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ASSESSING THE EFFECTS OF A HYDROPOWER PLANT BASIN ON FISH SPAWNING IN AN UPSTREAM RIVER TRIBUTARY

OCENA VPLIVA JEZA HIDROELEKTRARNE NA DRSTENJE RIB V GORVODNEM PRITOKU

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Keywords: environmental impact; habitat sustainability; hydro-dynamic model

Abstract

This paper presents a combined modeling approach to evaluate the ecological effects on the habitat of an upstream tributary of a river with a series of hydropower plants. The influence is investigated of the last planned hydropower plant to be built, which has a large impact on the river ecosystem. The new hydropower plant basin will affect the tributary with hydropeaking in the upstream basin. A simulation was conducted of spawning conditions for two protected fish species. The analysis combined a hydro-morphological model with a fish module that considers the water depth and velocity necessary for fish reproduction. The different river discharge scenarios were simulated, incorporating the hydropeaking effects of the new hydropower plant basin on the upstream tributary. With the new hydropower plant, sustainable measures are planned to prevent the damaging negative impacts that could lead to the degradation of the river ecosystem and the destruction of the existing ecosystem at the river's confluence. The results indicate that, after the hydropower plant begins operation, the habitat`s suitability will decrease, and the planned sustainable measures will not provide a fully satisfactory solution.

Povzetek

Članek predstavlja kombinacijo modelov za oceno ekoloških učinkov na habitat reke, na kateri je že veriga hidroelektrarn. Načrtovana je zadnja hidroelektrarna v verigi in treba je raziskati njen vpliv na ekosistem reke, pravzaprav na pritok reke pred novim jezom. Novi jez hidroelektrarne

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bo močno vplival na zgornji pritok z nihanji gladine. Izvedena je bila simulacija pogojev drstitve za dve zaščiteni vrsti rib. Analiza je kombinacija hidromorfološkega modela in modela indeksa habitatov, ki upošteva predvsem globino in hitrost vode, potrebne za reprodukcijo rib. Simulirani so različni scenariji pretoka reke, pri čemer so bili upoštevani učinki spremembe gladine jeza zaradi obratovanja hidroelektrarne. Z novo hidroelektrarno so načrtovani tudi trajnostni ukrepi za preprečevanje negativnih vplivov, ki bi lahko pripeljali do degradacije ekosistema reke in uničenja obstoječega ekosistema na sotočju rek. Rezultati kažejo, da bo po začetku obratovanja hidroelektrarne ustreznost ekosistema padla, načrtovani trajnostni ukrepi pa ne bodo zagotovili povsem zadovoljive rešitve.

1 INTRODUCTION

Slovenia lies at the junction of four natural areas, the Alps, the Mediterranean, the Dinaric Mountains, and the Pannonian Basin. The Slovenian territory drains mainly through the Sava River and its tributaries into the Danube, and, finally, to the Black Sea (approximately 80%), while the rest drains into the Adriatic Sea. In the highland Alps and subalpine mountains there are many torrential streams in which flash flooding can occur during excessive rainfall [1]. Because of Slovenia's specific structure, its river basins, steep slopes, and impermeable bedrock, flash floods are the prevailing type of floods along most Slovenian watercourses [2].

The river ecosystems of the area undergo natural fluctuations in their hydrological cycle, with a variability ranging from floods to droughts. To deal with this variability, the common human response was to regulate rivers. Hydropower is a leading renewable energy resource in Europe, which has a "green image" due to its low greenhouse gas emissions. Hydropower plants (HPPs) are a synergy of river regulation and electricity generation, but they have negative impacts on aquatic ecosystems. The mitigation of the negative impacts on the environment is necessary.

