Arch. Pol. Fish.	Archives of Polish Fisheries	Vol. 16	Fasc. 2	203-212	2008

HYDROELECTRIC FACILITIES AND FISH

Wiesław Wiśniewolski

Department of River Fisheries, The Stanisław Sakowicz Inland Fisheries Institute in Olsztyn, Poland

ABSTRACT. This article gives an overview the impact hydroelectric power facilities on ichthyofauna and river ecosystems. Issues addressed include the destruction of fish by grates and turbines; disturbances in the hydrological regime of rivers; changes in the water physicochemical regime resulting from damming; the muddying of spawning and feeding grounds. Suggestions are made for counteracting these disadvantageous transformations. This is achieved by equipping hydroelectric facilities with appropriate safety devices that lead fish away from the facility to a secure place where they can swim safely downstream, and also eliminate sharp fluctuations in water level that can occur below dams. It was determined that none of the existing methods eliminate ichthyofauna losses. It is recommended to combine several protection methods such as grates and electric barriers. Due to the negative impact hydroelectric plants have on the ichthyofauna, it is essential that the energy consumers participate in the costs of fish stocking to compensate for losses.

Key words: HYDROELECTRIC FACILITIES, ICHTHYOFAUNA, CONSEQUENTIAL EFFECTS, RIVER ECOSYSTEMS

INTRODUCTION

The necessity of maintaining the relatively restored ecological continuity of rivers so that fish can reach spawning grounds in the upper reaches of courses is now rarely questioned. Numerous articles have been published describing the importance of rivers as migration corridors for ichthyofauna (Vannote et al. 1980, Jungwirth 1998, Wiśniewolski 2002). Other studies present various technical solutions that are implemented to help fish pass through dams (Gebler 1991, Krüger et al. 1993, Wiśniewolski 2003).

Hydroelectric dams can be barriers to upstream-migrating fish and a source of mortality from turbine passage to downstream migrants. A major environmental issue for hydroelectric power production is injury and mortality to fish that pass through the turbines. After spawning, adult fish have to be able to return to the place where their spawning migration began. Their young must also be able to swim downstream. The

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CORRESPONDING AUTHOR: Wiesław Wiśniewolski, Inland Fisheries Institute, Departament of Rivier Fisheries, Główna 48, Żabieniec, 05-500 Piaseczno, Poland, Tel./Fax: +48 22 7562044,+48 22 7562088; e-mail: rzeki@infish.com.pl

hydroelectric facilities they encounter while swimming downstream are deadly obstacles (Kulmatycki 1930, Juszczyk 1951, Berg et al. 1995, Bartel et al. 1996, Jens et al. 1997). Consequently, an integral part of restoring fish migratory routes has to include measures to protect fish swimming downstream from being destroyed in turbines and ensuring that there is safe passage around these facilities (Ferguson et al. 1998, Odeh and Orvis 1998).

MATERIALS AND METHODS

This paper is a synthesis of results reported in the Polish and international literature focusing on the impact hydroelectric facilities have on ichthyofauna and river ecosystems. These are discussed in light of the author's own observations made while writing expert evaluations of the losses incurred in ichthyofauna due to hydroelectric power generation.

FISH DESTRUCTION ON GRATES AND TURBINES

The destructive impact of hydroelectric facilities on ichthyofauna is widely documented in the literature (Kulmatycki 1930, Juszczyk 1951, Einsele 1957, Bartel and Bontemps 1989, Berg et al. 1995, Bartel et al. 1996, 1998, Jens et al. 1997). In contrast to the widely held belief that this is a clean, ecologically-sound source of energy, hydroelectric facilities are not environmentally friendly to the aquatic ecosystem and cause substantial losses among the ichthyofauna and other aquatic organisms. The harmful impacts of these facilities can be categorized as follows: losses incurred on grates, in the turbines, from shifts in the physicochemical parameters of the water in the dammed river segment, rapid changes in water level in the river downstream from the dam, and the muddying and flushing of sediments.

