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CONSERVATION OF FISH MIGRATIONS AT HYDROELECTRIC POWER PLANTS: FISH PASSAGE SYSTEMS AS AN ENVIRONMENTALLY RESPONSIBLE MEASURE

OHRANJANJE RIBJIH MIGRACIJ OB HIDROELEKTRARNAH: PZVO KOT OKOLJSKO ODGOVOREN UKREP

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Abstract

The geostrategic situation in the world is a stark reminder that, for any country seeking to be sovereign, it is essential to strengthen the degree of energy and food self-sufficiency as soon as possible, all the while also ensuring sustainable environmental and social development. In terms of renewable energy sources, Slovenia has the greatest privilege in being able to utilise hydropower and wood biomass for energy uses. The paper discusses the importance of implementing multipurpose and goal-oriented projects such as hydropower plants (HPPs), which fulfil a number of strategies set by the state and local communities. Since every human intervention in the environment has certain impacts, the paper shows how synergistic effects can be created between environmental protection and energy sector development through responsible environmental planning and implementation of the best possible measures, drawing from a practical example of the multipurpose construction project of HPPs on the lower course of the river Sava. The paper addresses the issue of fish migration and barriers in watercourses, presenting the current situation in Slovenia and worldwide. It also examines the success of fish passes at HPP Arto-Blanca, based on several years of monitoring. Such passes enable fish to

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migrate past hydropower plants, maintain healthy fish populations, preserve genetic diversity, and ensure the connectivity and preservation of the entire aquatic ecosystem. The example of the future Mokrice hydropower plant illustrates the trend and commitments in the planning of such passes in the future.

Povzetek

Geostrateška situacija v svetu opozarja, da je za državo, ki želi biti suverena, nujno, da čim prej okrepi stopnjo samooskrbnosti z energijo in hrano ob sočasni skrbi za vzdržni okoljsko-družbeni razvoj. Slovenija ima na področju obnovljivih virov energije največji privilegij v koriščenju hidroenergije in lesne biomase. V prispevku je obravnavan pomen izvajanja večnamenskih in ciljno usmerjenih projektov, kot so hidroelektrarne, ki izpolnjujejo več zadanih strategij države in lokalnih skupnosti. Upoštevajoč dejstvo, da ima vsak človekov poseg v prostor določene vplive, je na praktičnem primeru večnamenskega projekta izgradnje HE na spodnji Savi prikazano, kako se lahko z odgovornim okoljskim načrtovanjem in izvedbo najboljših možnih ukrepov ustvarijo sinergijski učinki med varovanjem okolja in razvojem energetike. Predstavljena je tematika ribjih migracij in pregrad na vodotokih, prikazano aktualno stanje v Sloveniji ter po svetu in na podlagi večletnih monitoringov obravnavan primer uspešnosti ribjega prehoda pri HE Arto-Blanca. Tovrstni prehodi omogočajo ribam: migracijo mimo hidroelektrarn in ohranjajo zdrave populacije rib; vzdrževanje genetske raznolikosti; povezanost in ohranitev celotnega vodnega ekosistema. Na primeru bodoče HE Mokrice so predstavljeni trend in obveze pri načrtovanju tovrstnih prehodov v prihodnje.

1 INTRODUCTION

The geostrategic situation in the world is a stark reminder that, for any country seeking to be sovereign, it is essential to strengthen the degree of energy and food self-sufficiency as soon as possible, all the while also ensuring sustainable environmental and social development. In terms of renewable energy sources, Slovenia has the greatest privilege in being able to utilise hydropower and wood biomass. At the turn of the millennium, Slovenia's political strategy in the context of energy and climate change made bold strides towards increasing the share of electricity generated from renewable energy sources (RES). The actual effects of the special Act adopted in 2000 – "Conditions of the Concession for Exploitation of the Energy Potential of the Lower Sava River Act" (abbr. ZPKEPS) – are today reflected in the fact that Slovenia produces as much as 37% of electricity from RES. Hydropower plants (HPPs) account for the largest share, specifically 92%. The 4,880 GWh of net electricity production from HPPs in 2021 represents a 60% increase compared to the period 25 years ago *[1]*.