Since their development, physical habitat models have become an essential tool for evaluating the habitat suitability for aquatic organisms, based on physical variables, such as depth, flow velocity, and substrate. This is particularly useful in assessing the impact of hydropower plants on the ecological state of the river, and the determination of the requirements for sustainable conditions for the aquatic population. Many rivers are characterized by structural disturbances, such as embankments and flood control weirs. As a significant migration barrier, these weirs alter habitat conditions, due to direct changes of the flow characteristic. Physical habitat models could enhance and evaluate the selection of options to reduce the impacts of water infrastructures on aquatic habitats in Slovenia and elsewhere.

The fish module of the habitat simulation model Computer-Aided Simulation Model for Instream Flow Requirements (CASiMiR) [3] was used to predict habitat availability and suitability for the fish species reproduction. PHABSIM is an alternative that must be supplemented with multiple observations of the same areas to develop a flow-habitat relation. In [4], the combination of HEC-RAS and PHABSIM carried a modeling framework comprised of hydrological, hydraulic, and habitat models for water management of unidirectional and tidal rivers. HEC-RAS is an integrated system of software, designed for interactive use by the Hydrologic Engineering Center of Engineers River Analysis [3]. This software allows researchers to perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling.

The evaluations of both models are presented in [5], showing strong and weak points in the simulations. The conclusions present sufficient coverage of the results, and, because CASiMiR is used commonly in Europe, it was suitable for our investigation. Habitat suitability is evaluated for the targeted life stage as in [6]: spawning in each cell with a direct method. The most used index of habitat is the Habitat Suitability Index (HSI), which is a tool to represent the preferences of different species for a combination of instream variables (water velocity and depth, the substrate, and cover, or shading with trees) [7]. The indices are in the range of 0–1 for each variable. Several suitability indices are combined to define a composite suitability index, assuming that all the variables are equally important, all the environmental variables are independent, and there is no interaction between them. Different methods could be used in CASiMiR to combine the different suitability indices obtained for each physical factor, and the indices are combined to calculate a composite HSI [8, 30]. The methods to obtain HSI are compared in [9]: the product method assumes that the most limiting factor determines the upper limit of habitat suitability, and the fact that high values cannot compensate for low values of other variables; the arithmetic-mean method is based on the assumption that the habitat variables are compensatory, and that the good habitat conditions on one variable can compensate for bad conditions on others [10]; the geometric-mean method also implies some compensation, but the product method yields zero suitability for any zero-valued indices. In the literature, CASiMiR is used often, and emphasized because of fuzzy rules to define the relationship between input variables and habitat suitability for certain species' life stages, which is not the case in PHABSIM. Different scenarios and their effects can be investigated, to find the most suitable conditions for species in all life stages [11]. Since the amounts of fish data available for this study were limited and the development of fuzzy rules for the description of habitat suitability was based on expert knowledge and the limited database (Table 1), a quantitative validation of the model could not be performed within this study. The outputs of CASiMiR were used to assess the changes in fish habitat availability and suitability. First, habitat suitability maps for fish species at each combination of river flow and HPP hydropeaking (normal and minimal basin levels) were generated, to visualize the areas within the river that provide certain physical conditions for fish under a steady flow situation.

In the simulation, we used the CASiMiR standard preference function method, in which the condition of an aquatic ecosystem is coupled directly with the physical conditions of the reference species, focusing on spawning. Changes to the flow rate result primarily in impacting the water depth, flow velocity, and substrate conditions, all of which are major factors in determining the habitat suitability for spawning, and are evaluated directly with numerical models [12, 13, 32].

This study aimed to assess the effect of a hydropower plant basin and hydropeaking on those river habitat descriptors that depend on flow characteristics. Based on this, we evaluated sustainable habitat measures that are planned to reduce the impact of the hydropower plant basin. This paper aims to apply the CASiMiR approach, to investigate the impact of the hydropower plant basin on the habitat suitability of an endangered species spawning in Slovenia. The current situation in the tributary stretch will be compared with a simulation of the planned sustainable measures situation after the hydropower plant basin implementation. The investigation results will apply to other rivers with similar ecological problems.

