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Original article

The European Fish Hazard Index – An assessment tool for screening hazard of hydropower plants for fish

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ABSTRACT

Hydroelectricity is critical for decarbonizing global energy production, but hydropower plants affect rivers, disrupt their continuity, and threaten migrating fishes. This puts hydroelectricity production in conflict with efforts to protect threatened species and re-connect fragmented ecosystems. Assessing the impact of hydropower on fishes will support informed decision-making during planning, commissioning, and operation of hydropower facilities. Few methods estimate mortalities of single species passing through hydropower turbines, but no commonly agreed tool assesses hazards of hydropower plants for fish populations. The European Fish Hazard Index bridges this gap. This assessment tool for screening ecological risk considers constellation specific effects of plant design and operation, the sensitivity and mortality of fish species and overarching conservation and environmental development targets for a river. Further, it facilitates impact mitigation of new and existing hydropower plants of various types across Europe.

Introduction

Mitigating impacts of climate change while simultaneously meeting growing energy demands necessitates the transition to decarbonized renewable energy [108]. Globally, hydropower is the major source of renewable energy, with a total installed capacity of 1308 GW [73] and production of 4306 TWh in 2019 [73], of which around 8% (348 TWh) were generated within the European Union [2]. Hydropower counts as key technology of the decarbonized energy sector, because of its highly predictable base-load generation, high stability, flexibility, and as most efficient large-scale mode to store energy [51]. Not surprisingly, >1000 large hydropower plants (HPPs) have been built within the last 50 years and >3000 are planned within the next decade (e.g., [68,71,93,146]). In addition, >80,000 small HPP with a capacity <1 MW are existing or under construction; a number is predicted to triple if total generation potential is developed [41]. But this vast majority of small HPPs produce just 13% of global hydro-electricity, while 87% is produced by just 9% of the HPPs (typically large plants) [9].

Irrespective of their size, HPPs have substantial impacts on fish [7,19,84,119], with small schemes inherently having the highest impacts relative to their capacity. Their dams fragment rivers and block up- and downstream fish migrations (e.g. [91]). Their impoundments alter flow regimes, sediment transport and sorting resulting in the loss of suitable habitats for riverine species (e.g. [94,112]), also in the tail water (e.g. [145]). HPPs themselves cause direct injury and mortality of fish, e.g. by sheer forces, pressure changes and collision with fixed or moving parts during both turbine and spillway passage (e.g. [5]). The impacts of HPPs cause strong conflicts with conservation needs of freshwater biodiversity, in particular of riverine and migratory fish species, as they are most affected by hydropower dams [90]. Correspondingly, habitat loss and hydromorphological alteration had been identified as prime impact on European water bodies [49] compromising environmental targets not only of the Water Framework Directive (2000/60/EC), but also of the Habitats Directive (92/43/EEC) and the Eel Regulation (1100/2007/EC). Consequently, reconnecting fragmented freshwater habitats is explicitly mentioned in the European

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Union's Biodiversity Strategy for 2030 [38]. Very obviously, there is a trade-off between the generation of renewable hydro-electricity and the adverse environmental effects of HPPs on river ecosystems. Therefore, it is important to evaluate hydropower impacts on river ecology to prevent potentially severe environmental disruption for a rather limited power generation at the expense of threatening freshwater biodiversity (e.g., [88,115]). Consequently, sustainable hydropower development and operation, and especially the environmentally sensitive management of small HPPs (e.g. [68]), has to account for hazards for affected fish populations that cause injuries and elevated mortality rates. To date, however, neither environmental impact assessment of hydropower is commonly agreed on, nor does a tool exist that allows highly resolved impact assessment of various hydropower set-ups on the ambient fish assemblage across Europe.

Despite of a broad variety of HPP types and individual design specifications, turbine passage constitutes the main hazard, especially for larger fishes [34]. Numerous studies have attempted to quantify turbine mortality rates and found them highly variable [17,29,50,57,80]. Reportedly common mediators were species identity [114], body size [34], individual behavior [40], turbine type [31,42,50,105] and operating condition [6]. Mortality risks are species-specific and depend on the autecological characteristics of the species' life history, and so are the individual implications for long-term population development. For example, turbine mortality correlates with the size and shape of the fish [31], the probability to encounter an HPP is influenced by a species' migratory behavior, the entrainment probability by its swimming performance as well as migratory behavior [65] and the impact of an interrupted river continuum is most pronounced for migratory species [12]. Generally, species that are long-lived and have a slow generation turnover are more susceptible to individual mortality [39], while at the same time, smaller species with rapid reproduction rates and high natural mortality rates might recover faster following individual losses due to mortality [134]. Furthermore, independent of their intrinsic sensitivity to HPP-related mortality, species require different management and prioritization related to their conservation value and protection. This is mostly because of different regional protection levels (e.g. IUCN red list listings of species or species groups), ecological aspects, management considerations (e.g. international agreements of stakeholders) or individual, site-specific conservation targets (e.g. EU habitats directive). Correspondingly, a risk-based assessment framework needs to consider species-specific sensitivities and conservation statuses to evaluate the environmental impact of HPPs appropriately.

