

Shaping changes in the ecological status of watercourses within barrages with hydropower schemes – literature review

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Abstract: Hydropower use of watercourses has tangible consequences for the environment, society and economy. Based on a literature review and their own research, the authors present current data on changes in the ecological status of waters within run-of-river and reservoir hydropower plants, i.e. changes in biological elements (benthic macroinvertebrates, plankton, ichthyofauna, macrophytes), as well as hydromorphological and physicochemical changes. Previous researchers have noted that the impact of hydropower use of rivers on ecological status of those rivers is extensive, consisting of, among others, changes in species structure and populations of macrophytes, benthic macroinvertebrates, plankton and ichthyofauna (positive as well as negative changes), algal blooms due to increased turbidity, constrained migration of water organisms, changes in temperature within hydroelectric power plants, the phenomenon of supersaturation, eutrophication, changes in hydrological conditions (e.g., increased amplitudes of diurnal water levels and their consequent annual reduction), and increased erosion below the damming and deposition of bottom sediments on the damming barriers. In addition to such changes in ecological status, hydropower use also has a visible impact on socio-economic conditions (e.g., living standards of the population) and the environment (e.g., quality of bottom sediments and biodiversity). The article offers an assessment of the impact of hydropower use of rivers on ecological status (biological, hydromorphological, physicochemical elements and hydrological conditions of such rivers), society, economy and environment; it also proposes a research scheme to assess the impact of hydropower structures.

Introduction

Hydropower use of watercourses has tangible consequences for the environment, society and the economy. There has been comprehensive research conducted in this area by, for example, Bakken's scientific team in 2012 (Bakken et al. 2012), in which they collected results of research on 27 small hydropower plants (HPs) in Norway, each with a capacity of 1 to 10 MW. It was possible to conclude that there is a certain reduction in flow near HPs, and in most cases, to note changes in fish populations, as well as effects on aquatic habitats (Table 1). Facilities that are important for cultural heritage are, quite often, at risk, and the other impacts concerned a small portion of the tested HPs. This article verifies these assumptions based on a literature review.

To specify the scope of the article, several divisions of HPs should be listed. There are two main divisions of HPs, distinguished on the basis of capacity and the type of energy obtained (Figure 1). (Elbatran et al. 2015). This distinction is important, because most of the literature focuses on the impact of reservoirs that resulted from partitioning the riverbed of the

watercourse, while neglecting to determine the changes in the environment that the construction and operation of run-of-river HPs entail. However, pumped-storage HPs are not a renewable energy source and, for this reason, they were omitted in further analysis. (Erinofardi et al. 2017, Rotilio, Marchionni & De Berardinis 2017). The article focuses mainly on small (capacity < 10 MW) diversion and impoundment HPs.

The purpose of the article is to present, based on the literature and authors' own research, current data on changes in the ecological status of waters within barrages with hydroelectric buildings, taking into account the impact on the environment, society and economy.

At first, to introduce the subject of the article, a definition of the concept of the ecological status of waters is presented. The requirements to assess the ecological status of the watercourses, in line with the provisions of the Water Framework Directive, are very carefully presented. Then, a summary of the assessment of the impact of HPs on the biological aspects of the ecological status of water is presented – based on a literature review, as well as on hydromorphological and physicochemical elements and on hydrological conditions.

The next part of the work develops and proposes a research scheme on hydropower facilities, and provides an assessment of the impact of hydropower use of rivers on these individual elements: ecological status (biological, hydromorphological, physicochemical and hydrological conditions), society, economy and environment.

Impact of barrages with hydropower schemes on ecological status of watercourses, society, economy and environment

Ecological status of watercourses

The definition of ecological status derives from the provisions of the Water Framework Directive (WFD) (EP 2000). This status consists of three types of elements characterizing the aquatic environment: biological, hydromorphological and physicochemical (Nõges et al. 2009; Wiatkowski & Wiatkowska 2019). It is appropriate to use the term “ecological status” when the watercourse is natural, whereas in the case of artificial and heavily modified watercourses, it is appropriate to refer to “ecological potential” (Borja & Elliott 2007). Due to the fact that long-term changes in river ecosystems better reflect occurring organisms, biological elements are the foremost in the assessment of ecological status (Szozkiewicz et al.

2009). Physicochemical and hydromorphological elements complement this assessment by providing information on the physics and chemistry of the water at the time of measurement, while hydromorphological elements provide an assessment of the naturalness and/or transformation of river habitats (Carballo et al. 2008). The methods in European Union countries differ due to local conditions, but there has been a unification of the division of research sections into elementary parts – the so-called uniform surface water element is such an elementary part that has similar hydrological properties (e.g. characteristic water levels and flows). In the case of watercourses, there are surface water bodies (SWB), as in the case of reservoirs or seas (Voulvoulis et al. 2016; Poikane et al. 2014; Pawłowski 2010). Thus, the WFD assumes achievement of at least good ecological status in the SWB, which ensures appropriate conditions for the growth and development of organisms, as well as provides good water quality to meet the needs of industry, services and households (Carvalho et al. 2018; Loga, Jeliński & Kotamäki 2018).

The article describes, in detail, the impact of HPs on the biological elements (plankton, benthic macroinvertebrates, ichthyofauna, macrophytes), hydromorphological elements and physicochemical elements (especially dissolved oxygen and pH), as well as on hydrological conditions in the watercourse. In addition, the article describes the impact of

Table 1. Types of small hydropower plant impacts with their percentage share in the total number of tested hydropower plants (Bakken et al. 2012)

Type of hydropower plants' impact on the environment, economy and society	Percentage of impact in the total number of tested hydropower plants
flow reduction	100%
changes in fish populations and abundance	78%
impact on aquatic habitats	67%
threatened cultural heritage	44%
changes in the landscape	11%
changes of water quality	11%
threat to aquatic organisms	7%
reduction of river habitats for birds and fish	7%
threat of landscape changes	7%
water temperature changes	7%