2 MATERIALS AND METHODS

Slovenia produces approximately one third of its electric energy by hydropower on its main rivers: the Drava, Soča and Sava. HESS (Hidroelektrarne na Spodnji Savi) is a Slovenian hydroelectric power company, with its core mission of producing and promoting the construction of hydropower plants, and of engaging in electricity generation that is sustainable, reliable, competitive, and environmentally friendly [14] on the lower Sava River, and of improving protection from the flooding that occurs in the area annually. The construction of a series of five HPPs on the lower Sava started in 1999. The penultimate HHP, Brežice, entered service in 2018, and the final HHP, Mokrice, should be active by 2026. Their total output shall account for 21% of the Slovenian hydropower production, and it is anticipated that they will meet 6% of the Slovenian energy needs. They are all designed and provided with bays, fish paths, channels and spawning grounds, additional animal habitats, birds nesting grounds, and maintained or improved farming conditions. The last planned HPP is positioned near the Croatian border, where the Sava River is enriched by the Krka River; it will have a smoothing reservoir role in the scheduled streaming and storage regime on the Sava River. In the area is the Krško Nuclear Power Plant, which uses the Sava water to dissipate excess heat. The plant began operating in January 1983. This study focuses on the lower part of the Sava, and particularly on its tributary the Krka, presented in Figure 1.

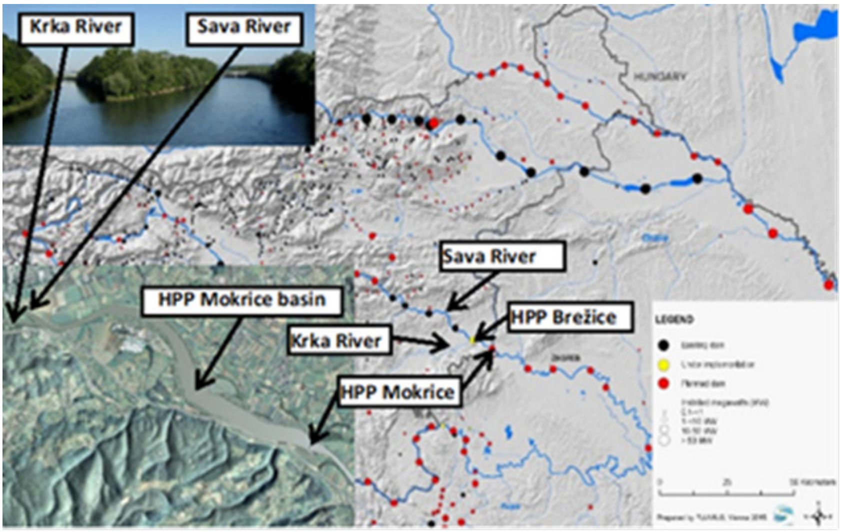


Figure 1: *Location of the study site. In the map of Slovenia are shown the existing and planned hydropower plants [15]. With arrows are marked HPP Brežice, that was put into service in 2018; the Sava River and tributary Krka River; their confluence and planned HPP Mokrice and its basin*

The region of the lower Sava is surrounded by hills. It is riddled with numerous permanent streams, as well as intermittent springs and streams. The two major rivers that cross the valley are the Sava and the Krka. The Sava is the longest river in Slovenia, and the Krka is its largest tributary. The area has experienced many flood events throughout its history, the biggest in 1990, and the last in 2010 [16]. The Sava River is sensitive to precipitation due to human impacts, such as urban development, and stream channel straightening. Intensive peak flows are observed several times a year, sometimes resulting in flooding of inhabited areas. It has to be pointed out that the ratio between the flow rates of the Sava and the Krka, especially when they exceed the average rate, is high. The power of the Sava's flow blocks (acting almost as a dam) the flow from the Krka and increases the floods upstream of the Krka drastically (Figure 1). Since 1999, the lower Sava has been the subject of human alterations, owing to the constructions of dams for hydropower production and embankments. The construction of a chain of hydroelectric power plants contributes to the reliable supply of electric power in Slovenia.