Ichthyofauna losses occur on the grates due to the suction of the water current. This happens when the grates are installed directly in front of the water intake to the turbines. The water flow is so strong in this area that the fish pushed up against the grate are unable to free themselves from the bars to swim through or away from them. If they are not damaged and collected by the device that clears the grate of debris, they finally die of exhaustion (Kulmatycki 1930, Berg et al. 1995, Jens et al. 1997). The magnitude of losses that occur like this can be illustrated by observations of the Lilla Edet hydroelectric facility on the Götaälv River (Kulmatycki 1930). Over a period of 16 days between May 30 and July 26, 1927 the following fish were collected from grates with 20 mm spacing: 137 eel, *Anguilla anguilla* (L.), 63 bream, *Abramis brama* (L.), 6 pike, *Esox lucius* L., 85 perch, *Perca fluviatilis* L., 58 burbot, *Lota lota* (L.), 31 pikeprch, *Sander lucioperca* (L.), 133 roach, *Rutilus rutilus* (L.), 7 salmon, *Salmo salar* L., 9 whitefish, *Coregonus lavaretus* (L.), 4 ide, *Leuciscus idus* (L.), and a quantity of small specimens of various species that was not counted but described as 'a substantial amount'. These data indicate that during the observation period an average of 33 large fish (not counting the small fish) died on the grate daily. A high number of descending salmon, which are weakened after spawning, also die on grates in this manner (Kulmatycki 1930 after Alm). Observations at the Dringenauer Mühle hydroelectric facility on the Emmer River confirmed that losses of descending eels on dense grates was comparable to those caused by the turbines (Rathcke 1994). This is true of other species, too, and Weibel (cited in Adam et al. 2005) confirmed this in experimental investigations. The examination of fish damaged on the intake grates at two hydroelectric facilities on the Rhine confirmed that more than 50% of the fish that encountered the grate suffered serious bodily injury, and that the species composition of these fish was proportionally representative of that of the ichthyofauna in those segments of the river. The hypothesis that primarily weakened and diseased fish are suctioned into the water intake was not proved to be true. Rauck (1980) reached similar conclusions in an investigation of fish pressed up against grates at an intake where water was flowing at 33 $m^3 s^{-1}$ for a nuclear power plant cooling system. Most of the fish died from either being crushed against the grate by the water current or by the mechanized device that cleared debris from the grate. It was demonstrated experimentally that Rainbow trout, *Oncorhynchus mykiss* (Walbaum) smolts measuring 14.7 cm in total length can swim through bars spaced at 15 mm (Fig. 1), while fish measuring more than 17.5 cm cannot (Lubieniecki 2002). In order for the grates to be effective, the water flowing through them cannot exceed a rate of 0.4 $m s^{-1}$ (Berg et al. 1995). In order to decrease water current suction, the grate is mounted at an angle to the intake; this also permits directing fish toward a pass or overflow (Adam et al. 2005). These observations indicated that although it is necessary to deploy grates with small bar spacings, this does not guarantee effective protection for the fish.