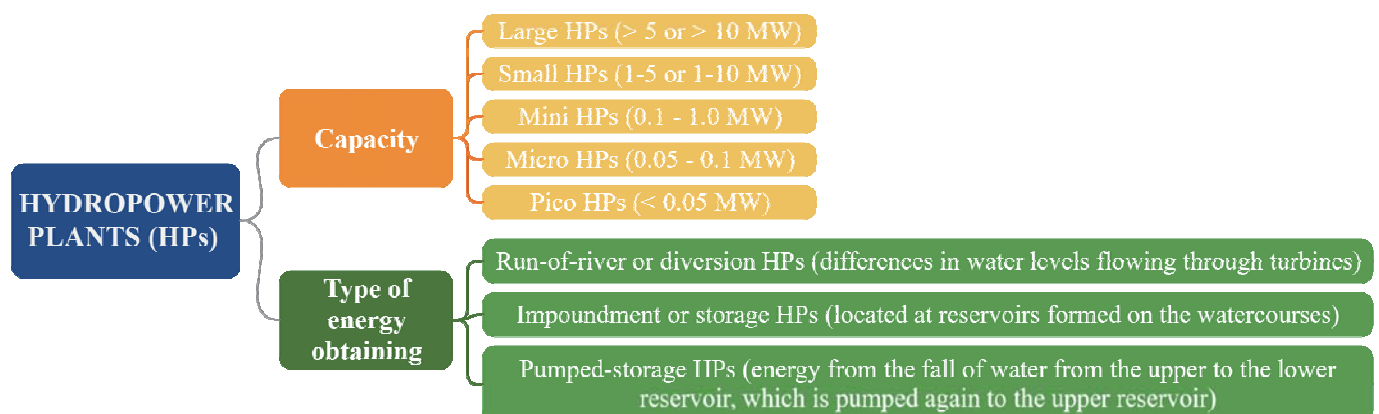


Fig. 1. Division of hydropower plants based on capacity and type of energy obtaining

hydropower river use on society and the economy, as well as on the environment.

Biological elements

Benthic macroinvertebrates

Benthonic organisms, which live at the bottom of watercourses and water reservoirs, are a good indicator of ecological status, thanks to their limited range (specific habitat requirements) and their stability over time (Armanini et al. 2014). In this case, the focus was limited to animal organisms (zoobenthos) that have dimensions visible to the naked eye (macroinvertebrates), unlike plant organisms (phytobenthos) with dimensions that are not visible to the naked eye (microinvertebrates) (Aller & Stupakoff 1996).

These animal organisms include many taxa, but the most important in water environment are Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies) – also known as EPT (Bruno et al. 2010; Wang et al. 2016; Álvarez-Troncoso 2015). In the context of assessing impacts of the operation of HPs, it is currently impossible to determine a clear impact on these organisms, in terms of their number and structure (Abdel-Gawad & Mola 2014).

In the first case, the reduction in the number of organisms was evident in the source areas of the rivers, where the banks of the watercourses (especially floodplains) underwent significant transformations conditioned by higher altitude and higher concentration of river sediments (de Figueroa et al. 2013; Malmqvist & Englund 1996). Such conditions caused a reduction in the number of macrozoobenthos in these regions, which was therefore not a result of the presence of HPs (for example, above the Jiangrang run-of-river HP on the Qiemuqu River in China, the average number of macroinvertebrate taxa was 10 and below 8; density: 59 ± 30 and 43 ± 31 individuals per m^2 , respectively; for comparison: in the riverbed these values were 7 and 11 ± 11 and in riparian wetland – 14 and 232 ± 92) (Pan et al. 2013). However, another source identified a noticeable impact of HP on benthos – on sections above HPs in five German rivers in Bavaria, researchers detected an average of 18 ± 2 species (maximum 64; characteristic taxa: Oligochaeta and Chironomidae), and below, 25 ± 2 (maximum 81; characteristic taxa: Plecoptera and Trichoptera) (Mueller et al. 2011).

Other studies have shown that the impact of HPs is significant, and that it concerns fluctuations in water levels caused by the operation of impoundment HPs (e.g., the Lundesokna and the Bævra rivers in Norway). The greatest impact was recorded in the case of mayflies and chironomids (although chironomids returned to equilibrium before the accumulation after 48 days), whereas the population of earthworms did not change significantly. In addition, filter feeders tend to increase their populations in terms of their wealth (abundance from 20% to 50% below HPs and approximately 10% above), while collectors and grazers tend to decrease (relative abundance from 20% to 40% downstream from hydropower stations for collectors and 20% for grazers, and upstream, 40% and 35%, respectively). These trends mean that the overall pollution of the aquatic environment, as a result of water level fluctuations, is greater than without water level fluctuations phenomenon – this is indicated by the increased population of chironomids and the reduction of mayflies (Kjærstad et al. 2018).

In addition, other studies have not only observed increased populations of chironomids and earthworms, but also a decreased population of beetles, along with the maintenance of a relatively high number of mayflies. Under fluctuating conditions (HP operations), 91 organisms per square meter were recorded, relative to the 743 recorded when there were no fluctuations in water levels (the Missouri River, reservoir hydropower on Gavins Point Dam, United States) (Troelstrup & Hergenrader 1990).

Other researchers have studied the impact of HPs on the richness and population structure of macroinvertebrate species, as well as the impact of HPs on different feeding groups of organisms. Such prior research consists of the following specific studies: the spatial distribution of macroinvertebrate assemblages in 5 cascade HPs along the Xiangxi River in China (Xiaocheng et al., 2008); the assessment of effects of hydropeaking and cold thermopeaking on the drift of selected aquatic macroinvertebrates in the Seebach River in Austria (Schülting et al. 2016); the impact of the HP and dam on richness and population structure along the Poio and the Balsemão rivers in Portugal (Cortes et al., 1998), the influence of water abstraction for run-of-river HPs on benthic macroinvertebrates microhabitats – the Lathkill River in Great Britain (Anderson et al., 2017); threshold responses of macroinvertebrate community composition to stream velocity in the Guayas River in Ecuador (Nguyen et al., 2018); benthic macroinvertebrates organization (abundance, diversity and composition) near HPs along the Virvyte River in Lithuania (Vaikasas et al. 2013); characterization of the ecological effects of a run-of-river and impoundment HPs on the structure of benthic macroinvertebrate assemblages in the Pandeiros River in Brazil (Linares et al., 2019)).

Plankton

Plankton are organisms, both animal (zooplankton) and plant (phytoplankton – mainly algae), that are unable to move actively in water, and they are displaced by currents and tides (Rajfur et al. 2011; Moog 1993). Research has shown the direction of changes in the structure of plankton to be rather unfavorable, as evidenced by the fact that organisms belonging to the euplankton decreased in number, whereas tychoplankton increased (Tudesque et al. 2019; Dembowska 2009). Tycho plankton, a set of organisms that accidentally found themselves in the water column and started to belong to phytoplankton (periphyton and benthos), indicates major changes in the conditions of transport and circulation of water masses in the reservoir or watercourse; this happens when these organisms are torn off the ground, as, in natural conditions, this should not happen (Vranowský 1997; De Oliveira Naliato et al. 2009). Such research was conducted, for example, on the Colorado River below Lake Mead (United States), which, contrary to reservoir HPs, have high damming conditions, in which tycho plankton occurs less than in low damming conditions (3% and 8%, respectively), but more of them are bottom diatoms (90% and 55–77%, depending on whether communities have been exposed to water discharges) (Peterson 1986).