The functioning of the energy facilities and the related infrastructure also serve as flood preventers. However, the infrastructure impact on the environment causes the degradation of river ecosystems and biotic diversity, changing the hydro-morphological characteristics of the riverbeds [17] and their habitat suitability [18]. The infrastructure obstructs the connectivity of river habitats [19], and fish paths are implemented for the migration of fish; on high waters the fish swim down the river, and when the water level decreases the fish migrate upstream, which can be observed primarily in regulated rivers [20].

When the chain of HHPs are operating in peak time but in lower than the installed flow $Qi=500m^3/s$, the accumulation basins of the HPP Brežice and HPP Mokrice have the role of equalizing the daily Sava variability of water flow from the upstream HPPs. In the flow balancing, the fluctuation in the accumulation basin of HPP Mokrice is calculated to be up to 1.3 m, the normal water level at 141.7m above sea level, and minimum water level at 140.4m above sea level.

By fluctuating the level of the last two basins, the upstream HPPs will work with the full installed flow at peak time. Outside the peak time the upstream HPPs will operate at a lower flow, filling the basins, while the HPPs Brežice and Mokrice will have the opposite rhythm of operating conditions. The effect of the Sava River with the HPP Mokrice basin on the Krka River with the daily fluctuation of water level is hydrologically and morphologically tremendous: changing the drainage regime from the river to the regime of slowly running water in the river mouth, changing the natural dynamics of the river, changing the physical conditions of the aquatic habitat, and the river mouth is the spawning grounds of many species.

The hydrological data for all the Slovenian rivers and lakes are available on the web page of the Slovenian Environment Agency (ARSO) [21]. ARSO performs expert, analytical, regulatory, and administrative tasks related to the environment at the national level. The riverbed's form and elevation were obtained from the project of the HPP basin provided by INFRA [22], which was established as a public company for the implementation and maintenance of the water infrastructure facilities in the lower Sava.

The hydraulic structures, such as hydropower plants, dams and wires, affect the water environment for plants and aquatic lives in and around rivers. Therefore, before the construction of such hydraulic structures, it is necessary to conduct environmental assessments [23]. The abiotic parameters, with the morphological characteristic of the river, determine the physical habitat for living organisms. Consequently, the availability and suitability of this habitat are altered by the modification of the abiotic parameters. Fish are very valuable aquatic organisms, and as good indicators of the environmental state of the ecosystem, they are often chosen as the target species to study the impact of HPPs on the environment [24]. The studies demonstrated that the fish populations are less abundant and have reduced population sizes in hydro-peaking rivers in the River Cabriel, Spain [25]. The results from [26] show how the overall habitat quality fluctuates daily due to the dam operation in a big river.

Table 1: *Fish spawning conditions*

fish	depth [cm]	substrate size [cm]	flow velocity [m/s]
Alburnoides bipunctatus	*14–20*	*2.0–10.0*	*0.2–0.5*
Squalius cephalus	*15–30*	*>0.5*	*0.2–0.5*
Barbus barbus	*15–50*	*2.0–5.0*	*0.3–0.5*
Vimba vimba	*<50*	*0.2–6.0*	*>0.2*
Rutilus rutilus	*15–45*	*5.0–15.0*	*>0.2*
Chondrostoma nasus	*15–30*	*2.0–6.3*	*0.9–1.1*
Romanogobio uranoscopus	*15–20*	*5.0–20.0*	*1.0–1.3*

The physical habitat conditions were assessed from the Fisheries Research Institute of Slovenia, that is a central, expert institution in the field of Fisheries in Slovenia. The institute is engaged in activities that contribute to the sustainable management of fish populations and the preservation of their diversity; it is very active in order to preserve or substitute fish area habitats. They prepared Table 1 on the spawning conditions for some fish species spawning in the Krka River. Most fish species in the Krka are spawning in the springtime, from March to May. The mean discharge for the previous ten years was calculated for both rivers. The spawning time often coincides with a low discharge of the Krka, so we also take into consideration the minimal mean discharge for the same period. The Fisheries Research Institute of Slovenia confirmed the selected discharges used in the simulations: mean discharge Qs=54.5m^3/s and minimal mean discharge nQs=10.9m^3/s.

