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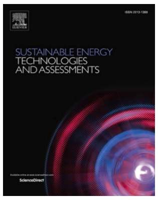

Original article

Comparative assessment of hydropower risks for fishes using the novel European fish hazard Index

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ABSTRACT

In context of transitioning towards renewable energy, hydroelectricity has gained global relevance. However, hydropower plants have severe impacts on aquatic habitat and biota: Dams disrupt migration routes of diadromous and potamodromous fish species, degrade the hydro-morphology of streams and turbines cause high mortalities in fishes. To support risk assessment and mitigation, the European Fish Hazard Index EFHI identifies potentially harmful constellations of existing and planned hydropower plants adjusted to the reference fish assemblages of the affected stream sections. In this study, we applied the EFHI to seven small, low-head hydropower plants of various types and compared our results to those of extensive empirical fish mortality estimates independently conducted at the same sites. We illustrate how hydropower hazards go beyond turbine mortality and that the EFHI widely reflects site-specific risks of flow manipulations, entrainment, and upstream and downstream fish passage. Based on the EFHI results we found that environmental impact assessments based on the present fish community tend to underestimate hazards, particularly when the fish assemblage is already degraded. We further examined the EFHI's performance and identified some potential for future implementations of new fish mortality models and novel, fish safer turbines.

Introduction

Hydropower as a means of renewable energy has become increasingly relevant for the energy transition towards a decarbonized electricity supply. However, this often comes at the expense of disruption of free-flowing rivers, degraded ecosystems, and loss of aquatic species diversity [1–5], fueling a debate about the environmental sustainability of hydropower [6]. This holds especially true for small, low-head hydropower plants (HPPs) because of their severe impact on the environment relative to their electricity output [7,8]. Their detrimental impacts are further aggravated by cascading effects of multiple consecutive HPPs [9,10], as well as by some of their technical features (e.g., fast rotating turbines) leading to high fish mortalities [11–18]. Water wheels and recent turbine developments towards higher fish safety, such as the Very Low Head (VLH) turbine or Archimedes screw [12,19–28], potentially provide improvements. Yet, a holistic risk assessment of HPPs including their manifold impacts on fishes as well as mitigation strategies is still missing. The European Fish Hazard Index

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; EFHI, European Fish Hazard Index; HPP, Hydropower plant; FLOW, Overall flow alterations; ETM, Entrainment and turbine mortality; US, Upstream fish passage; DS, Downstream fish passage.

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EFHI [29] provides this important keystone towards a holistic hydropower assessment. The EFHI is a freely available, Microsoft Excel-based tool with a user-friendly interface (Supplement Figs. S1 and S2) and available for download at https://zenodo.org/record/4686531. It scores risks related to hydropower operation considering plant size and type, location in the stream, the ambient fish assemblage and conservation constraints. The EFHI scores four main hazard components: i) the degree of flow alterations imposed by the HPP upstream and downstream of the barrier, ii) the risk of fish entrainment and subsequent turbine mortality, iii) risks related to impeded upstream fish passage and iv) risks related to downstream fish passage routes[29]. As such, it is a systematic, universally applicable, and transparent risk-screening framework for fishes in hydropower-affected environments that goes beyond existing spatially, and biologically explicit, hydropower-related assessments (e.g., by Ziv et al. [30]) as well as those primarily focusing on turbine blade strike or pressure-related injuries (e.g., by Vowles et al. and Pracheil et al. [31,32]). The EFHI uses conceptual knowledge and empirical models of hydropower-related hazards for fish and offsets both with i) site-specific information on stream discharge patterns, ii) the ambient fish assemblage, iii) management targets, iv) species-specific life-history-mediated sensitivity scores to additional (i.e., artificial) mortality ranging from 2 (low sensitivity) to 4 (high sensitivity) [33], and v) fish size and swim bladder anatomy. It then translates these partly convoluted risk factors into an overall hazard score that is comparable within and across installations and biogeographical regions running from 0 (no risk) to 1 (high risk). The EFHI can be used in various scenarios e.g., to compare risks of multiple hydropower setups in the same stream, of similar setups in different rivers or to track the hazard of a single HPP for fish over time (i.e., after upgrading components or changing operation modes). This makes it a highly versatile tool to facilitate comprehensive risk assessment conducted by operators, water authorities and other stakeholders. While the EFHI framework was developed to assess the impact of individual hydropower plants, an assessment of cumulative effects of hydropower cascades considering population metrics may be a logical next step for a more comprehensive assessment of impacts on entire river systems. Until then, the usefulness of the EFHI is probably greatest for the comparative application across different hydropower types and (bio)geographical regions, such an assessment has, to the best of our knowledge, not yet been performed. Consequently, this study applied the EFHI to seven small, low-head hydropower plants of various types and contrasted the tools' results to the findings of extensive empirical fish mortality estimates conducted at the same sites. The main objective of this study was to examine the applicability, usefulness, and performance of the EHFI in comparison to commonly applied empirical estimates of fish mortality at HPPs. Particularly, we aim to: i) investigate how and to what extent the EFHI and its hazard components flow alterations ("FLOW"), entrainment and turbine mortality ("ETM"), upstream fish passage ("US"), and downstream fish passage ("DS") add to or go beyond typical impact assessments; ii) assess the correspondence between EFHI scores and empirical fish mortality rates as well as to reveal mechanistic factors for deviations, and iii) identify potential improvements of the EFHI and its components.