The above conditions increase turbidity, which leads to an increase in phytoplankton (i.e. to algal blooms using increased resources of organic material), a phenomenon called

eutrophication, which leads to the formation of anaerobic conditions in river and reservoir habitats that negatively affect the existence of higher organisms (at higher levels of the trophic chain), especially fish (Smith et al. 1999; Staniszewski et al. 2019; Wiatkowski et al. 2013). Sometimes, however, they also use the supplied material that uses algae, but their biomass growth is dynamically reduced by the zooplankton that consumes them. This is because they require much less energy to consume larger individuals that belong to a lower level of the food chain, which makes this profitable for them. In the first case, phytoplankton regulation operates from lower to higher trophic levels (bottom-up), and in the second, from higher to lower (top-down) (Finger et al. 2007; Dobberfuhl & Elser 1999). The main difference is that, in the first case, the conditions in which phytoplankton was growing massively were caused mainly by the influx of large amounts of organic matter rich in biogens (usually from arable fields), whereas in the second, the environment was more natural, and the increase in the number of bottom sediments was caused by the sustainable activity of reducers (Goldammer et al. 2010). Zoobenthos enjoyed good development conditions (aerobic conditions) in the second case, and unfavorable conditions (anaerobic conditions) in the first case (Sinistro 2010).

As evidenced by eight reservoir HPs in Brazil (Manso, Luiz CB de Carvalho, Mascarenhas de Moraes, Furnas, Serra da Mesa, Corumba, Itumbiara, Funil), the development of phytoplankton biomass is influenced by various factors: changes in water levels due to the operation of HPs (hydrology), light availability, regulation by zooplankton, water temperature and availability of nutrients. It has been proved that phosphorus content in water and hydrological conditions resulting from the HP have the greatest influence on algal bloom (Rangel et al., 2012).

However, other studies have shown that the passage of water masses through the turbines of the HP destroyed (fragmentation and deformation) the internal structures of phytoplankton, affecting organelles, cell walls and plasma membranes. A small run-of-river HP was tested. It has been noted, however, that using certain compensatory measures can significantly reduce or almost eliminate this impact (Vaikasas et al. 2015; Chaparro et al. 2019).

Considering the analyzed literature, the species structure after the damming caused by a HP does not differ significantly from the species structure before the damming. At most, differences consist of disparities in the frequency of occurrence of some species – for example, more protozoa were found below the HPs, as along with some rotifer species that are not present in front of the HPs. These species are thermophilic and characteristic of the fertile habitats of water reservoirs (the impact of reservoir HPs was studied) (Zhou et al. 2009). Therefore, it is also worth considering this group of organisms when studying the impact of hydropower units on the aquatic environment.

Various researchers have investigated the impact of HPs on the plankton community – diatoms, colony organisms, periphyton, tycho plankton and microalgae. The following studies are worth mentioning: effects of flow regulation caused by HPs on periphyton communities (abundance, structure), the Soča River in Slovenia (Smolar-Žvanut & Mikoš 2014); changes in benthic algal communities (species richness,

diversity, characteristics of individuals) following construction of a diversion dam on the Xiangxi River in China (Wu et al. 2009); comparative analysis of the influence of a dammed versus an undammed section of Alpine lakes in NE Italy on zooplankton and phytoplankton (abundance, biomass, density) (Spitale et al. 2015); succession and physiological health of freshwater microalgal fouling in Tarraleah hydropower channels in Australia (Tasmania) (Perkins et al., 2010); impact of cascade HPs on the composition, biomass and biological integrity of phytoplankton assemblages in the Lancang-Mekong River in China (Li et al., 2013); gastropods and periphyton relationships near HP on the Pasłęka River in Poland (Zębek & Szymańska, 2014).

Ichthyofauna

Ichthyofauna is one of the key biological elements in the context of the potential impact of HPs (Resende et al. 2010). The operation of hydropower complexes risks the loss of ecological integrity of the streams, which can manifest as the collapse of the longitudinal continuity of the river (Fette et al. 2007). In such conditions, the fish confront difficult conditions for hiking up and down the watercourse, and, in the event of inappropriate construction solutions, they can be significantly damaged or even killed after passing through the HP (Mueller et al. 2017). However, other factors, such as river pollution, navigation and uncontrolled fishing also affect ichthyofauna (Benejam et al. 2014; Rosik-Dulewska, Ciesielczuk & Krysiński 2012). Moreover, such a change in environmental conditions is not indifferent to other aspects that are not purely only environmental – for example, conditions for recreation or distribution of drinking water, which can be facilitated or impeded by changes in river continuity (Branche 2017).

Researchers investigated mercury content in the dorsal muscles of fish in Brazil's rivers, and showed that the formation of a reservoir at a HP does not affect the high net methylation of mercury in fish bodies (Cebalho et al. 2017). WHO standards recommended for fish consumption were not exceeded. The increase in mercury was due to environmental laws: the larger the fish body and the higher the fish was in the trophic chain, the greater the mercury content in its body (methylmercury magnification) (Calder et al. 2016).

The impact of HPs, particularly changes in the level of water after regulation, may effect changes in productivity of lakes and the availability of food for fish, due to the reduced production and diversity of organisms in the littoral (by drying and physical changes in shallow bottom surfaces) and change in production and pelagic diversity (changes in abiotic conditions and predatory fish load). In addition, ecological interactions among organisms and between organisms and the environment are changing, which may affect the frequency of occurrence of fish and their numbers (in the context of composition and species structure) (Hirsch et al. 2017).

The behavior of fish is greatly influenced by the flow distribution between the natural and artificial beds, which transports waters to the HP. In such conditions, fish are stressed and their behavior changes. Some of these fish, in the absence of guidance devices, go to the artificial trough, where, in the absence of applicable compensation solutions, they are damaged or die on their passage through a HP (the most vulnerable are Pacific salmonids, river herring and

freshwater eels) (Algera et al. 2020). Also, changes in water thermics and flow dynamics affect fish, causing them to lose their orientation in space due to changes in water movements and thus, a change in water pressure – barotrauma (in this case the orientation in space is caused by the lateral line) (Vowles et al. 2014; McManamay et al. 2015; Coutant and Whitney, 2000; Pleizer et al. 2019).