The HPP construction project in the lower course of the Sava is designed as a multipurpose project, the positive effects of which are manifested mainly in improved flood safety, development of the environment and biodiversity, agriculture, tourism, sports and recreational activities, and local and national infrastructure. It is also necessary to highlight the project's important contribution to the implementation of sustainable development, increasing the share of renewable energy sources and fulfilling Slovenia's commitments to the European Union (EU), maintaining competitiveness and strengthening Slovenia's industry, ensuring higher employment levels, and contributing to revenues for the national budget and the budgets of local communities *[2]*.

For centuries, man has reconfigured and blocked watercourses continually, with the aim of facilitating work, improving the quality of life, and making the energy of water do the physical work for him. In the area of present-day Slovenia, the energy of water was used predominantly to drive sawmills, pumps and grain mills. The latter began to appear there in the 9th century (Kos, 1906), and became widespread in the 12th and 13th centuries (Bogataj, 1982), with around 1,700 of them in operation by the end of the 19th century. The first hydroelectric power plants (HPPs) began to be built on the river Drava more than 100 years ago.

The construction of barriers on rivers therefore affected the migration routes of aquatic organisms and ecosystems. The problem of barriers and fish migration is much more widespread globally than it is in Slovenia. In the past, rivers in the European countries Spain (Cortes-La Muela Dam), Germany (Rappbode Dam, Bleiloch Dam, Eder Dam), France (Grand'Maison Dam), Portugal (Tamega Giga Battery Dam) and Switzerland (Grande Dixence Dam, Luzzone Dam) were outfitted with large barriers or HPP reservoir dams with depths exceeding 100 m and storing some 100 million cubic metres of water. Such impoundments can cause extensive changes in aquatic ecosystems, leading to declines in fish populations and loss of biodiversity.

Compared to abroad Slovenia practically does not have such barriers, as we have developed run-of-the-river reservoir HPPs with depths varying up to around 20 m and only storing some 10 million cubic metres of water. During the construction of the HPPs on the lower course of the Sava a number of nature conservation measures were taken into account, in order to reduce the impact of barriers on fish migrations and ecosystems. One of the key approaches was the development of run-of-the-river HPPs, which, with flow rates above 1,000 m^3/s, allow a river to flow freely over the HPP and enable the downstream migration of fish. In addition, other important solutions were also implemented at the HPPs Arto-Blanca, Krško and Brežice, such as fish passes (fishways) and other structures (spawning grounds, inlets, resting pools, quiet areas, replacement habitats) that help aquatic organisms and other animal species to overcome obstacles caused by barriers in the river. As part of the HPP chain on the lower course of the Sava, special attention was also placed on the planning of nature conservation measures, which allow the intervention in the environment to have the smallest possible impact [3][4], and which were approved by nature conservation, biology, ichthyology, water science, and technical specialists.

2 EXAMPLE OF GOOD PRACTICE – FISH PASS AT HPP ARTO-BLANCA

The Arto-Blanca hydropower plant was built in 2008 and went into operation in 2009. Next to the hydropower plant, a fish pass was built, the first of its kind to be situated next to an HPP on the Sava. The fish pass was designed with the aim of allowing the passage for all species of fish found in the lower course of the Sava. Ichthyology specialists and the Fisheries Research Institute of the Republic of Slovenia (ZzRS) were involved in the project from the outset.

The fish pass at HPP Arto-Blanca consists of a close-to-nature section imitating natural watercourses, and a technical inflow section made up of two branches and designed to regulate the flow with a double-gate system. The fish pass is of vital importance, particularly for the fish species that migrate over long distances in search of food and spawning grounds within the watercourse. These species include the common nase, common barbel, cactus roach, chub, ide, asp, vimba bream, carp bream, pike, huchen, brown trout and ruffe.