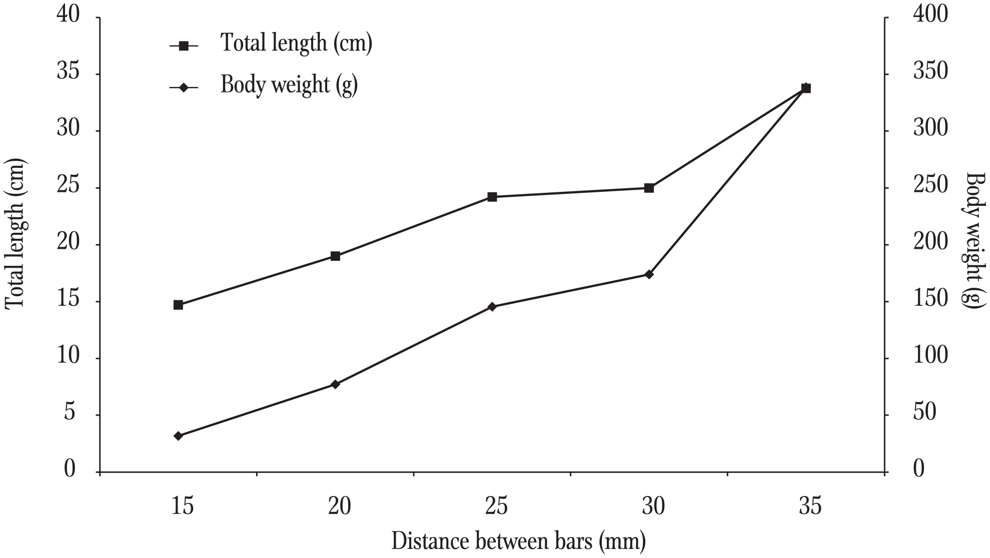

Fig. 1. Rainbow trout passing through a grate according to fish size and the distance between the bars (based on data from Lubieniecki 2002).

Another serious problem is the ichthyofauna losses caused by the working turbines of the hydroelectric facilities. Fish swim into the turbine chambers where they are either injured or killed by the rotating blades of the turbines. In higher dams, fish are exposed to rapid pressure changes as they pass through the turbines, and these results in serious internal injury and a mortality rate that is difficult to estimate. It was established in experiments that, depending on dam height and turbine type, from 40.1 to 87.1% of fish passing through are undamaged (Bieniarz and Epler 1977). Of the fish passing through the hydroelectric turbines at the Rożnowski Reservoir, from 15.7 to 46.2% of the specimens were damaged (Juszczyk 1951). Due to their long bodies, adult eel on spawning migrations are particularly susceptible to damage, and nearly 100% of them are injured as they pass through the turbines (Lundbeck 1927). The turbine revolution speed also has an impact. At speeds of under 100 rpm, eel losses were as high as 35%, while at speeds over 150 revolutions, this figure rose to 50 and even 90% (Jens et al. 1997). In the case of rainbow trout, at a size that corresponds to descending smolts of salmon or sea trout, *Salmo trutta* m. *trutta* L., it was demonstrated experimentally that mortality is dependent on the height of the dam and the type of the turbine, and can be as high as 56% (Table 1).

TABLE 1

Impact of hydroelectric facilities on rainbow trout mortality (Lt 12-22 cm; Francis turbines; according to Bartel et al. 1993, 1994, 1996, 1998)

	Height of damming (m)			
	1.8-2.5	3.2-5.0	7.5-8.0	12.0-38.0
Damaged fish (%)	5.7-6.8	18.0-21.7	32.8-41.9	46.9-55.8

It is generally acknowledged that facilities equipped with more fish-friendly Kaplan turbines produce a fish mortality rate between 15 to 50% (Jens et al. 1997). However, here too rotation speed determines how harmful they are. At a speed of 150 rpm^{-1}, 24% of the descending eel were injured, while at a speed of 88 rpm^{-1} this was reduced to 11% (Hadderingh and Bakker 1998). The least dangerous turbine for fish is the snail type. Of 158 fish measuring from 36 to 58 cm in length that were released into this type of turbine with a diameter of 0.7 m and length of 8.4 m, only 4.4% of the fish had scale loss or bruising. No fatal injuries were noted (Adam et al. 2005 after Späh). These examples illustrate that while its essential to install barriers to limit fish entering turbine chambers, it is also imperative that the appropriate type of barrier is installed.