Material and methods

Test cases

To test how the EFHI performs under real-world conditions it was applied at seven small (<1 MW), low-head HPPs and analyzed in context of already published results of empirical fish mortality assessments independently conducted between 2014 and 2016. All studied HPPs are located in Bavaria, Germany in small, low mountain range, subalpine or alpine rivers: Au at the river Iller [34], Baierbrunn at the Isar [35], Baiersdorf-Wellerstadt at the Regnitz [36], Eixendorf at the Schwarzach

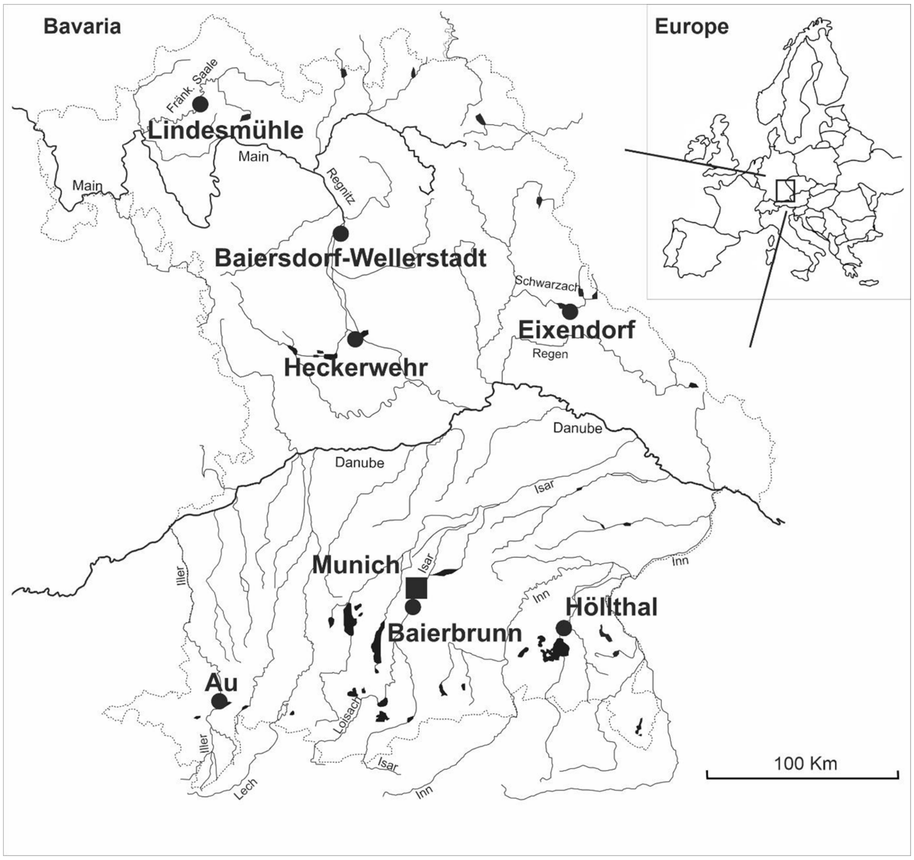

Fig. 1. Study sites of the project on innovative and conventional hydropower production in Bavaria, Germany, comprising seven hydropower stations (filled circles).

[37], Heckerwehr at the Roth [38], Höllthal at the Alz [39] and Lindesmühle at the Fränkische Saale [40] (Fig. 1). The fish community in these rivers is largely dominated by rheophilic salmonids and cyprinids.

As part of the empirical studies, fish mortality (direct and delayed after 96 h) was assessed at each site using both standardized fish release and capture of fish naturally passing through turbines at varying turbine loads. During standardized experiments, defined numbers of fish were released at different positions in front of the turbine intakes and recaptured after turbine passage with stow-fyke nets directly at the turbine outlet. Fishes were checked for damages prior to their release and after re-capture. Methodological details are given by Mueller et al. [41]. In addition, damage rates of fish migrating through up- and downstream passage facilities, flow and discharge patterns, the degree of hydromorphological degradations and reference fish communities were reported. The latter describe the anthropogenically uninfluenced fish community, mark the rehabilitation target for a stream section and are used for conservation planning and ecological status assessment in the Water Framework Directive monitoring [42].

Parametrization of single EFHI components

For each site, the following technical information was obtained for parameterizing the EFHI: turbine specifications, hydraulic head, stream discharge metrics, hydropower-related flow manipulations, fish protection and passage facilities as summarized in Table 1. The EFHI evaluates four hazard components that collectively contribute to the final EFHI score: FLOW, ETM, US, and DS (Fig. 2). For more details of the tool's mechanistic behavior, the implemented models, and empirical data we refer to van Treeck et al. [29].