In relation to fish, the following impacts are indicated: qualitative and quantitative reduction of habitats, barrier to migration, and fish abduction by HPs (Gousskov et al. 2016; Zdankus et al. 2008). In relation to specific cases, changes are most often examined by assessing the abundance and structure of the bi-environmental fish populations (catadromous and anadromous – e.g. Atlantic salmon and rainbow trout) (Silva et al. 2018), migrating from rivers to the sea and vice versa, where development is the goal in one direction, and spawning in the other. For example, in the Rhone River in Switzerland, a reduction of biomass of brown trout was found (median value in hydropeaking segments = 6 g/100 m² and in natural flow segment = 100 g/100 m² (Fette et al., 2007)); a second example is the loss of sea trout and Atlantic salmon in the Salten River in Denmark (from 18% to 71% and 53%, respectively (Aarestrup & Koed, 2003)). Instead of bi-environmental fish species, there are more species characteristic of stagnant waters, resistant to tougher environmental conditions, such as certain species of the barbel and barbatula genus (Sharma & Thakur 2017; Rangel et al. 2015). Despite this, there are studies showing that the number of these fish, after the launch of = HPs, has decreased (results of comparison before and after 30 years) – from 350 to 127 (the Jihlava River, Czechia) (Prokeš et al., 2006). In addition, these fish have problems moving through the resulting transverse obstacle; in the Lucas and Frear (1997) study on the Nidd River in the UK, 6 out of 23 tested individuals of the *Barbus barbus* species managed to pass through a hydropower station.

Moreover, apart from ecosystem losses, reducing the population of certain species of ichthyofauna can also affect the standard of living and the economic situation of regions and countries (de Faria et al. 2017). This applies especially to places where inhabitants survive mainly from fishing in rivers and reservoirs, where the death of fish can cause problems in feeding the population, as well as more far-reaching effects, such as limiting the import of fish, the subsequent sale which is the basis of the economy of such countries. An example is the Mekong River, in which the biomass of fish is forecast to decrease, by up to 51.3% in the period 2015–2030, and critically endangered species are predicted to increase, from 1 to 100. These changes will also affect many people, including more than 65 million people living in Laos, Thailand, Cambodia and Vietnam (Ziv et al. 2011; Hecht et al., 2019).

The degree of impact on fish is influenced by factors such as the nutrition of ichthyofauna, as well as their way of movement, preferred habitats (flow rate, bottom substrate, vegetation structure, etc.), and fish dimensions (length, width, weight) (Simonov et al. 2019). For each fish, not only within species, but also considered as a single individual, passing through a HP can have a different impact, in terms of its mortality and in the context of its behavior after passing through the building and their orientation in space (Vowles et al. 2014; Dobicki & Polechoński 2003).

Worldwide, a number of studies have been carried out to determine the mortality of fish after passing through a HP, depending on the technological solution used and the species of fish (e.g., silver eel (*Anguilla anguilla*) assessment: the Drawa River, Poland – 30% mortality (Dębowski et al. 2016); the Kennebec River, USA – 20% (McCleave, 2001); the Nemunas River, Lithuania – 25–100% (Dainys et al. 2017).

For this reason, it is necessary to recognize the most fish-friendly solutions when constructing a HP; this includes the use of low-speed turbines (e.g. the mortality of fish passing through Francis high-speed turbines is 90%, Kaplan – 20%, and at low-speed Archimedes' screw – 5%), fish passes, guidance and protection devices. Moreover, it is appropriate to use the most natural materials for this purpose, and to restore the natural course of the river, if possible, because fish do not prefer artificial stands. The impact of a HP may be small, provided that such measures are implemented (Liu et al. 2013; Luderitz et al. 2004; Puzdrowska & Heese 2019; Larinier 2008; Odeh & Orbis 1999).

Fish ladders are the most commonly used water devices to ensure the free migration of fish, increasing the ecological continuity of rivers and the availability of functional habitats (Clay 1995; Benitez et al. 2015). There are two types of fish ladders: technical ladders, which are made of artificial materials (chamber fishways, slotted fishways, Denil fishways, eel fishways, fish elevators, fish sluices), and nature-like (semi-natural) ladders, which are made of natural materials (bottom ramps and bottom slipways circulation channels (bypasses), fish ramps at the steps) (Baumgartner et al. 2012; Foulds & Lucas 2013; Kasperek & Wiatkowski 2008; Teppel & Tyimiński 2013). Nature-like fishways are especially recommended because they reproduce natural river conditions (type of ground, depth distribution, vegetation, etc.) and interfere much less with the natural environment, unlike technical fishways (Franklin et al. 2012). Designing and constructing fish ladders requires that a number of factors be taken into account, especially fish ecology, local hydrological and hydraulic conditions, fish types (life stage, structure, swimming capacity, etc.) and geometrical parameters of designed fish ladders (Williams et al. 2012; Rodgers et al. 2014). Fish ladders are complicated enterprises, and their creation should therefore involve specialists from various professions (Kuby et al. 2005). Research has shown that the average efficiency of fish ladders varies, depending mainly on the type of fish ladder, the species of migrating fish and the length of the fish ladder (Noonan et al. 2012; Volpato et al. 2009; Hämmerling & Kałuża 2018; Croze et al. 2008). Selected performance indicators for various criteria are shown in Table 2.

Additional luring devices, such as physical barriers (e.g., protective screens) and behavioral barriers (e.g., acoustic, light electric), can be used to increase the efficiency of fish ladders (Larinier et al. 2002; Bilotta et al. 2016). The use of such safeguards can minimize the lethal or sub-lethal effect of fish when they are trying to pass through turbines (by directing them to a fish pass), but can also help in environmental compensation and minimize environmental impacts, especially on the living world (Clarkson 2004; Welton et al. 2002).

Macrophytes

Macrophytes (i.e. aquatic plants) are an important indicator in assessing the dynamics of changes in ecological status within

Table 2. Average efficiency of fish ladders depending on various criteria based on 65 articles from the period 1960–2011 (Noonan, Grant & Jackson 2012)

Criterion	Specification	Average fish ladder efficiency
Fish entry to the fish ladder	Downstream (D)	68,5%
	Upstream (U)	41,7%
Type of fish	Salmonids (S)	D – 74,6%, U – 61,7%
	Non-salmonids (NS)	D – 39,6%, U – 21,1%
Type of fish ladder	Pool & weir	S – 71%, NS – 42%
	Natural fishway type	S – 66%, NS – 20%
	Pool & slot	S – 52%, NS – 32%
	Fish elevator	S – 33%, NS – 8%
	Denil	S – 19%, NS – 11%

hydropower complexes, as they indicate long-term trends (Resende et al. 2010; Szoszkiewicz et al. 2020).