More than half of all HPPs worldwide have either already undergone, or will soon require, upgrades and modernization [85], a process accelerated by some national legislatives that demand nationwide relicensing of all older HPPs, e.g. in Sweden between 2022 and 2036 (e.g. [62]). Therefore, the needs for comprehensive assessment of the overall hazard of HPPs on riverine fish communities and for prioritizing mitigation efforts have never been higher. Thorough evaluations of hydropower-induced hazards on fish species and communities are essential for efficient management and conservation schemes and to supporting informed decisions during the planning, commissioning, and operation of HPPs. While previous hazard assessments of hydropower projects provided important insights, they have mostly been restricted to the description of observed, direct consequences at a given study site (e.g. [30,40,43,50,102]) and commonly lack broader applicability.

Therefore, the hydropower sector needs a comprehensive assessment framework to evaluate the hazards of hydropower schemes for fish assemblages without the necessity for detailed site-specific mortality studies or population models. The framework should assess the hazards of one hydropower constellation relative to others as a function of (1) the specific operational, constructional and technical characteristics of an HPP and (2) the ambient fish community, the sensitivity of species and their specific mortality risk.

Here we introduce the European Fish Hazard Index (EFHI), an assessment tool for screening the risks of hydropower for fish. It has been developed by transferring conceptual knowledge about hydropower-related hazards for fishes into a means of evaluating site-specific risks. The EFHI is designed as a modular framework that offsets the relative hazard of a specific planned or existing HPP with the susceptibility of the local fish assemblage. It explicitly considers specific autecological characteristics of species in the target fish community [134] as well as their conservation value and the specific management targets of the ambient water body. Via the selection of candidate species, the tool can be adjusted to local environmental conditions and conservation objectives and is applicable across all European biogeographic regions. At the same time, the EFHI is comprehensive and sufficiently versatile to be applied to a wide range of HPP designs in various stream types. In addition to a comprehensive description of the technical implementation and the ecological reasoning of the EFHI we also demonstrate the tool's applicability related to hypothetical scenarios.

Conceptual functioning of the European fish hazard Index and its principal components

The European Fish Hazard Index (EFHI) integrates (1) species-specific sensitivities of the ambient fish community derived from species' life-history traits and conservation value and (2) the specific operational, constructional, and technical characteristics of an HPP. As the principal mechanism, the overall EFHI score increases with increasing severity of operational, constructional, and technical hazards of the HPP and with increasing sensitivity of the affected, ambient species community. Consequently, highest EFHI scores can be expected for HPPs associated with high overall hazards (e.g. mortality risks) installed in streams with numerous sensitive or conservation-critical species (see Box 1 for an example application). Additionally, the EFHI also considers measures that mitigate hazards posed by the HPP-specific components (e.g. state-of-the-art fish guiding systems or ecologically augmented migration facilities).

Hazards of hydropower to fish

Using extensive literature reviews, expert consultations and the consortium of 26 partners from science to operators within an European Horizon 2020 project (https://www.fithydro.eu/) we identified five constructional, technical and operational aspects of hydropower schemes that directly affect fish mortality: (1) upstream and downstream flow alterations; (2) entrainment risk; (3) turbine mortality; (4) upstream fish passage and (5) downstream fish passage (Fig. 1).

The impact of an HPP on a river's natural discharge pattern strongly depends on the plant's type and mode of operation, i.e. how it stores and releases water over time [98,101,112]. Generally, all barriers create impoundments depending on their height and the river slope, which alter otherwise free-flowing river sections and their associated habitat structures and substrates [20,113,144]. Specifically, storage-type HPPs feature large reservoirs and retain large volumes of water which is released during defined time periods. A storage-type plant is therefore associated with large reservoir fluctuations, aggravated by seasonal drawdowns as well as alterations and shifts of the natural hydrologic regime depending on the specific release scheme. Moreover, impoundments with storage capacity exceeding the river's discharge of several months or even years form a rather stagnant water body with lake-like vertical temperature and oxygen profiles, fine sediment accumulations and changes in nutrient availability [14,95]. Habitat and flow alterations caused by dams and their associated reservoirs, threaten fish populations especially of rheophilic guilds and cause community shifts [83,110,127]. Moreover, impoundments cause disorientation in fish because of the lack of migration cues such as attraction flow [10,118] and might even induce morphological adaptations in migratory fish species [63].

Downstream of HPPs, two major flow alterations primarily impact river fish populations: hydropeaking and residual flows. Hydropeaking