We obtained spawning data for seven fish species (Table 1). Considering the spawning conditions, we classified the seven species into two categories with similar requirements. Two reference species (marked in Table 1) could represent the hydrological spawning conditions for all the species.

2.1 Planned sustainable measures

It was expected that the HPP basin would have an impact on the Krka ecosystem (confirmed with the simulations in Figure 5). Without measures to prevent the damaging of the drainage section of the Krka, there would be negative impacts that would cause degradation of the river ecosystem and the destruction of existing fish habitats in the affected area.

Several main measures are planned to preserve a sustainable regime in the Krka River [27]:

- The Sava riverbed will be deepened, to lower the water surface of the river and to prevent floods in the confluence.
- The bottom of the Krka's riverbed will be widened and raised, to maintain the hydro and morphological river characteristics of the Krka: depth and water velocity.
- A Cascade passage will be constructed at the Krka mouth with a length of 150m, to prevent the spread of fluctuations of the HPP basin into the Krka.

- Four approximately 150m-long pebbled shallows will be implemented in the riverbed of the Krka, arranged as spawning grounds for fish species. The locations of shallows are presented in Figure 2.

The status of the aquatic system and suitability for fish spawning was simulated, considering no sustainable measures applied, implementation of sustainable measures (change of the riverbed geometry), with the hydrological parameters for fish spawning.