The impact of HPs on macrophytes is ambiguous. There are studies suggesting that, below HPs, there is an increase in the number of macrophyte taxa and an increase in their value, qualitatively speaking (Tomczyk et al. 2019); other studies point to the impoverishment of macrophyte species and the disappearance of certain population structures (Mueller et al. 2011). Research results differ depending on the tested object (i.e., at different dam heights the degree of transformation varies due to differences in water levels resulting from the operation of a HP). It was assumed that the higher the level of accumulation, the greater the impact on macrophytes. This impact applies especially to impoundment HPs, in which the water level in the reservoirs usually changes more than it does in rivers, where run-of-river HPs are used. Species impoverishment applies to macrophytes occurring at low and medium depths, and not to species preferring deep habitats. In reservoirs under the influence of HPs, there are more ruderal strategy species, and fewer stress-tolerant and competitive species (Ochs et al. 2018). This means that the human impact is noticeable in such waters, and that ruderal plants thrive in heavily transformed, often urbanized areas (Jones et al. 2020).

There are studies confirming both positive and negative impact of HP impact on macrophytes – in this case, total plant coverage, species diversity and species richness within hydrotechnical constructions were examined (the Duraton and the Tajuña rivers, Spain). The equality of species showed no correlation, although a slight dominance was found for *Leptodictyum riparium* and *Veronica anagallis-aquatica* in the studied streams. They are rush plants that inhabit the banks of watercourses. They are resistant to various habitat conditions and they also robustly accumulate various substances in their tissues. (Camargo 2018; Pokorny et al. 2015, Borowiak et al. 2016).

Table 3 summarizes the assessment of the impact of HPs on biological elements of the ecological status, based on a literature review.

Hydromorphological elements

Hydromorphological elements, understood as natural and artificial elements in the watercourse channel and surrounding areas, related mainly to the morphological conditions of the riverbed and floodplain, are subject to the influence of hydropower units. In this case, the impact results more from

the specific design of the hydropower unit itself, and not from its operation. The main impact is associated with the need to strengthen the bottom and the edges of the streambed above and below the HP, often by using artificial materials (del Tánago et al. 2015). These materials significantly reduce the value of the river in terms of its ecological status, because natural river processes are difficult on such sections, and biological life is very limited or does not develop at all. Significant sealing of the surface protects the population from floods, and protects its property, but it destroys the natural hydromorphological nature of the watercourses. Such rivers are straightened, their slopes are profiled, and in the riverbed and adjacent areas, it is possible to see waste that is not neutral for the environment, and not just water. In addition, infrastructure related to accessing the HP is being built – these are roads, as well as bridges separating the river (Anderson et al. 2014).

The operation of hydroelectric power plants only changes the flow characteristics locally; it is more turbulent below hydrotechnical constructions (Kougias et al. 2019). In addition, more invasive taxa have been observed to displace native plant species. As a result of HP operation, the natural morphological forms of rivers can be flushed due to the high strength of water that flows below the HP and into the watercourse. The so-called bottom sediment granulation is noticeable in this case – sediments with the largest diameters are retained closest to the HP or on dams, and sediments further away from the HP consist of finer material (Bishkawakarma & Støle 2010). Below HPs, due to increased erosion processes, undercutting of banks, if they remain natural, is quite often notable, as is the formation of evacuation boilers and rapid stream flows. Despite this, the variety of flow forms in watercourses, as well as natural morphological forms, such as spurs or mid-dumps, are usually simplified (Wiatkowski & Tomczyk 2018; Wyźga et al. 2012).

The above conditions seriously affect other elements of the environment, although the same phenomena occur along with the progressive urbanization process in the world, in which many more artificial than natural elements are used to protect people's heritage, and adapt natural conditions to human needs (Camargo 2018; Zaharia et al. 2016). It is possible to find more objections to the construction of a HP in valuable natural areas; in this case, the greatest naturalness of the materials used should be ensured, which compensates for lost hydromorphological values (Lüderitz et al. 2004). In urban and transformed areas, HPs blend well with the landscape.

Table 3. Impact of hydroelectric power plants on the biological elements of the ecological status of waters – based on a literature review

Biological element	Impact	References
Benthic macroinvertebrates	Changes in the abundance of feed groups of organisms (above: filter feeders 10%, grazers 35%, collectors 40%; below: 20–50%, 20–40% and 20%) – water level fluctuations as a result of the operation of a hydropower plant	Kjærstad et al. 2018
	Marginal impact on average number and density of macroinvertebrate taxa below hydropower plants, respectively: 10 and 8 taxa (above/below), 59 and 43 per m ²	Pan et al. 2013
	Noticeable effect on average number and taxa composition: above 18±2 (mainly chironomids and earthworms); below – 25±2 (mainly stoneflies and caddisflies)	Mueller, Pander & Geist 2011
	Decrease in organism density: under fluctuating conditions (operating hydropower plants) – 91 organisms per m ² ; no fluctuations – 743 per m ²	Troelstrup & Hergenrader 1990
Plankton	Less tychoplankton and more bottom diatoms in high damming conditions – respectively: 3% and 8%; 90% and 55–57% (changes in the conditions of transport and circulation of water masses)	Peterson 1986
	Algal blooms as a result of increased turbidity – eutrophication, difficult regulation by organisms from higher trophic levels (anaerobic conditions)	Sinistro 2010
	Destruction of internal phytoplankton structures when passing through turbines of water masses	Vaikasas et al. 2015
	No clear differences between the species structure before and after the damming caused by hydropower plants – slightly more protozoans and rotifers below the hydropower plant than above (thermophilic species)	Zhou et al. 2009
Ichthyofauna	Limiting the possibility of anadromous and catadromous fish migration – creation of a transverse obstacle	Travade et al. 2010
	No effect on mercury methylation in fish bodies (Brazil)	Cebalho et al. 2017
	Change in lake productivity and availability of food for plants – as a result of the impact of hydropower plants; changes in fish prevalence and abundance through changes in ecological interactions; e.g., decrease in biomass of brown trout in River Rhone – from 100 g/100 m ² to 6 g/100 m ²	Hirsch et al. 2017; Fette et al. 2007
	Changes in fish behavior – distribution of flow between natural and artificial beds, leading water to the hydropower plant (lethal or sub-lethal effect after passing fish through the turbines of the hydropower plant, loss of orientation in space); e.g., loss of sea trout and Atlantic salmon in River Salten after creating hydropower plant – from 18% to 71% and 53%	Vowles et al. 2014; McManamay et al. 2015; Aarestrup & Koed, 2003
	Reduction in the number and structure of bi-environmental fish populations after passing through hydropower plants; e.g. mortality of silver eel between 20 and 100%, depending on the type of hydropower plant, turbine type and damming height	Dainys et al. 2017; McCleave 2001
	Deterioration of the standard of living and the economic situation of regions and countries dependent on the size of the fish population; e.g., in Mekong River, the biomass of fish is forecast to decrease by up to 51.3% in the period 2015–2030 basin – affected over 65 million people in Laos, Thailand, Cambodia and Vietnam (fish as the main source of income)	Ziv et al. 2011; Hecht et al., 2019
Macrophytes	Increasing the number of macrophyte taxa and increasing their value in a qualitative context – an imperceptible or positive impact	Tomczyk, Wiatkowski & Gruss 2019
	Depletion of macrophyte species and disappearance of certain population structures (mainly species preferring shallow positions)	Mueller, Pander & Geist 2011
	More ruderal species below impoundment hydropower plants – high human impact; e.g. <i>Potamogeton pectinatus</i> (20.5+6.3% and 25.7+5.8% of macrophyte coverage share)	Camargo 2018

Physicochemical elements

The impact of hydropower complexes on physicochemical elements is not as great as on the biological and hydromorphological elements. However, it is possible to observe several phenomena associated with such elements. They particularly concern dissolved oxygen content, temperature and turbidity below hydrotechnical constructions.