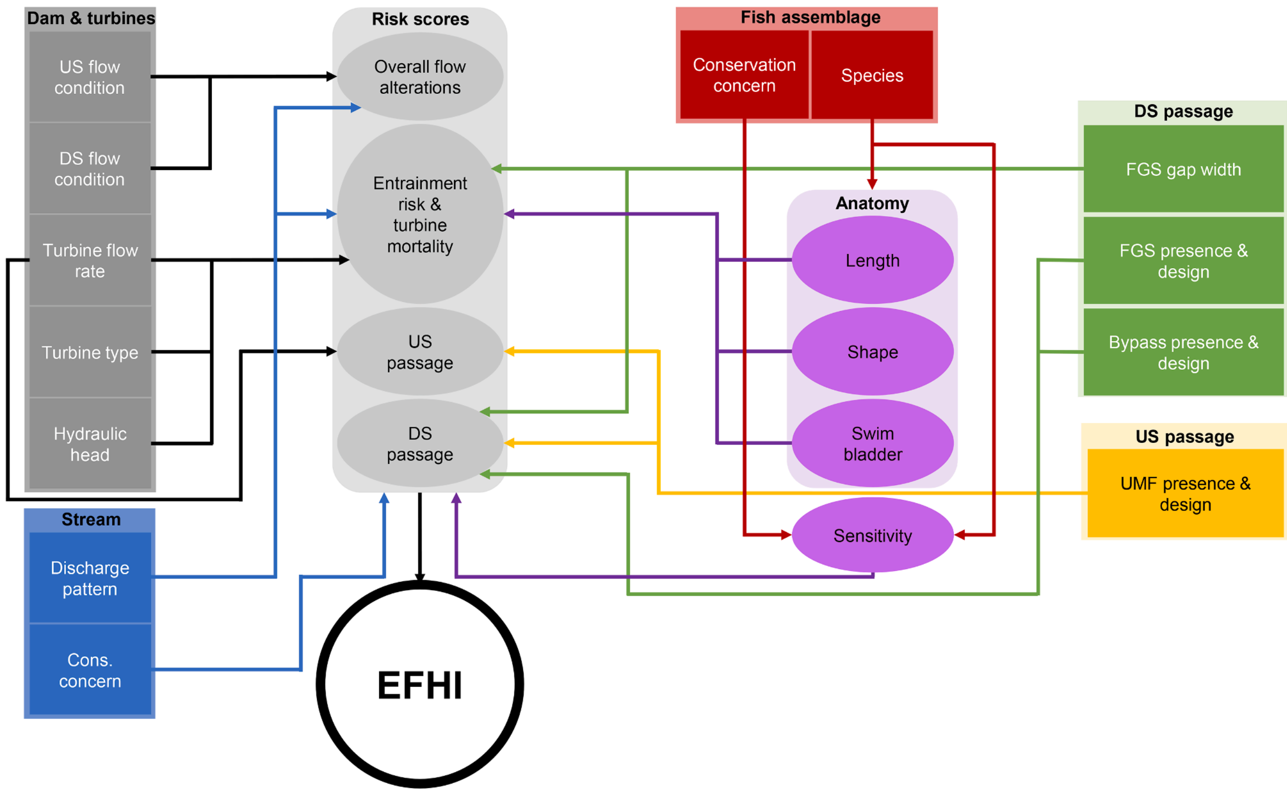

Fig. 1. Mechanistic model of the components of the European Fish Hazard Index. Rectangles = input parameters; ellipses = derived variables; open circle = final index. The "risk scores" box represents the process of transferring risk classes, species sensitivities and anatomies into adjusted and unadjusted hazard- and species-specific risk scores as shown in Table 1. These are then aggregated to the EFHI.

is the rapid and frequent fluctuation in discharge and water level resulting from intermittent electricity production [120], which was found having severe impacts on river fish [145] including stranding and displacement [67,120], dewatering and degradation of habitats [22], increasing water turbidity and reducing food uptake of fish [21,70,111,120,132]. Water abstraction and lack of residual flow occur mainly in diversion-type HPP, where the dam does not create the desired hydraulic head but serves to divert (usually) the majority of the discharge over a penstock to a distant powerhouse, where it gets turbinated and released to the original river further downstream. Often at length' of tens of kilometers the original river section gets widely dewatered receiving only a reduced residual flow that often lacks seasonal variability depending on the proportion of water abstracted. This manipulated flow is a major stressor on aquatic biota and causes shifts in fish communities and declines in abundance flow [7,64,78,99].

Compared to other hazards, turbine-related mortality is probably the best studied impact at HPPs. It is generally caused by either one or a combination of the four factors i) abrupt pressure changes ii) turbulent flow iii) shear forces and iv) turbine blade strikes [44]. Despite various attempts to deflect fishes from entering the turbines or to increase their fish friendliness, mortality caused by turbine passage remains a major issue. Depending on operating condition, turbine design and fish species a combination of pressure changes, shear stress and strike directly affects the fish. Blade strikes dominate at smaller turbines with higher rotational speed [31,36,139]. Predicting when and where a fish gets hit by a physical part of the turbine remains difficult but can be modeled most accurately for Kaplan and Francis turbines (e.g. [125,136]) as a function of fish length, rotational speed of the turbine, number of blades and decreasing space between blades (e.g. [100,18]). In larger plants with bigger turbines, the importance of pressure-related injuries affecting fish survival increases [25,31,37,116,124]. Previous studies indicated an increase of pressure-related fish mortality with barrier height [90] due to the more severe pressure changes during passage [24,37,116,138]. Generally, the susceptibility to pressure-related injuries varies with species: Barotrauma (primarily caused in Kaplan and Francis turbines) seems to be more pronounced in physoclistous than in physostomous species and least problematic for species without a swim bladder [26,27,38,66,139]. In our framework we acknowledge numerous technical advancements towards less harmful turbine types and operation modes, which can lower fish mortalities and reduce the overall hazard of an HPP. More detail on fish mortality across turbine types is provided by [46].

On their way downstream, fish generally choose a migration route based on its respective discharge [74,77]. Therefore, the amount of water that is passing through the turbines compared to what is released through alternative pathways such as e.g. bypasses, fishways, spillways or sluice gates is a significant predictor of fish being entrained into the turbine. Accordingly, discharge ratios between turbine and all alternative pathways might serve as suitable proxy for a baseline turbine entrainment risk of a fish.