Figure 1: *Fish pass next to HPP Arto-Blanca, allowing the migration of aquatic organisms.*

By building fish passes or fishways, we allow the fish to pass smoothly past the dams over the long term, which prevents the fragmentation of populations, enables gene flow between populations, and, therefore, preserves the species` diversity in inland waters, while also allowing us to follow and meet the requirements of European and Slovenian legislation.

Standardised evaluations of the efficiency of the fish pass at HPP Arto-Blanca were carried out in 2009 *[5]*, 2010 *[6]*, 2012 *[8]*, 2015 *[9]* and 2022 *[11]*. In the close-to-nature section, the fish sampling was carried out using electricity or electrofishing, and in the technical part, in addition to the above method, sampling was also performed using creels (Figure 2, Figure 3). Already after the first two years of operation, it has become clear that the fish pass operated well and fulfilled its function fully *[6]*. The fish pass was recognised as an example of good practice in 2013, and was also cited in the report of the International Commission dealing with the Danube basin – the International Commission for the Protection of the Danube River (ICPDR) *[10]*.

The fish pass was negotiated demonstrably along its entire length by the common nase, chub, brown trout, vimba bream, cactus roach, common barbel, carp bream and five species from Appendix II of the Habitats Directive: the Danube gudgeon, white-finned gudgeon, Danube streber, spined and Balkan loach *[6], [7]*. In all the monitoring activities to date, a total of 35 species of fish and one species of lamprey have been recorded in the pass, and the functionality of the spawning grounds has also been confirmed. Eggs of the common nase were also observed attached to the stones in the fishway, which goes to show that the common nase spawned inside the very fishway *[6]*.

Figure 2: *Electrofishing in the fishway – close-to-nature section [8].*

Figure 3: *Deployment of a creel in the technical section of the fish pass [8].*

Species such as the common rudd, tench, Kessler's gudgeon, zander, burbot, white bream, Danube gudgeon and Danube streber were rare in this part of the Sava even before the construction of the HPP *[6], [8], [15]*. The fact that the above fish species were observed during previous run-of-the-river reservoir monitoring activities upstream and downstream of the HPP Arto-Blanca fish pass suggests that they were able to pass upstream past the dam structure, but, due to their rarity, they were not recorded during the fish pass samplings, or were only recorded during some samplings. Here, it needs to be pointed out that the incidence or observation of some species may also have been affected by the time of the year in which the sampling was carried out *[15]*.

The sampling with electrofishing in 2009, for example, was carried out over a period of 3 fieldwork days in the autumn, for the first time in September, when the fishway was still in trial operation, followed by the second and third times in November and December. In 2010, electric sampling was carried out over a period of 3 fieldwork days in March, June and October *[6]*, in 2012 over a period of 3 fieldwork days in May and September *[8]*, and, in 2022, over a period of 2 fieldwork days in May and September *[11]*. Creel sampling was carried out over a period of 8 days in July, September and October 2010 *[6]*, 10 days in April, June, July, August, September and November 2012 *[8]*, 5 days in March, May, June, September and November 2015 *[9]*, and 6 fieldwork days in April, May, June, July, September and October 2022 *[11]*.

In 2022, during the upstream passage along the fish pass, the highest number of species were recorded in the spring during spawning, and the lowest in the autumn. The passage along the fish pass is, therefore, connected most closely to the spawning migration, where sexually mature specimens move upstream between individual run-of-the-river reservoirs to spawning grounds, where the conditions for spawning in the fish pass are favourable for all the present species, allowing them to spawn inside the pass as well. The results of the monitoring activities confirmed that all the potamodromous fish species present in this stretch of the Sava can travel along the entire length of the fish pass, and that they also use the pass outside the spawning season. Based on several years of monitoring, it has been confirmed that the fish pass fulfils its function effectively, and is a key measure that allows the settlement and long-term survival of fish populations in the run-of-the-river reservoirs of hydropower plants.