The most noticeable effect is the increase in dissolved oxygen concentration below the damming up construction. However, this impact is purely local, depending mainly on the damming height of the HP, but also on its size (relative to the entire width of the watercourse) (Álvarez et al. 2020). This impact is due to the vertical drop in water columns directed to turbines or weirs. In each case, it changes from potential

energy to kinetic energy, which has the highest value at the lowest point of liquid fall when it makes contact with bottom water. At the bottom station of the HP, the phenomenon of hydraulic jump (i.e., the formation of a vortex movement with significant speed) is observed. This water is strongly saturated with oxygen, due to extensive mixing of water masses. The impact of such a phenomenon ranges from several to several hundred meters, depending on the size of a HP and its location (Wu & Ma 2018; Florentina et al. 2010).

The second phenomenon is temperature change; in this case, HPs increase it in the cold season, whereas the temperature decreases in the warm season (Pimenta et al. 2012). Warming is visible when the temperature of water entering the HPs is lower than the temperature of the mechanisms of the plant, whereas cooling occurs when the temperature of the mechanisms is higher. Due to the increase in temperature in winter, the ice covering may weaken and last for a shorter time, which can disturb the stratification of reservoirs at this time. In turn, that may disturb the living conditions of the organisms because the abiotic conditions change (Valero 2012; Fantin-Cruz et al. 2016).

The turbidity of water below HPs increases due to the strong mixing of water masses and the creation of whirling movement. Increasing turbidity has a significant impact on living conditions for aquatic organisms that have different ecological tolerances; organisms that prefer clean waters with low turbidity are replaced below aquatic power plants by aquatic organisms the ecological optimum of which is in high turbidity conditions (Finger et al. 2006; Bogen & Bønsnes 2001).

The construction of a cascade of dam reservoir hydroelectric plants is a special case. It is often associated with an unfavorable phenomenon of supersaturation (shown in Figure 2) (Witt et al. 2017). The most noticeable effect of this phenomenon is fish bubble disease (barotrauma), which, if present for a long time, can cause significant restrictions in the functioning of ichthyofauna (sub-lethal effect) or cause their death (lethal effect) (Richmond et al. 2014). Such a supersaturation with oxygen is adversely affected by the hydrological conditions of the watercourses, water quality and sedimentation processes. In the case of run-of-river HPs, non-cascading reservoir HPs or smaller reservoir HPs, it is rare because the water pressure does not change rapidly; therefore, there is no oxygen supersaturation, thereby maintaining the

balance between dissolved oxygen and atmospheric oxygen. In this case, an additional modifier is the water temperature, which causes a lower or higher oxygen solubility. Oxygen supersaturation is also accompanied by an increase in the concentration of dissolved elements, mainly aluminum, zinc, cobalt, titanium and iron (Ma et al. 2018; Xue et al. 2019; Kobus et al. 2016).

Algae blooms have a negative effect on the aerobic conditions of water, and their appearance is usually not directly related to the operation of the HP, but rather to the use of water reservoirs located next to them – depending on whether it is the dry reservoir phase, the filling phase, the full reservoir phase or the emptying phase, the conditions for algae development are different (Padedda et al. 2017). The main cause of algae is excessive enrichment from nutrients, especially phosphates and nitrates, which mainly come from runoff from agricultural areas (excessive use of fertilizers and plant protection products). Most often, eutrophication near HPs appears in agricultural or urban areas, carrying a large load of nutrients, so the operation of HPs plays a secondary role in shaping the eutrophication process in watercourses (da Costa Lobato et al. 2015; Smith et al. 1999; Wiatkowski, Rosik-Dulewska & Kasperek 2015).

Hydrological conditions

The assessment of changes in hydrological conditions of the watercourses supplements the assessment of impacts caused by the hydropower use of watercourses. This impact is double-sided; HPs increase the daily flow amplitudes and water levels, whereas, annually, they flatten these characteristics (they are maintained at the assumed minimum and maximum levels). In addition, the following hydrological characteristics are indicated: the amount of the lowest monthly flow; the minimum flow of 1, 3 and 7 days; the maximum flow of 90 days; and the number of high and low waves (exchange of nutrients and organisms between the riverbed and floodplain). According to the literature, changes in flows range from several to several dozen percent (from 2% to 24%) (Chiogna et al. 2016; Bejarano et al. 2017; Fantin-Cruz et al. 2015; Młyński et al. 2019).

On the one hand, this is a positive phenomenon, because it entails effective use of water, thus supplying electricity to the electricity grid (Kasperek & Wiatkowski 2014). The equalization of flow and water levels protects residents against the risk of flooding, because the flood zone is effectively regulated, due to the regulation of hydrological characteristics

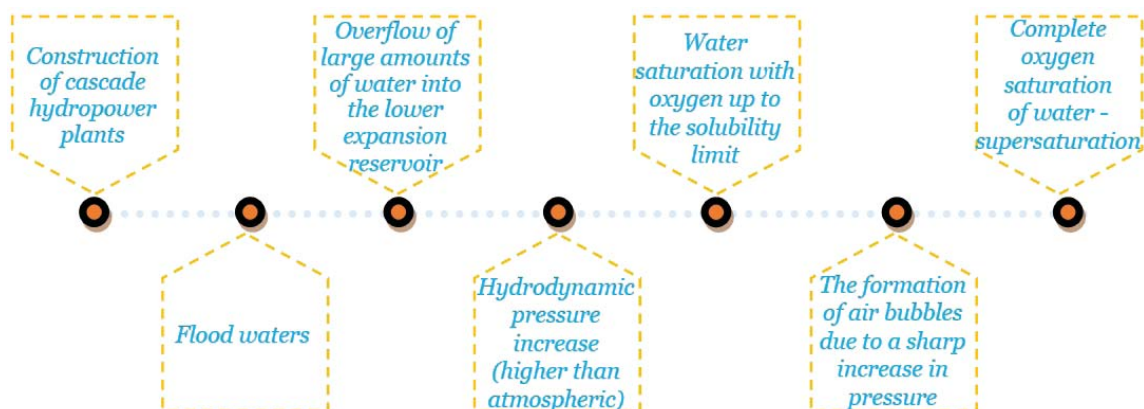


Fig. 2. Diagram of water supersaturation phenomenon with dissolved oxygen

(especially flow), so that it does not exceed the set level, safe for the public (Nguyen-Tien, Elliot & Strobl 2018; Greimel et al. 2018).