Successfully preventing fishes from entering the turbines and subsequently guiding them downstream unharmed is critical component of "fish friendly" installations and highly relevant for (re)licensing HPPs. The risk of entrainment and related turbine mortality can be significantly reduced by implementing technical fish guidance structures (FGS) subsequently facilitated by downstream bypasses [43,48,126] and are extensively described by Ebel [48] and [53]. Highly suitable FGS comprise vertically inclined bar racks or angled (=installed at a horizontal angle) bar racks both with fish guiding efficiencies of $\geq$ 80% [33,92]. However, research is devoted to even more advanced FGS with vertically oriented bars like Louvers, modified and curved bar racks. These have significantly reduced hydraulic losses at increased fish guiding performance of $>$ 95% [4,15,82] combined with nearly no injuries or mortalities as observed at regular FGS (e.g. [92,126]). Common fine screens act as physical barrier for fish being only permeable for individuals leaner than the gap width of the screens. However, while narrower spacing prevents smaller and thus probably more fish from passing through, the overall efficiency of finest screens might be reduced due to sub-optimal hydraulic conditions and excessive accumulation of floating debris [92]. Previous studies indicated FGS with < 20 mm gap width and a functional bypass protected large proportions of migrating fish [1,23,61,92]. Louvers, modified or curved bar racks perform even better as FGS with significantly wider gap widths of up to 50 mm [4,15,82]. Other deflection devices like optical, acoustic, electric or other barriers have either not been conclusively studied or not sufficiently proven reliable in the long-term [23,75,90,107,126] and thus, were not considered here.

Furthermore, given the overwhelming evidence of the importance of unhindered fish migration [8,11,103] the presence of an upstream fish migration facility is considered an indispensable element of a modern HPP. Successful upstream migration of fish at barriers is achieved by fishways and thus, a lack thereof constitutes a major hazard for fish populations. Numerous types of fishways exist; however, their passage efficiency is highly variable and strongly determined by their design (size, openings, slope, flow velocities, head), location relative to the barrier, and attraction to migratory species [28,47,53,54], as well as their admission flow [142]. Discharge in a fishway usually ranges between < 1% and 5% of the average stream discharge [89] with relatively higher proportions being necessary for smaller streams [142]. Some types like nature-like fishways promise higher overall efficiency and lower mortality for both upstream and downstream migrating fishes (e.g. [32,104]) especially for small species and juveniles, whose needs are often overlooked when designing upstream migration facilities [54]. Furthermore, nature-like fishways can provide additional fish-ecological benefits like juvenile habitats, shelter or spawning grounds [60,109].

Fish species and community sensitivity

As general principle, the EFHI considers the hazards caused by HPPs in relation to the unique characteristics of the ambient, site-specific fish community. In our tool, the fish community is characterized by the sensitivity of species to additional mortality, which has been derived from several species-specific life-history traits and conservation aspects [134]. It has repeatedly been shown that a species' unique suite of life-history traits reflects its individual performance in resisting mortality [81,117,122] and recovering from abundance drops [72]. [134] analyzed indicative life history traits and derived a single species-specific score that reflects a species' overall sensitivity against mortality resulting from its specific combination of resistance and recovery traits. This sensitivity classification of European lampreys and fishes has been implemented into the EFHI. In addition, species and populations might be threatened or considered of conservation concern for various reasons. These include (but are not limited to) legally protected species at different levels from regional to international, red listed fish species, e.g. by the IUCN [129], species of conservation or management concern as well as target species for environmental improvements, e.g. according to the Water Framework Directive in Europe. The European eel is explicitly considered, because its stock improvement is specifically targeted by the EU Eel Regulation as well as all species of common conservation concern listed in the EU Habitats Directive, because many of them are migratory and, by default, highly threatened by HPPs. By selecting respective species of interest, all regional conservation targets can be explicitly implemented in the EFHI assessment.

Technical implementation and mechanistic functioning of the EFHI

The EFHI (v2.1.3, November 2020) is programmed in and compatible with Microsoft Excel (2016 Professional Plus or newer) and available online (Zenodo repository, DOI: https://doi.org//10.5281/zenodo.4250761).

The EFHI requires users to input information about the: i) HPP's main dimensions, turbine specifications, operating conditions and fish migration and protection facilities; ii) target species and iii) stream reach. Impacts of the above discussed HPP-specific hazards are classified according to defined thresholds derived from conceptual knowledge or model results, and subsequently categorized into "high", "moderate" or "low" risk classes. These categories are then cross-tabulated and contrasted to the rounded integer value of the species' biological sensitivity (obtained from [134]) to produce a numerical score for each hazard and species as shown in Table 1. Individual hazard scores can take values of 0, 0.25, 0.5, 0.75 or 1, with higher scores corresponding to more severe hazards. Up to five target species are selected by the user to best reflect the local fish assemblage, conservation concerns and river region. Selected species can be manually assigned to the highest sensitivity class, regardless of their original score, to account for regional conservation concerns or environmental targets for species and water bodies. Subsequently, all single hazard scores are aggregated to the EFHI. The modules and workflow as well as the input and output variables of the EFHI are presented in Fig. 1 and Table 2 and discussed in the following section.