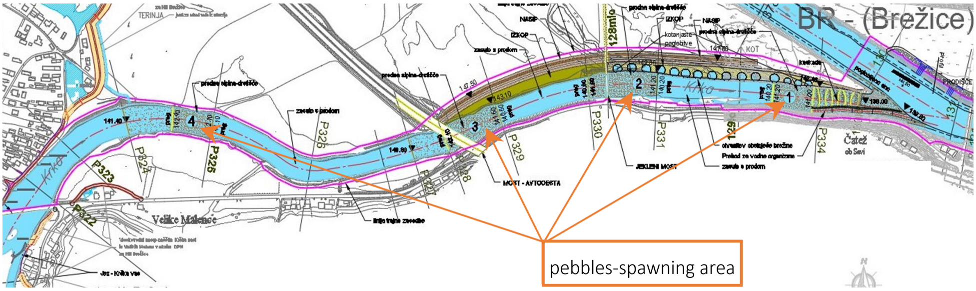


Figure 2 *The part of the Krka River with marked shallows as spawn areas [27]*

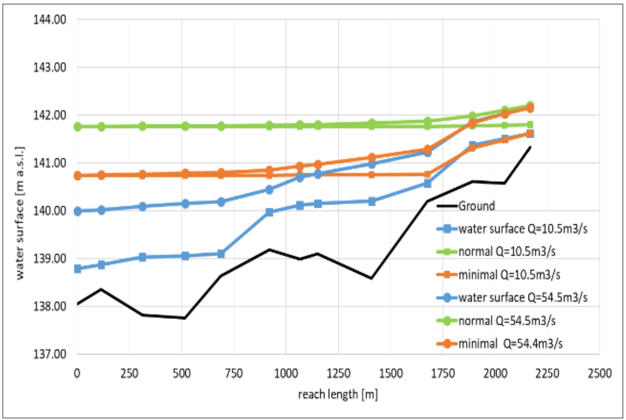
3 RESULTS

The hydraulic component of this study was performed using the HEC-RAS model [19] to construct a one-dimensional hydraulic model simulating water surface levels for the studied stretch, based on the prismatic riverbed elevation values [28, 32]. Since changing flow rates influence the flow velocity and consequently the fish habitat significantly, water depths and velocities were simulated for two different flow values: mean and minimal mean discharge. The HEC-RAS model uses geometric and flow data to calculate steady, gradually varied flow water surface profiles (steady-flow module) from the energy loss computations. A quasi 2D approximation [28] was obtained, by dividing each transect into subsections and distributing the flow along the subsections using simple linear interpolation techniques, and respecting the conservation of energy. The modeling capabilities of HEC-RAS for the water flow rate and calculated velocity values were found to be adequate with the measured values in many publications [e.g., 10, 20, 29].

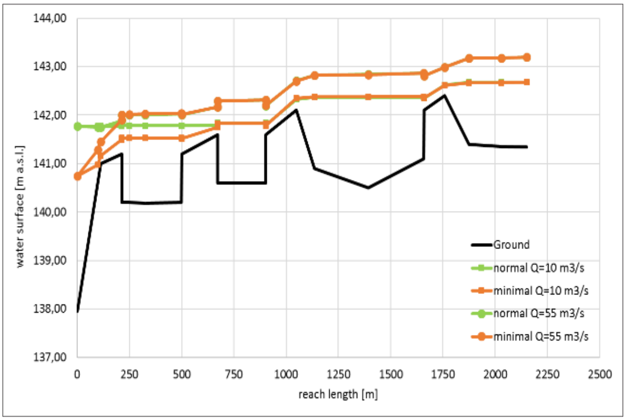
The hydraulic model was calibrated and validated (Manning's values) using the values of the velocity and depth measurements taken during ongoing field investigations by INFRA.

Each cross-section was divided into several longitudinal subsections, defining a grid for every study reach. The water surface levels and flow velocities were simulated for two scenarios: the current situation without an HPP basin, and the new situation after the HPP basin implementation. The results of these simulations could only be calibrated for the first scenario, since the implementation of the HPP basin has not yet been conducted. The study reach was analyzed hydraulically, with hydraulic controls at the downstream end.

In the second scenario, the bed elevation in the Krka River was changed according to sustainable measures. The bed of the Sava River was deepened, and the bed of the Krka River was raised, with spawn areas and deepened buffer intermediate spaces. The change of the Krka riverbed is seen in Figure 3 (Ground), and the results of a water surface analysis in the Krka River are presented for the current situation and planned change of the riverbed for normal and minimal basin levels.



a) Current situation



b) Planned situation

Figure 3: *Results of the water surface level from HEC-RAS for a normal basin level (141.7m a.s.l.) and minimal basin level (140.4m a.s.l.) a) currently, and b) Status after the planned measures*

The results in Figure 4 present the Krka reach. CASiMiR linked the water surface level simulations from HEC-RAS with morphological data, to calculate and interpolate the flow velocity in the river stretch. The depth, flow velocity and dominant substrate values were assigned to each cell of the grid, based on linear interpolation. The simulations were performed for two flows of the Krka River (mean and minimal mean discharge) with the current form of the Krka riverbed. We performed the analysis to simulate the HPP basin impact at normal and minimal basin elevation as hydropeaking disturbances [30,31].

The results presenting water depth and flow velocity showing significant ecological impact of the HPP basin are shown in Figure 4. Even at minimal basin water level, the changes in water depth and velocities are large. The water depth increases severely, and, consequently, the water velocity declines severely, especially in the confluence where the elevation of the basin is higher than the water surface of the Krka River.

