most significant impacts on river hydromorphology: by disrupting the longitudinal connectivity of water and sediment flux, it often results in channel narrowing, incision and reduction in bar occurrence downstream [2,46,47]. Significant alterations in river hydromorphology have been recorded in the upstream river sections as well [48,49]. For example, on the Guadalquivir River (Spain), progressive siltation upstream of a dam caused bed aggradation and channel narrowing, which resulted in reduced flow capacity during high discharges and increased flood risk [50].

Longitudinal connectivity is also considered to be an important factor of the ecological continuum; therefore, it was unquestionably included in the assessment.

Morphological indicators were mainly kept the same as in the methodology for assessing natural water bodies HYMO_HR [29]. The two indicators which were omitted are lateral connectivity with the floodplain and land-use in the floodplain. Erba et al. [39] also did not include land-use in the wider environment as a component for determining MEP for Italian HMWB lowland rivers. Similar to this study, MEP sites were selected based on different assemblages of natural features representing mitigation measures, consisting of the main four components: (i) riparian vegetation complexity, (ii) in-channel habitat diversification, (iii) embankment characteristics and (iv) reinforcement characteristics [39].

It is important to note that the assessment scale in this study was lessened in comparison to the scale for NWBs since the environmental objectives for HMWBs and AWBs should be less strict than for NWBs. Likewise, in the case of transitional water bodies, Borja et al. [51] found that present MEP values should lie at around 75% of the natural reference conditions for biological quality elements, while Ondiviela et al. [52] calculated MEP as the 90th, 75th or 25th percentile value calculated at reference sites with undisturbed or minimally disturbed hydromorphological conditions.

The number of indicators was greatly decreased for the assessment of AWBs, with the most important hydrological indicator being *days without flow in the channel*. The assessment of the hydrological regime for AWBs does not seem to be sensible; hence, the assessment of seasonal discharges was omitted from the analysis. The hydrological regime of an HMWB, no matter how morphologically altered, can be compared to its natural reference condition in terms of water quantity since it has a source and tributaries, and it depends on the precipitation regime and characteristics of its catchment. On the other hand, e.g., a drainage (flood protection) canal does not have its own hydrological regime. Water is diverted into the canal during high discharges of the main river, while during the rest of the year, it has only, conditionally speaking, landscape value as a green area with little moisture at the bottom of the channel. The same applies to drainage canals/ditches along the edge of reservoirs. They do not have a catchment or flow regime. Their amount of water depends on the water level in the reservoir since they receive water by underground and surface connections.

However, according to the WFD, GEP is also an ecological objective for AWBs, which should be achieved by implementation of mitigation measures. Although these measures are not as clearly defined as for HMWBs, the stress should be on the preservation of the ecological continuum. Examples of measures from the Netherlands include the gradual cleaning of canals, preservation of ecosystem network connectivity, stimulation of macrophyte growth by adjusting canal cross-sections and maintaining ecological flow throughout the year [14]. The maintenance of ecological flow is the most important measure since it enables the life of aquatic biota; however, it is often not feasible to implement in the case of small drainage dykes. According to the report by the ECOSTAT working group [53], many EU Member States argue that a significant effect of the benefits served by drainage can lead to a barely functioning ecosystem, and generally there is no common understanding of the minimum ecological requirements for GEP related to impacts from drainage. Vartia et al. [53] further emphasised the following hydromorphological changes as having the greatest impact on the reduction of good ecological status: reduction of biological continuity of watercourses due to loss of shading or removal of riparian vegetation, changes in flow minimums and flow rates, changes in substrate composition, changes in the slope of the banks and the loss of natural shapes and structures in the channel.

These hydromorphological changes, as well as measures noted in the case of the Netherlands, are in line with the indicators for the assessment of AWBs with the use of drainage in this methodological framework. Therefore, good conditions of flow, longitudinal connectivity, artificial materials in the channel, bank structure, bank slope and riparian corridors can be highlighted as important requirements needed to achieve GEP for AWBs.

5.3. Impact of Hydromorphological Modifications on Biological Quality Elements

To obtain a complete picture of ecosystem function and distinction of MEP sites, the results of this study should be combined with the results of biological monitoring in order to determine the response of biological communities at different levels of degradation [36,37]. In Croatia, a study on hydromorphological alterations of natural water bodies [54] showed that homogenization of the substrate is especially problematic for invertebrates.

A study of HMWBs in Germany [55] showed that at the reach scale, river bank conditions most strongly affected fish, while the naturalness of channel planform was best related to the ecological status of macroinvertebrates. However, pressures at larger spatial scales, such as catchment land use, especially urbanization and hydromorphological alterations in the river network, were generally more important than hydromorphological alterations at the reach scale [55].

Many studies have shown the importance of riparian vegetation for both river hydromorphological processes and ecosystem functioning [56,57]. The continuity of a woody riparian zone on the riverbanks provides channel shadowing and woody debris in the channel, thereby reducing the water temperature and ensuring morphological heterogeneity of channel features and habitats [58]. Erba et al. [39] found that tree cover, large woody debris and set back embankments were the most important variables determining differences between MEP and non-MEP sites, which showed significant differences regarding invertebrate assemblages. Furthermore, Buffagni et al. [59] found that the microhabitat mosaic together with substrate diversity can be used directly to assess the overall quality of microhabitat structure and heterogeneity and thus serve as useful elements for the evaluation of ecological status or potential. They also found a positive effect of mitigation measures on benthic communities, including improvement of riparian vegetation and in-stream habitats. Therefore, González del Tánago et al. [60] proposed a further improvement of hydromorphological assessment methodologies by implementing a more thorough investigation of riparian vegetation characteristics.

6. Conclusions

The definition of MEP is still an ongoing and challenging issue related to the implementation of the European Union's WFD. The lack of clearly defined and exact methodologies and the pure nature of HMWBs and AWBs, whose designation depends on the Member States' judgement of the applicability of potential mitigation measures, leaves a great deal of space for different interpretations and assessments. Although important steps have been made since the issuing of the WFD in 2000, especially regarding a common library of measures, much decision-making still depends on the water management systems of the Member States. Hydromorphology plays a decisive role in the designation of HMWBs and AWBs as well as in the determination of MEP. An exact and comprehensive methodology used for the assessment of hydromorphological quality elements should serve as a basis for all later analyses, assessments and restoration activities. Therefore, it is crucial to carefully examine the development of hydromorphological monitoring and assessment systems. This study presented a methodological framework consisting of the typology of HMWBs and AWBs, guiding principles and the selection of indicators for monitoring and assessment of hydromorphological potential in Croatia. For only about a third of analysed water bodies, the hydromorphological conditions were assessed as being satisfactory and in line with the criteria for good ecological potential. The lowest scores were generally noted for morphological indicators due to widespread usage of hard engineering approaches such as river channelization and straightening. Furthermore, the water bodies with lower morphology scores are generally the shorter ones, meaning that smaller rivers have on average less favourable hydromorphological conditions than large rivers.

We believe that the approach taken in this research could be transferred to other Member States. In the future, further developments should be made regarding the determination of environmental flows and identification of the response of biological quality elements to hydromorphological mitigation measures.

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