Flow alterations

HPPs may exert impacts up- and/or downstream of their dam and at different magnitudes. Upstream flow alterations, i.e. impoundment effects are most pronounced in large, reservoir-type HPPs. Here, we assessed the impact of upstream flow alterations as dependent on storage capacity, which is often described relative to the average net inflow per time period [87,97]. In our framework, reservoirs with a storage capacity exceeding average annual net inflow were always scored as high risk. Schemes with smaller reservoirs and impoundments were further discriminated into two categories: Those that still cause substantial storage and reduce flow velocity through the impoundment below 0.5 m/s were classified moderate risk and those maintaining a continuous, minimum average flow velocity of ≥ 0.5 m/s were classified low risk.

Downstream flow alterations can be attributed to two distinct stressors: hydropeaking and water abstraction. Because hydropeaking inherently results in a completely altered discharge regime with severe impacts on stream biota, this operation mode was always scored high risk. The hazard of water abstraction, particularly problematic in residual river stretches of diversion schemes, was scored by applying recommendations for sustaining full ecological functionality, i.e. environmental flows, following [130]: If the discharge in the residual river stretch is <10% of the mean annual low flow the risk was scored high. Residual flows of less than or equal to 10% of the stream's mean annual flow were scored moderate, and >10% of its mean annual flow scored low risk, respectively. The overall downstream risk was assigned according to the higher score. Upstream and downstream hazard classes were aggregated into the total flow alteration hazard using the same principle.

Entrainment risk

The combined flow rate of the installed turbines (corresponding to the total generation capacity at a location) was used to derive a proxy of

Table 1
Generating the numerical impact scores for a specific hazard and species contributing to the calculation of the EFHI.

Hazard classification	Target species sensitivity		
	4	3	2
High	1	0.75	0.5
Moderate	0.75	0.5	0.25
Low	0.5	0.25	0

Target sensitivity score from 2 (low) to 4 (high) obtained from [134].

Table 2
Risk classification of the main HPP-specific hazards contributing to the calculation of the EFHI.

Hazard type	Evaluated attribute	Risk class		
		Low	Moderate	High
Flow alterations	Differentiated alteration of flow US and DS	Both, US, and DS flow alterations are low	One, US or DS flow is altered moderately, the other is low	Either one, US or DS flow is highly altered
Entrainment risk	Discharge ratio($Q_{installed\_total}/Q_{mean}$)	≤0.5	>0.5-<1	≥1
Turbine mortality	Blade strike models	$M_{Monten} < 4\%$	$M_{Monten} = 4\%$-8%	$M_{Monten} > 8\%$
	Empirical turbine mortality	Water wheel Pentair Fairbanks Kaplan VLH	Archimedes screw	Ossberger Pelton
	Barrier height (Barotrauma mortality)	<2 m	2–10 m	>10 m
Upstream passage	UMF presence & characteristics	Existing and Q ≥ recommended	Existing and Q up to 50% < recommended	Missing or Q < 50% recommended
Downstream passage	FGS presence & characteristics	FGS Installation angle ≤ 45° and DS bypass across whole water column	FGS installation angle > 45° or DS bypass not fully accessible	Missing FGS or missing DS bypass

Acronyms: US = Upstream; DS = Downstream; Q = Flow rate; M = Blade strike mortality; VLH = Very Low Head turbine; UMF = Upstream migration facility; FGS = Fish guidance structure.

the entrainment risk for fish. This risk describes the baseline probability of fish passing through the turbine(s) rather than taking any other route downstream and was estimated from the quotient of the installed total turbine flow rate ($Q_{installed\_total}$) over mean river discharge (Q_{mean}). Turbine entrainment was divided into three classes based on thresholds provided in Table 2.

To account for the fish-deflecting effect of potential FGS, entrainment risk score was individually adjusted for every installed turbine and turbine mortality hazard score as follows: In a first step, gap width of the FGS and length-to-width ratios of the five target species were used to derive the maximum length L_{max} of both eel-like and non-eel-like (e.g. fusiform) species that could pass the screen. For that purpose, [48] provided empirically derived estimates of the relationship (ratio b) between a fish's width and length, whose grand average is $b = 0.11$ for fusiform and $b = 0.03$ for eel-like body shapes, respectively. Accordingly, the maximum length L_{max} of a fish that can pass the screen is

$$L_{max} = gapwidth/b \quad (1)$$

For example, an FGS with a gap width of 20 mm is therefore permeable for fusiform species of $L_{max} = 18cm$ and eel-like species of $L_{max} = 67cm$. In a second step, L_{max} was compared to the common adult length (L_{common}; obtained from Fishbase [56], of the selected species and processed as follows: If L_{common} of a species was shorter than L_{max} the entrainment hazard score remained unchanged. If L_{common} was larger than L_{max} the installed fine screen would lower the entrainment risk for adults. In that case, the entrainment score was adjusted by weighing it with the factorL_{max}/L_{common}. This ratio assumes values closer to one when L_{max} is relatively large and values closer to zero when L_{max} is relatively small. This ratio was then used as an additional weighing factor in the assessment of the turbine mortality hazard.

Turbine mortality hazard

The assessment of turbine-specific mortality risk was based on the three components i) model-based turbine blade strike rates for Francis and Kaplan turbines and similar types, ii) literature-informed, empirical mortality rates for Archimedes screws, Kaplan very-low-head, Ossberger, Pelton, Pentair Fairbanks and water wheels, and iii) empirical turbine barotrauma mortality rates. Following an established classification by [141], we scored mortality rates of i) and ii) between 0% and 4% as low, between > 4% and 8% as moderate and > 8% as high risk. To evaluate HPPs with more than one turbine, the EFHI assigns risk scores of i), ii) and iii) for each individual turbine and species as shown in Table 1 and subsequently, aggregates the relative contribution of each turbine to the overall mortality rate weighted by the turbines' relative flow rates (Supplement S2). For all turbine types other than Kaplan and Francis, the score of i) was directly summed up across all installed turbines, for Kaplan and Francis turbines the risk scores of ii) and iii) were aggregated before being summed up across all installed turbines. The summed scores were only allowed to reach a maximum value of 1, regardless of their actual value and multiplied with the weighing factor of the entrainment risk score. The result comprises the overall turbine mortality score.