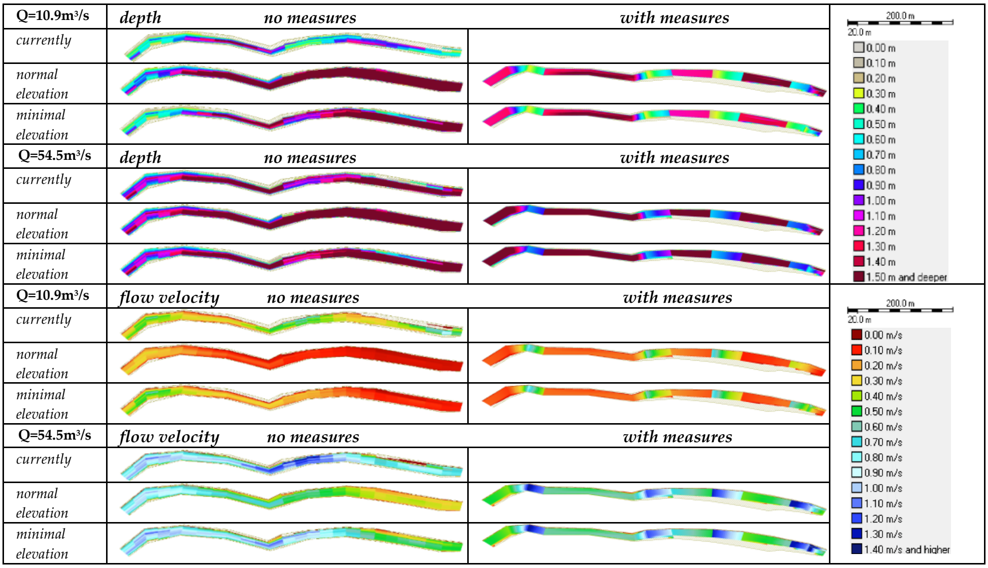


Figure 4: *Results of water depth and flow velocity with CASiMiR for minimal mean discharge nQs=10.9m³/s and mean discharge Qs=54.5m³/s with the current riverbed for HPP Mokrice normal basin level (141.7m a.s.l.) and minimal basin level (140.4m a.s.l.), with and without sustainable measures implemented in the simulation*

The planned sustainable measures were simulated for the same water regime: two flows of Krka minimal mean discharge and mean discharge at normal and minimal basin elevation. The new riverbed geometry was updated with widened banks and elevated bottom of the Krka River; four pebbled shallows were added (spawning area). The results reveal a much more varied picture (Figure 5).

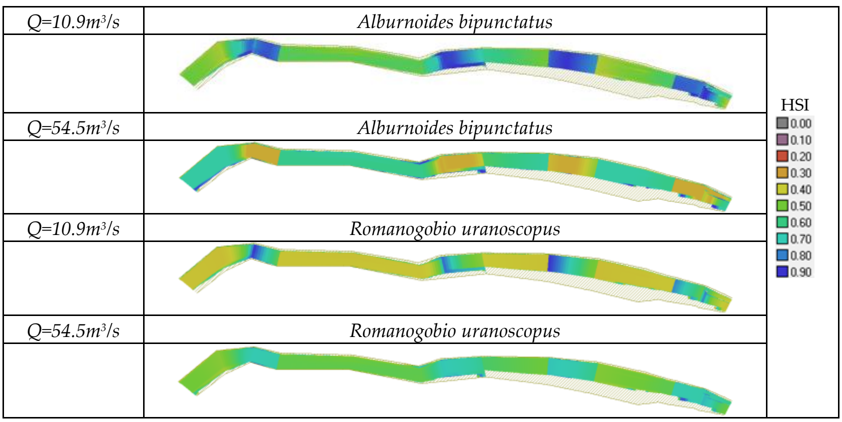


Figure 5: *HSI results from CASiMiR for two fish species for minimal mean discharge nQs=10.9m³/s and mean discharge Qs=54.5m³/s with sustainable measures implemented in the simulation for the minimal basin level (140.4m a.s.l.)*

The depth and water velocities at the shallows are much more suitable for fish spawning. We simulated spawning conditions for two reference fish species with the data from the Fisheries Research Institute of Slovenia presented in Table 1. The results are presented in Figure 5, with the HSI index calculated for two fish species for the mean and minimal mean discharge for normal and minimal basin levels. The results indicate that the hydropeaking (different basin level) has less influence on the HSI index in comparison with the river discharge, which is the primary influence parameter. As can be seen from the results of the simulation, the basin level has less influence on the spawning parameters than expected, much less than the river discharge.