3 PLANNED MEASURES TO PRESERVE FISH MIGRATIONS AT HPP MOKRICE

In order to ensure connectivity, a fish pass was already included in the project solutions during the Strategic Environmental Assessment (SEA) process, and followed the designs of the already operational fish pass next to HPP Arto-Blanca, which has been confirmed to be effective in practice *[7], [10]*. During the Environmental Impact Assessment (EIA) process, based on the guidelines for introducing measures to ensure fish migration *[12]*, significant progress has been made towards improving connectivity solutions. Based on the recommendations from the guidelines, it makes sense to build 2 fish passes on larger rivers (wider than 100 m) during the construction of HPPs, specifically one fish pass on either side of the river. In accordance with this requirement, an additional fish pass or diversion channel on the left bank of the Sava was added as part of the modification of Quiet Area 4 (MO4). Both fish passes are designed so as to achieve two essential objectives, i.e., passage for all fish species past the dam structure and establishment of conditions for their spawning. An essential element of the fish pass is a close-to-nature section ,designed in the form of a close-to-nature river channel.

Figure 4: *Fish Pass 1 on the right bank next to HPP Mokrice.*

Fish Pass 1, on the right bank, is 655 m long, and has an average longitudinal gradient of 1.3%, the total length of 6 spawning grounds in the close-to-nature section is 180 m, and all spawning grounds are the same length and more than 9 m wide. The spawning grounds are designed in the form of two parallel corridors, so that the spawning of lithophilic spawners is enabled along one bank, while along the other bank fish can pass upstream in all sections.

Fish Pass 2, on the left bank, or the diversion channel, has a close-to-nature section 1,260 m long with an average longitudinal gradient of 0.65%, with 4 spawning grounds with a combined length of 240 m, 3 resting pools with a combined length of 115 m, hiding spots, pools, and habitat structures. Adequate flow rates will be provided in both fish passes, enabling water flow velocities suitable for the migration of all species of fish in the area.

The spawning grounds will, thus, be located close to where the fish enter the pass, which is essential for the spawners during the spawning season. Stone-lined spawning grounds are provided, with conditions suitable for lithophilic spawners. Four types of structures are defined that represent different habitats: inlet chutes, spawning grounds, passages and pools. Fish travelling through the pass will be able to continue their journey up the run-of-the-river reservoir, and will also be able to access the Krka. It should be noted here that the Mokrice HPP is designed as a run-of-the-river HPP, where the water in the run-of-the-river reservoir can be exchanged up to 6 times a day. When constructed, HPP Mokrice will take over the function of ensuring the daily natural flow rate on the border profile within the HPP chain on the Sava. Therefore, there is no defined ecologically acceptable flow rate for HPPs on the lower course of the Sava, as is typically determined for derivative power plants. The following section provides an explanation behind the determination of the flow rates in the fish passes.

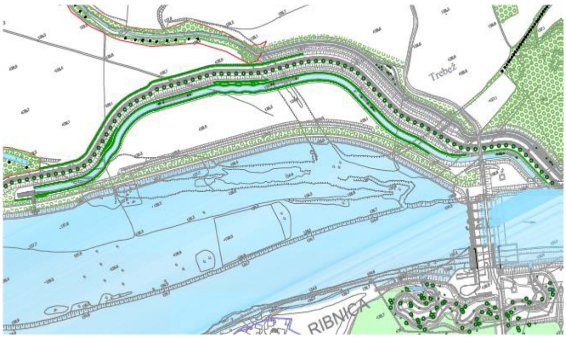

Figure 5: *Fish pass on the left bank, developed during the Environmental Impact Assessment (EIA) phase.*

The basic flow in the fish pass was determined according to the biological needs of migratory fish species that are located in, or that migrate in the river Sava in the area of the barrier inhabited by the fish of the barbel zone. The determination of the geometric and hydraulic variables in the fish pass, including the flow rate, is based on taking into account the following conditions, as provided in various authoritative manuals and Standards for the Danube region; ICPDR *[10]*, DWA-M-509 , BAW BfG Guideline, and others *[13], [14]*:

- the weakest swimmers of all age groups above 1+ are taken into account by determining the maximum permissible velocity of the water flow occurring in the narrowed sections, in the vertical slots of the compartmented section, and in the openings between the rocks of the close-to-nature ramps;
- in the vertical slots of the technical part of the inflow facility, the maximum permissible velocity is Vmax = 1.1 m/s. The velocity was determined through hydraulic model research at the Institute for Hydraulic Research;
- in the openings/gaps between the rocks on the ramps in the close-to-nature channel, the maximum permissible velocity of the water flow is Vmax = 0.6 m/s;
- the largest fish from the set of relevant fish species are taken into account, by considering the recommended minimum widths of narrowed sections and the minimum water depth

for them, taking into account the permissible maximum water velocity in the narrowed sections;

- the level of the upper and lower water at the barrier and the fluctuation of levels for a period of 300 days per year are taken into account, i.e., according to the recommendations of the ICPDR for the Q flows of the Sava between Q30 and Q330, i.e., for the period for which the passability, functionality and efficiency of the fish pass is ensured. This defines the height difference in the gaps between the chambers in the inflow technical facility, and on the ramps between the pools in the close-to-nature section.

Flow rate in Fish Pass 1: The basic flow rate in Fish Pass 1 is 800 l/s. Three operating flow modes with different flow rates are envisaged for different cases of ecological needs in the close-to-nature section of the fish pass in different seasons. At different flow rates, different water depths are established in the fish pass, while the water flow velocities are maintained.

Flow rate in Fish Pass 2: In the Technical Guidelines of the Fisheries Research Institute of Slovenia, a range of acceptable or optimal flow rates were determined, to ensure the functionality of all structures in this fish pass. The range of flow rates was determined between 2 m^3/s and 3 m^3/s, with the fact that Fish Pass 2 is already fully functional at a flow rate of 2 m^3/s, which means that, in this case, both objectives have been achieved: passability and spawning for lithophilic spawners. The central technical part of the inflow facility is dimensioned to support a flow rate of 800 l/s. The difference to the full flow rate of 2 m^3/s will be provided by a parallel channel next to the central part of the inflow facility, which will ensure the supply of additional water flow directly to the close-to-nature section of Fish Pass 2.

4 CONCLUSION

The energy sector and environmental protection have undergone significant changes over time, reflecting advances in technology and a growing concern for sustainable development. A historical review of the development of hydropower projects reveals changes in the approach to HPP construction, particularly regarding the inclusion of environmental measures such as fish passes. Until the end of the 1990s, HPPs and other dams were built without fish passes, which resulted in the fragmentation of fish populations and had a negative impact on the biodiversity of aquatic ecosystems. With advances in the knowledge of ecosystems, projects began to appear that already included environmental aspects at the planning stage. HPP Arto-Blanca, built in 2008, represents an important turning point in this regard, as it includes the very first fish pass on the Sava.

Evaluations of the efficiency of the fish pass at HPP Arto-Blanca yielded positive results. Monitoring has confirmed that all the fish species present in the area have negotiated the fish pass successfully, affirming the efficiency of the fish passes and their importance for the preservation of fish populations. A total of 35 species of fish and one species of lamprey were recorded in the fish pass, which confirms its functionality and allows fish species to pass between individual run-of-the-river reservoirs.

In the designing of the latest hydropower plant, HPP Mokrice, experience from past projects was taken into account, leading to the inclusion of two fish passes in the project. The basic flow rate in the fish pass was determined according to the biological needs of migratory fish species, ensuring that the efficiency and functionality of these passes are in accordance with European and Slovenian legislative requirements.

The shift from the construction of HPPs without fish passes to the inclusion of advanced fish passes in modern projects such as HPP Arto-Blanca, HPP Brežice and HPP Mokrice, reflects significant progress in terms of the integration and synergy of the energy sector and environmental protection. These projects not only contribute to the production of clean energy, but also support the preservation of natural habitats and biodiversity, which is crucial for sustainable development, the future of our ecosystems and the mitigation of climate change.

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Nomenclature

EIA	environmental impact assessment
HPP	hydropower plant
SEA	strategic environmental assessment
MO	quiet area
RES	renewable energy sources