Blade strike models

Fish mortality of Kaplan, Kaplan bulb, Kaplan minimum gap runner and Francis turbines has been frequently studied in the field [6,16,29,58,114,123,128], which allowed the development of various blade strike models producing reliable outputs for these turbine types. We explicitly used blade strike models to assess turbine mortality for these turbine types (Supplement S1) allowing for more standardized estimates depending on detailed turbine characteristics. We applied the frequently used blade-strike model by [100] that calculates the probability of a fish striking a blade depending on the fish's length and the relative space between blades s_{rel_mid}. This accounts for the angle of the blades that might be variable depending on discharge, e.g. in Kaplan turbines. The blade angle of Kaplan turbines can be estimated from inflow velocity, velocity of the runner blades and the head. Models for Francis turbines use a two-dimensional projection of the velocity characteristics (i.e. a velocity parallelogram) at the turbine entrance [18,48,100,125]. Technical details on how to estimate relevant variables leading to the calculation of β are described in Supplement S1.

Based on the relative spacing of the turbine blades s_{rel_mid} and the fish length L, the strike mortality (in %) of Kaplan and Francis turbines can be calculated following [100] as:

$$M_{Monten} = ((0.5 \times L)/s_{rel\_mid}) \times 100 \quad (2)$$

For the calculation of M_{Monten} we used L_{max} from Eq. (1) (for L) which refers to the body length of fish that can pass the FGS. Analogous to [141] and the risk scoring of the generic turbine risk we classified mortality rates for Francis and Kaplan turbines [100] as low for rates between 0% and 4%, moderate (between > 4% and 8%) and high (rates of > 8%), respectively.

Empirical turbine mortality

For turbine types that cannot be assessed with Montén's mortality model, empirical data were used to establish hazard classes. Lowest mortality rates were reported for water wheels (<1%; [121]), Pentair Fairbanks (<1%; [133,140]), and very-low-head (VLH; <4%; [69,86,55]) turbines. These turbine types were therefore classified as low risk. Comparably higher mortality rates are caused by Archimedes screws (<8%; [141]), which are considered moderate risk types, accordingly. Very high mortality rates (>99%) were reported for Ossberger [59,79] and Pelton turbines [31], which are consequently classified as high risk.

Barotrauma mortality

Because the modelled mortality rates are based solely on blade strike probability, they were complemented with the risk for pressure-related injuries, i.e. barotrauma, which was derived from the specific hydraulic head. We scored barrier heights of < 2 m as low, 2–10 m as moderate and > 10 m as high risk based on empirical data [141]. However, the susceptibility to barotrauma is highly species-specific: Physoclistous fish (e.g. Percidae) are most at risk, because they cannot acclimatize to pressure changes and release gas quickly enough during decompression, followed by physostomous fish with an open swim bladder (e.g. Salmonidae) and species without swim bladder, the latter considered of very low susceptibility to barotrauma [37,66,138,26,27]. We used these differences to adjust the barotrauma risk score according to quantitative model observations by [138] as follows: i) 50% increase for physoclistous, ii) unchanged for physostomous, and iii) zero for species without a swim bladder. Energy converters operating at atmospheric pressure induce no barotrauma risk, e.g. water wheels, screws.

Upstream fish passage

A major factor affecting the effectiveness of upstream fish passage facilities is their discharge relative to the mean discharge of the river, with higher values increasing passage success [142]. Here we used two linear regressions to determine the minimum recommended discharge in an upstream migration facility (UMF) as a function of the total installed flow rate derived from [46].

$$Q_{UMF\_opt} = -0.0801 \times Q_{mean} + 5.0008 \quad (3)$$

$$Q_{UMF\_opt} = -0.0006 \times Q_{mean} + 3.014 \quad (4)$$

Eq. (3) was applied to plants with an installed flow rate of $<25\ m^3/s$ that require a discharge in the UMF between 3% and 5% of that value, with smaller installations requiring proportionally more water to be functional. Eq. (4) was applied to UMFs in larger installations that require proportionally less water, e.g. between 3% and 1%. User input values for the discharge in the UMF as well as interpolated discharge values were rounded to one decimal point and compared: If the discharge in the UMF was equal to or higher than the calculated recommendation, the risk class was scored low. A discharge $\leq$ 50% of the calculated recommendation was considered a risk to full functioning of the fish pass and scored moderate. Discharges $<$ 50% of the calculated recommendation or no UMF altogether were both considered inadequate passage facilities and scored high risk. The superior passage performance of nature-like fishways was considered by lowering both the upstream and downstream passage score by 20% each, assuming an FGS was in place appropriately preventing turbine passage (gapwidth $< L_{max} \times b$).