4 CONCLUSIONS

Artificial hydraulic river structures, such as HPPs, introduce discontinuity and disturbances to river natural flows and ecosystems. This paper examines finding a balance between flood management, river regulation, and energy production on the one hand, and the preservation of river ecosystems on the other. The implementation of the chain of HPPs in recent years on the Sava River has consequences. Many modifications of the flow channel due to HHPs and flood control weirs have led to higher depths than under natural conditions and a reduction of the flow rate. The last HPP in the chain on the lower Sava River and its basin influence its upstream Krka tributary significantly.

Non-government organizations and local initiatives in Slovenia [33] argue that the approved project of HPPs leads to the destruction of the flora and fauna of the Sava River, especially because the mouth of the Krka into the Sava River is one of the most important spawning grounds of this species in Slovenia. Eleven fish species (*Barbus balcanicus, Zingel streber, Romanogobio uranoscopus, Romanogobio kesslerii, Cobitis elongatoides, Cobitis elongata, Alburnoides bipunctatus, Rutilus virgo, Hondrostoma nasus, Barbus barbus and Vimba vimba*), protected under the EU Habitats Directive (Directive 92/43 of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora), are endangered by the project. The proposed measures for these species, according to [33], are not conducive, since the basin level intervenes the tributary. According to the study of Schwarz [15] commissioned by Riverwatch and EuroNatur, the dispute about HHP Mokrice is, thus, crucial for the future of the Sava River and for the ecosystem of the Krka River. In contrast to the Sava, the Krka is not a regulated river and is one of few in Slovenia with rich fish habitats, particularly with indigenous fish species.

Within the framework of the projects of HPPs, the level of floods at the Sava and Krka are reduced significantly, with deepening of the three kilometers of the Sava River downstream from the HPP Brežice. The sublimation of the Sava goes a further two kilometers downstream of the Krka outbreak. With additional regulatory measures in the Sava and Krka, the flooding level is reduced by 1.3 m. These measures are strong: they reduce the required range of flood protection of sites that are flooded regularly. In the investigation, the sustainable measures were simulated for two flow rates of the Krka and two basin levels. In the simulations, emphasis was placed on the planned areas for fish spawning for two representative fish species. The results show that the HPP basin has an enormous impact on the hydrological and ecological parameters of the tributary (Figure 5). The depth of the Krka River increases, and the flow velocity decreases; without sustainable measures, the nature of the Krka is different. The changes in the Krka River caused by the basin could be prevented by lifting the bottom of the Krka River in the outflow section, and four pebbled shallows in the riverbed will be created to preserve the hydro morphological river characteristics of the Krka. Taking the planned sustainable measures into account, the hydrological characteristics and HIS (Figures 5 and 6) of the river are more suitable for fish spawning. As can be seen from results, there is no point in presenting weighted usable areas (WUA) or hydraulic habitat suitability (HHS), as only pebbled shallows areas are suitable for spawning. Without measures to prevent the damaging of the drainage section of the Krka, there would be negative impacts that would cause degradation of the river ecosystem and the destruction of existing fish habitats in the affected area. The planned measures need to be renamed from sustainable measures to mitigation measures. More thorough investigations should be carried out for endangered species for spawning, juvenile, and adult fish. The currently planned measures are focused only on spawning and river hydraulics. The uneven bottom along the cross-section of the riverbed could distribute the flow velocity, and an additional winding channel in the riverbed could increase the habitat quality for various fish species at lower flow rates.

The study showed the potential of the modeling approach, and more parameters have been planned to understand the quality and distribution of suitable habitats better very soon.

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