PROTECTING FISH FROM THE DAMAGING EFFECTS OF TURBINES

Grates are used widely as a protection device to limit the damaging effects hydroelectric facilities have on ichthyofauna. While the contention that using grates with narrow bar spacing significantly reduces the productivity of hydroelectric facilities is unfounded, such grates do require more frequent debris clearing. Observations indicate that at a 4 m dam exchanging grates with bars at 60 mm intervals for ones with 20 mm intervals did cause a decline in electric energy production, but only by 0.3% (Jens 1987). Grates serve mainly as a barrier to prevent fish from entering turbines, but they also cause fish losses. Thus, additional measures must be implemented to improve the effectiveness of directing the fish to a pass or overflow. One such solution is to install an angled screen of dense mesh behind the main grate and over which the fish are carried and then directed to a safe place (Taft et al. 1992). A prototype of this type of device was deployed with near 100% success during the Niagara Mohawk Greek Island Hydroelectric Project in 1995 (Hadderingh and Bakker 1998 after EPRI).

The numerous fish deterrent methods used to date include an air-bubble curtain formed by a conduit on the bottom that releases pressurized air bubbles that rise to the surface (Brett and MacKinnon 1953, Taft 1986), a curtain of suspended chains, flash lighting, sound emission, sudden releases of compressed air, a curtain formed by a strong stream of water (Taft 1986), and light from fluorescent and mercury lamps (Larinier and Boyer-Barnard 1991). The results were highly varied and depended largely on factors such as water current speed, turbidity, temperature, and fish behavior.

For many years, attempts have been made to create an electric deterrence device that would not only keep fish far away from the turbines, but would also direct them to a given area (Einsele 1957, Chmielewski 1966, Taft 1986, Halsband and Halsband 1992, Jens et al. 1997). The limiting factor with this method is that it is not effective when water currents are flowing fast. Fish that are swimming along rapidly with the current are not able to react to the electric field and escape from its range quickly enough (Jens et al. 1997, Rauck 1980). To date, the electric barriers applied have been either single- or three-phase. Those that were designed to deter fish swimming with the water current were equipped with pulsating alternating current (Chmielewski 1966). The effectiveness of these devices was highly varied, and depended on how and where the barrier was deployed and the local conditions, namely water current. The appropriate or inappropriate location of the electric barrier determined its effectiveness Observations by Collins (Chmielewski 1966 after Collins) confirmed this without a doubt. If the electric barrier directing descending salmon smolts to a pass is deployed at a current flow rate of 0.15 m s^{-1}, then effectiveness is as high as 80%. But if the current flow rate is increased to 0.45 m s^{-1}, this figure decreases to 62%. This indicates how important it is to deploy the electric barrier in a zone that has a relatively slow current that does not exceed 0.3 m s^{-1} (Lubieniecki 2002). Another important factor that contributes to the effective protection of fish descending the river is to deploy the electric barrier at an angle to the current. It has been proved experimentally that of barriers deployed at 90, 60, and 40° angles to the current flow, the best result was obtained with the latter (Chmielewski 1966 after Trefethen). It should also be pointed out that the conductivity of the water and the bottom type also impact the effectiveness of the electric barrier. Bearing all these factors in mind, the effectiveness of the barrier will depend on the type of electric field, which serves to deter fish and not injure them.

The varied, and often disappointing, results obtained thus far with electric barriers deployed to protect descending fish have contributed to shaping the prevailing opinion that this method is not very useful. This opinion begs verification, especially in light of the improvements in deterring fish with cutting edge electronics. These permit gradually building up a low tension electric field with electronic impulses (field intensity < 0.1 V cm^{-1}), which acts on the muscle and nervous systems of the fish. Both adult and juvenile fish that encounter such a field still far from the protected site, change direction and swim off in the opposite direction (Zioła et al. 2008). Deploying the barrier at an angle to the water current increases its effectiveness in deterring fish and guiding them off in the desired direction. It is important to remember that it is impossible to achieve 100% effectiveness in preventing fish from entering the chambers of hydroelectric facilities. This is why it is imperative that methods be combined, namely grates and an electric barrier, which will lead to improved fish protection.