Downstream fish passage

The hazards related to downstream migrating fish were assessed as follows: Angled bar racks, Louvers, modified and curved bar racks at a horizontal installation angle of $\leq 45^\circ$, or vertically inclined bar racks with an inclination of $\leq 45^\circ$, all in combination with downstream bypasses accessible across the whole water column have proven highly efficient [35,33,48], and were therefore scored as low risk. Less ideal are FGS installed at larger horizontal or rather steep vertical angle and with vertical bars: While those indeed prevent fishes from entrainment, they can also cause substantial injuries or mortalities due to impingement or sheer force (e.g. [35,33,34,92]). Furthermore, the efficiency of simple bypasses located at the bottom or surface of the water body seems to be highly variable [33,61,106,131]. Therefore, vertically inclined bar racks of $> 45^\circ$ as well as FGS at a horizontal angle of $> 45^\circ$ and any constellation without fully accessible bypass were scored as moderate risk. The total absence of an FGS or a downstream bypass was scored as high risk. Analogous to the treatment of the upstream hazard section, we reward the bi-directional performance of a nature-like fishway with a reduction of the downstream passage hazard score by 20%.

Aggregation of the final EFHI

Both the adjusted and unadjusted species-specific scores of the single HPP-specific hazards were aggregated into an index by calculating the arithmetic mean. The tool provides the possibility to explore the effects of alternative HPP-related components and constellations. By simulating changes to a range of measures with an immediate effect on the hazard classes, unadjusted and adjusted risk scores and the final EFHI, the EFHI facilitates achieving a desired risk class, respectively identifying configurations considered likely to be least harmful for fish.

Applicability and limitations

The European Fish Hazard Index (EFHI) detailed here constitutes a comprehensive, easily applicable, transparent, and reproducible screening tool for environmental risk assessment of both existing and planned hydropower plants and their effects on fishes. Thereby, the EFHI fills a methodological gap of considerable importance in relation to several European and national legislative frameworks that has not yet been addressed. In fact, the construction and operation of HPP is inevitably linked to impacts on rivers' hydromorphology and fish assemblages and thus, development of renewable hydropower may conflict with the environmental objectives of, for example, the EU Water Framework Directive, Habitats Directive (92/43/EEC) and Eel Regulation, to mention just some European laws. Accordingly, many existing hydropower installations are subjected to environmental impact assessment (2014/52/EU). In addition, REN21, the global renewable energy community, estimated that a significant amount of all HPPs worldwide will soon require upgrades and modernization [85]. Correspondingly, about 65% and 50% of small hydropower plants located in Western and Eastern Europe, respectively, are >40 years old [9]. Therefore, the EFHI supports the environmental impact assessment during the modernization of such HPPs by identifying relatively hazardous installations and prioritizing plants to upgrade fist.

Given the comprehensiveness of the EFHI, it is different from other hydropower-related assessment frameworks in many ways. For example, previous attempts were either assessing impacts on different biological endpoints [96], running cost-benefit calculations [143], targeting only single species or life stages [13,52], or aiming at maximization of electricity generation rates [3]. The EFHI addresses the various potential impacts of HPP on the conservation-critical animal group of fishes built on conceptual knowledge that is extracted from real case studies that can profitably operate even under maximum-mitigation scenarios. This innovative assessment tool constitutes a step towards recognizing and reducing the impacts of HPPs on fish and riverine environments.

There are also some limitations associated with the EFHI. First, as a risk screening tool it cannot replace detailed hydropower site-specific empirical impact assessment studies of fish mortality. Especially the mortality of large adult fish can be underestimated in Kaplan and Francis blade strike models [136] and deterministic models often do not match prediction accuracy of stochastic approaches [45]. However, such models rely on large amounts of data and could not be implemented while at the same time maintaining its desired relative simplicity and universal applicability. Furthermore, the tool neither informs nor provides input for fish population models and viability analyses and it does not reflect seasonality of fish migrations, life-stage effects, water temperature and other trigger that affect fish mortality [76,135,137]. Our

Box 1
Example application of calculating the EFHI.

To showcase the performance of the EFHI, it was applied to a scenario of a small-scale, low-head (2.3 m) run-of-the-river HPP generating about 0.15 MW in a small river with 7.5 m^3/s mean and 1 m^3/s mean low discharge. Flow velocity through the upstream impoundment is higher than 0.5 m/s. We considered four different example configurations to illustrate the different outcomes as a result of the sensitivity of the fish assemblage and the technical/operational HPP characteristics and to identify potential management interventions (Fig. 2 and Supplement S3a–d):