On the other hand, the same annual flattening of flows and water levels causes a disturbance of the natural hydrological regime for a given river, leading to difficult conditions for the growth of aquatic plants and other water-dependent organisms. In addition, water-dependent ecosystems are over-dried or wetted and the continuity between the riverbed and floodplains (the so-called river continuum) is disturbed; for this reason, nutrients exchange is impeded, as is genetic exchange between organisms between the flood zone and the main trough (Fantin-Cruz et al. 2015; Anderson et al. 2014).

Society and economy

In scientific research, the main emphasis is on the impact that HP complexes have on the environment, but they also have important effects on society and the economy. The largest effects are shown in Figure 3 (Kelly-Richards et al. 2017; Bakken et al. 2012; Rodriguez 2012; Ezcurra et al. 2019; Spänhoff 2014; Igliński 2019).

Changes in the living standards of the local population are also often visible; for example, after the construction of the Kamchay dam in Cambodia on the Prek Kampot River (supplies 193 MW reservoir HP), residents stopped experiencing power cuts, the price of electricity decreased, local infrastructure (e.g. roads, bridges) developed, but due to the need to cut local bamboo forests, the income of residents depending on the sale

of this raw material decreased (Pheakdey 2017). A similar economic decline occurred in the estuaries of the rivers Santiago, San Pedro and Acaponeta, located by the Pacific Ocean in Mexico; dams with HPs were created here in the 1970s and since then, a 95% decrease in income has been recorded among the local community (the economy based mainly on catching fish, oysters and shrimps) (Ezcurra et al. 2019). However, according to Spänhoff (2014), the development of small hydropower is an opportunity for developing countries suffering from electricity supply deficits and having optimal conditions for the development of hydropower (large mountain rivers with a significant decline); in the case of Asian, South American and Russian countries, medium- and high-capacity HPs are expected to be developed. It is profitable – the cost of generating 1 kWh of electricity from HPs is 3–12 US cents, whereas from other renewable sources, it is as follows: 9–40 US cents per kWh for photovoltaic panels, 4–16 US cents per kWh for wind farms, respectively, 5.5–20 US cents per kWh for biomass combustion (REN21 2014).

Other social conditions taken into account when constructing new HPs are: issues of public safety, employment opportunities, construction of new transportation routes, increasing the share of energy from HPs supplied as electricity and heat to households, increasing the level of education among young people, occurrence of public consultations between people involved in the establishment of the undertaking and interested parties, increasing the local population near the project area, and impact of the construction of a HP on

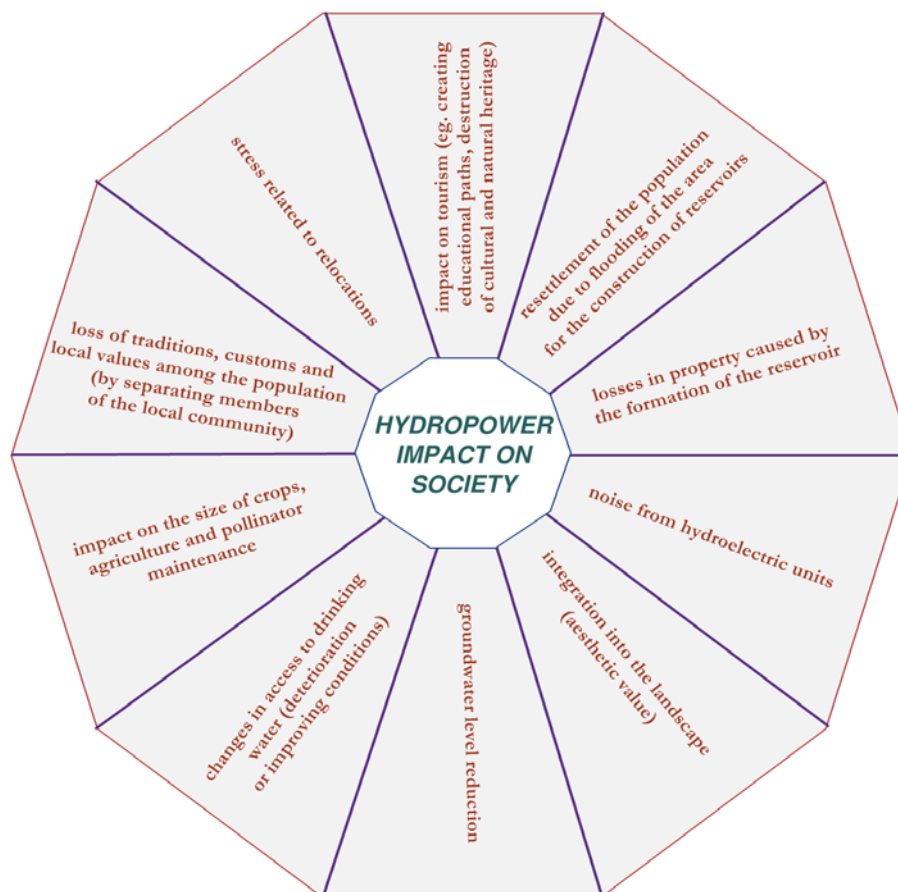


Fig. 3. The impact of hydropower plants on society

the functioning of water mills (Massarutto & Pontoni 2015; DeRolph et al. 2016; Sharma & Thakur 2017; Mattmann et al. 2016).