IMPACT OF THE HYDROELECTRIC FACILITIES ON RIVER ECOSYSTEMS

The negative impact on ichthyofauna and river ecosystems is not limited to the interruption of migration routes, but also include the effects water retention and the hydroelectric facility have on the river upstream and downstream. These include physicochemical water parameters that, due to retention, change in the new basin formed especially with regard to current speed, temperature, and oxygen saturation. The nutrient content usually increases, too. In effect, less advantageous developmental conditions are created for highly rheophilic fish, and assemblages of less demanding species adapted to variable conditions develop. There are also changes in the transport of debris; it accumulates above the dam and is swept away below resulting in increased erosion (Einsele 1957, Gebler 1991, Berg et al. 1995, Jens et al. 1997). Sudden changes in the quantity of water flowing in the river bed beneath hydroelectric facilities pose a very serious threat. A consequence of these is the sudden exposure of extensive areas of river bed that leaves fish and deposited spawn without water (Einsele 1957, Jens et al. 1997). This leads to substantial losses in fish stocks and to fisheries. This is intensified by the periodic flushing of sediments from the retention basin. This muddies the structures on the river bottom which destroys deposited eggs, hatchlings, older fish, food bases, and spawning grounds (Campbell 1954, Liepolt 1961, Herbert and Richards 1963, Klausewitz et al. 1973). The most dramatic example of this was when the bottom sediments were cleared from the Kamienna hydroelectric facility on the

Drawa River. The spawning grounds downstream from the facility were muddied by this for several years, and this ultimately drove the only remaining salmon population in Polish waters to extinction (Chełkowski 1986, Chełkowski and Chełkowska 1996).

CONCLUSIONS

1. In contrast to the prevailing opinion that hydroelectric facilities are a source of ecologically clean energy, these plants have a negative impact on riverine ichthyofauna, particularly on migratory species and are an especially dangerous barrier to species descending rivers with the water currents.
2. Hydroelectric turbines pose great danger to ichthyofauna and are responsible for mortality rates that can, under poor conditions, exceed 50%. Losses are increased through the deaths of fish on the grates designed to prevent them from entering turbine canals at water intakes. Juvenile and adult migratory fish are in particular danger.
3. There is currently no fully effective method to protect fish from hydroelectric facilities.
4. The application of combined protective measures is necessary: e.g., dense grates and electric barriers that prevent the fish from reaching the turbine chamber and direct them to either a fish pass or an overflow of low, graduated dams, which guarantees the preservation of downstream migrations.
5. Another way of minimizing the negative impact of hydroelectric facilities on riverine ecosystems and ichthyofauna is to eliminate sudden water level fluctuations in the river beneath the dam, as well as to perform the periodic flushing of the sediments collected above the dam.

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Received – 14 March 2008

Accepted – 02 July 2008

STRESZCZENIE

ELEKTROWNIE WODNE A RYBY

Praca przygotowana została w oparciu o przegląd literatury i wyniki własnych badań. Omówiono oddziaływanie elektrowni wodnych na ichtiofaunę oraz ekosystemy rzeczne. Zaliczono do nich: niszczenie ryb na kratach i przez turbiny elektrowni, zaburzanie reżimu hydrologicznego rzeki, zmiany parametrów fizykochemicznych wody spowodowane spiętrzeniem, zamulanie tarlisk i żerowisk. Wskazano na możliwości przeciwdziałania skutkom tych niekorzystnych przekształceń. Służy temu wprowadzanie na elektrowniach wodnych odpowiednich zabezpieczeń, pozwalających na oprowadzenie ryb do miejsca, którym bezpiecznie spłyną w dół rzeki, a także wyeliminowanie gwałtownych wahań poziomu wody w rzece poniżej elektrowni. Podkreślono, że nie istnieją metody całkowicie eliminujące powstawanie strat w ichtiofaunie. Polecane jest łączenie kilku sposobów ochrony, np. krat i bariery elektrycznej. Z uwagi na negatywne dla ichtiofauny skutki pracy elektrowni wodnych, konieczne jest rekompensowanie strat poprzez partycypację użytkownika elektrowni w kosztach zarybiania.