Assuming a baseline configuration, the HPP is operated with a Kaplan turbine (outer diameter = 2.0 m, hub diameter = 0.76 m, 150 rpm, 4 blades) at an average flow rate that approximates mean river discharge (7.5 m^3/s). The considered lowland river fish community at the HPP location comprises of small to large-bodied species of generally low sensitivity (sensu [134]: pike (*Esox lucius*; sensitivity score = 2.8), white bream (*Blicca bjoerkna*; 2.8), perch (*Perca fluviatilis*; 2.8), roach (*Rutilus rutilus*; 2.5), and bleak (*Alburnus alburnus*; 2.3). Fish protection is not applied in this baseline scenario, i.e. the HPP is equipped only with a vertically oriented trash rack of 100 mm gap width (installation angle of 70°). Neither an up- nor a downstream fish migration facility or bypass is installed. Accordingly, the resulting EFHI score is 0.64 indicating a moderate overall hazard given the low sensitivity of the fish community (S3a).
However, the EFHI for this HPP installation markedly increases for a slightly different fish community comprising more sensitive species. For example, considering in addition to pike and white bream the potamodromous Barbel (Barbus barbus; 4.1), the European eel (Anguilla anguilla; 3.7) and Asp (Leuciscus aspius; 3.3), with the latter two being of specific conservation concern (e.g. Eel regulation (Council Regulation (EC) No 1100/2007) and Annex II EU Habitats Directive (92/43/EEC), respectively), the EFHI raises to 0.8, a high overall hazard score for the same turbine configuration (S3b).
The high EFHI can be lowered by the installation of or upgrading certain fish protection measures. For example, an angled bar rack with a bar spacing of 20 mm (45° horizontally inclined) accompanied by a fully accessible downstream bypass and an upstream migration facility with a recommended discharge of 0.33 m^3/s (equivalent to 4.4% of the installed capacity) lowers the EFHI for the same sensitive species community and turbine type to 0.49, a moderate overall hazard (S3c).
As a further improvement, e.g. when refurbishing the HPP, the Kaplan turbine might be replaced by a fish-friendlier Kaplan very-low-head unit with a lower overall mortality risk, and the upstream migration facility is re-designed in a nature-like manner. In this mitigated scenario, the EFHI further decreases to 0.32 for the same flow rate and rather sensitive species community (S3d).

methodology considers mainly the common adults of a species as assessment target, and disregards potentially high hydropower-related mortality rates of eggs and larvae, which makes it inappropriate for the estimation of detailed, long-term population effects since their risk remains largely unquantifiable. Furthermore, a range of hazard parameters can be barely included in an assessment tool: e.g. the vertical position of a fish in the water column approaching the turbine, the actual angle of the blades in Kaplan turbines or their operation

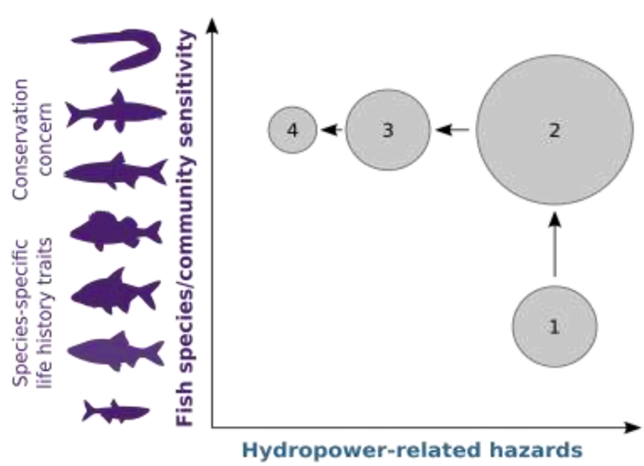

Fig. 2. Example illustration of the principal mechanism of EFHI. The technical and operational parameters of a specific HPP pose a certain constellation-specific mortality risk to fish (1). With increasing sensitivity of the ambient species community, the EFHI increases (1 → 2). The EFHI decreases if the severity of operational, constructional and technical hazards of the HPP are reduced, such as by the installation of or upgrading fish protection measures (2 → 3) and changing to a fish-friendlier turbine type and a nature-like upstream migration facility (3 → 4). Configurations at the bottom-left indicate no further management, while configurations at the top-right indicate priority for mitigation, respectively.

conditions (e.g. flow rates) over the course of a year. Consequently, we used simplifications, modelled data, and data approximated from empirical studies. Simplification applies to the mitigation measures considered by the tool, too, because they only comprise approaches to lower fish mortality directly at or in the vicinity of an HPP. Needs for appropriate river rehabilitation at the level of water bodies cannot be inferred from the EFHI results. All parameter thresholds were derived as accurately as possible using empirical data, models, expert judgement, and most-consensus schemes. But because of the high variability in construction details, spatial arrangements, modes of operation and their various interaction effects, it was impossible to derive a model sufficiently versatile to fully capture and precisely quantify the risk of different HPP constellations. To account for the corresponding uncertainties, the numerical scoring of the calculated EFHI was classified into just three hazard groups: "low", "moderate" or "high" risk.

In summary, the EFHI can assess single- and multi-turbine set-ups in a variety of HPPs and streams. It uses an optimized number of comparably easily obtainable input parameters, while all other relevant parameters resulting from their complex interactions are modeled or approximated from literature and empirical studies from similar systems. Regional biogeography and conservation concerns are specifically considered by the selection of target species and account for rehabilitation planning, protection requirements and other management decisions. The EFHI has implemented an inventory of 168 fish species native or established in European waters classified by sensitivity against mortality and other relevant traits, and it supports mitigation planning by enabling the selection of potential mitigation measures and measure combinations and assessing their effect on the hazard score.

The EFHI provides a robust, evidence-based, broadly applicable, and transparent screening tool for systematic risk assessment of HPPs for fishes and as such, we expect it to be highly useful to a wide range of stakeholders.

Author contributions

Ruben van Treeck designed and coded the tool and took the lead in writing of the paper.

Johannes Radinger modelled strike mortalities and participated in writing of the paper.

Richard Noble designed the EFHI's core mechanistic principles and participated in writing of the paper.

Franz Geiger revised and fine-tuned hydropower-related reasoning and participated in writing of the paper.

Christian Wolter conceptualized the study, revised ecological and biological interactions of the model, and participated in writing of the paper.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2020.100903.

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