Environment

HPs affect not only our economy and society, but also the environment. First, mention should be made of the impact of HPs on the composition of bottom sediment, which represents a change in the processes of accumulation and erosion, especially below the damming (accumulation on damming dams above HPs – material with higher granulation – up to 85% – accumulates on damming thresholds; increased erosion below HPs, resulting from the impact of hydraulic rebound – which also has consequences, for example, as in the drying of spawning grounds of ichthyofauna) (Bogen, J. & Bønsnes 2001; Wu & Ma 2018). Disturbances in the transport of suspended, dragged and lifted debris are an additional environmental consequence. These effects can be applied to both impoundment HPs and run-of-river HPs, whereas in relation to impoundment HPs, an additional effect of their operation is the creation of nutrient-rich zones (especially phosphates and nitrates in agricultural areas), which are a good environment for the development of algae, which in turn causes eutrophication (Smith et al. 1999; Bartoszek et al. 2017). This phenomenon causes the consumption of dissolved oxygen in water and the formation of anaerobic zones; causes a lethal and sub-lethal effect for most aquatic organisms, especially fish (Vowles et al. 2014; Puzdrowska & Heese 2019). In addition, in reservoir HPs, an increase in the concentration of dissolved substances carried along with bottom sediments is observed, especially Zn, Al, Co, Ti and Fe; these changes result from changes in the saturation of minerals that build bottom sediments, as well as suspended material (Klaver et al. 2007). Moreover, as a result of the decomposition of organic matter from sediments, there are greenhouse gas emissions that intensify global warming (Barros et al., 2011; Gagnon & van de Vate 1997; Agrawal & Sharma 2012; Soininen et al. 2019).

HPs cause changes in the ecological continuity of the areas in which they are located. On the one hand, HPs cause habitat fragmentation and hinder the migration of organisms from one place to another (Lees et al. 2016; Faulks et al. 2011), and on the other hand, the construction of a HP creates a new ecological balance, with specific food relations, circulation of matter and

energy flow, which are valuable in nature (Fette et al. 2007; Wiatkowski et al. 2018). In terms of negative impacts, it is worth mentioning the impediment to genetic exchange between organisms. Sometimes, the construction of HPs requires felling trees, but the creation of a transverse partition also leads to the separation of the population of organisms, especially moving passively in water – which sometimes paradoxically protects the genetic pool of certain organisms (Coleman et al. 2018). Natural habitats after the construction of HPs act on longitudinal continuity – along the watercourse, but also in width – between riverbanks. The structure and abundance of terrestrial plant populations, as well as living conditions for actively moving animals are changing (Alho 2011, Botelho et al. 2017).

In the context of terrestrial animals, the greatest impact concerns nesting birds, which have their breeding, mating and feeding sites within rivers; in the context of creating a water reservoir, these relations change, forcing the birds to look for alternatives, and perhaps destroying the nests of birds (Kenyon 1981). This is not the rule, however, because, for example, birds from the plush family prefer changed river channels to live, but not to breed (Silverthorn et al. 2018). Types of ecosystems may also change; wetlands are created as a result of excessive flooding, and when draining previously wet ecosystems – meadows and forests. It represents an interference with the natural succession, which is accelerated or its direction changes (Gracey & Verones 2016; Vale et al. 2008; Winemiller et al. 2016; Kobus et al. 2016; Obolewski et al. 2014).

Summary

Shaping changes of the ecological status of the watercourses within barrages with hydroelectric buildings is unclear, depends on many factors, including the damming height, turbines used, type of HP and its location.

The article describes an assessment of the impact of hydropower use of rivers on ecological status (biological, hydromorphological, physicochemical and hydrological conditions), society, the economy and environment; it also proposes a research scheme to assess the impact of hydropower structures (Figure 4).

According to the aforementioned information, the largest impact on the environment comes from HPs with high dam

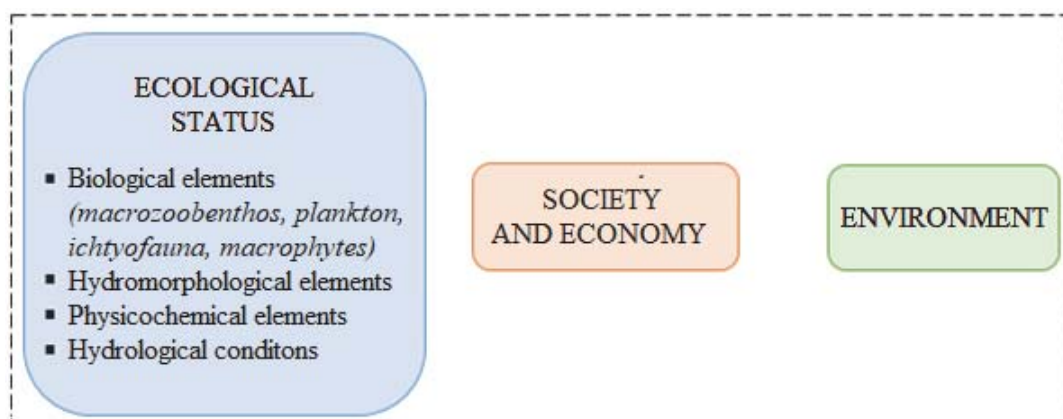


Fig. 4. Research scheme, along with assessment of the impact of hydropower use of rivers on various elements

heights (above 15 m), pumped storage, and high-speed turbines (e.g., Francis), in areas particularly sensitive to environmental changes (natural areas, especially mountains). Least impactful on the environment are run-of-river HPs with low dam heights (below 5 m), low-speed turbines (e.g., Archimedes screw), in areas that are sensitive to environmental changes (artificial areas, e.g., cities). This impact, however, is not obvious and can be modified; an example is the use of fish passes, together with other compensatory protections within HPs (e.g., protective screens) (Čada et al. 1997; Ma et al. 2018; Vučijak et al. 2013, Piper et al. 2018; Puzdrowska & Heese 2019; Taft 2000).

The conservation and restoration of natural floodplains are important for maintaining appropriate environmental conditions, but also for improving economic conditions; this is how the Alluvial Floodplain National Park in Austria was created in 1996 and how the Kopacki Rit Nature Park in Croatia was created (Reckendorfer et al. 2005; Tockner et al. 1998).

Successful implementation of projects related to the construction of HPs should comply with the principles of rational use of resources, as well as the principles of sustainable development. When deciding on such an investment, a number of specialists should be employed to evaluate its effects; this may include designers, scientists, and investors, as well as public figures who deal with water management issues in a given region. It is also invaluable to incorporate the participation of the public in the decision-making process, because society can enrich the current approach to the subject by providing other arguments (Liu et al. 2013; Ma et al. 2018; Auestad et al. 2018; Sharma & Thakur 2017; Operacz et al. 2018; Ilić et al. 2016).

The quoted results of various studies indicate the extent of the issue of shaping changes in the ecological status of rivers within barrages with hydroelectric buildings. This issue applies not only to the riverbed itself, but also to the adjacent areas, in terms of ecological status of the individual elements under assessment. In addition, HPs have an impact on the socio-economic situation of regions, depending on the resources that rivers carry, as well as on the biological diversity of nearby areas, on species, genetics, the ecosystem and landscape diversity.

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