The EFHI FLOW component independently evaluates up- and downstream flow manipulations. For the upstream part of FLOW, the impoundment storage capacity is assessed relative to the daily average inflow and regarding current velocities within the impoundment. The downstream FLOW part assesses the HPP operation regarding hydropeaking and discharge modifications of the annual mean and low flows and, in the case of diversion-type plants, potential residual flows. Data on upstream impoundment capacities were available for Au [34] and approximated using aerial photographs or recalculated from mean flow rates of the stream and the turbines for the other sites. Current velocities within the impoundments were extracted from the field studies for all seven HPPs.

The EFHI calculates the ETM risk by applying blade strike models for Kaplan-type and Francis turbines and empirical mortality observations for other turbine types. The modelled strike rate risk is complemented with scores for barotrauma risks depending on the plant's hydraulic head and the species' swim bladder anatomy. The turbine-specific mortality risk is translated into a score and offset with the species' basic probability of entrainment based on individual turbine flows in relation to stream discharge. The entrainment risk is corrected in cases of installed fine screens by regressing fish length based on width following Ebel [43]. The resulting maximum size of species passing through the turbine is then used in the fish length-dependent blade strike models.

The US component is calculated by determining an upstream migration facility's discharge proportion of the turbine flow, which is then scored in relation to the stream discharge, since larger streams require a relatively lower admission flow in the upstream migration facility compared to smaller ones. The DS hazard component is assessed by determining the presence of a downstream bypass and its accessibility for fish in the vicinity of a deflection screen. Furthermore, it rewards facilities allowing for both up- and downstream migration by lowering the upstream risk score by an increment. For example, HPP Baierbrunn is equipped with a pool pass and an additional rocky ramp. While the pool pass was exclusively designed for upstream migration, the rocky ramp was constructed to provide a safe corridor for downstream migration as well as to facilitate upstream migration for strong

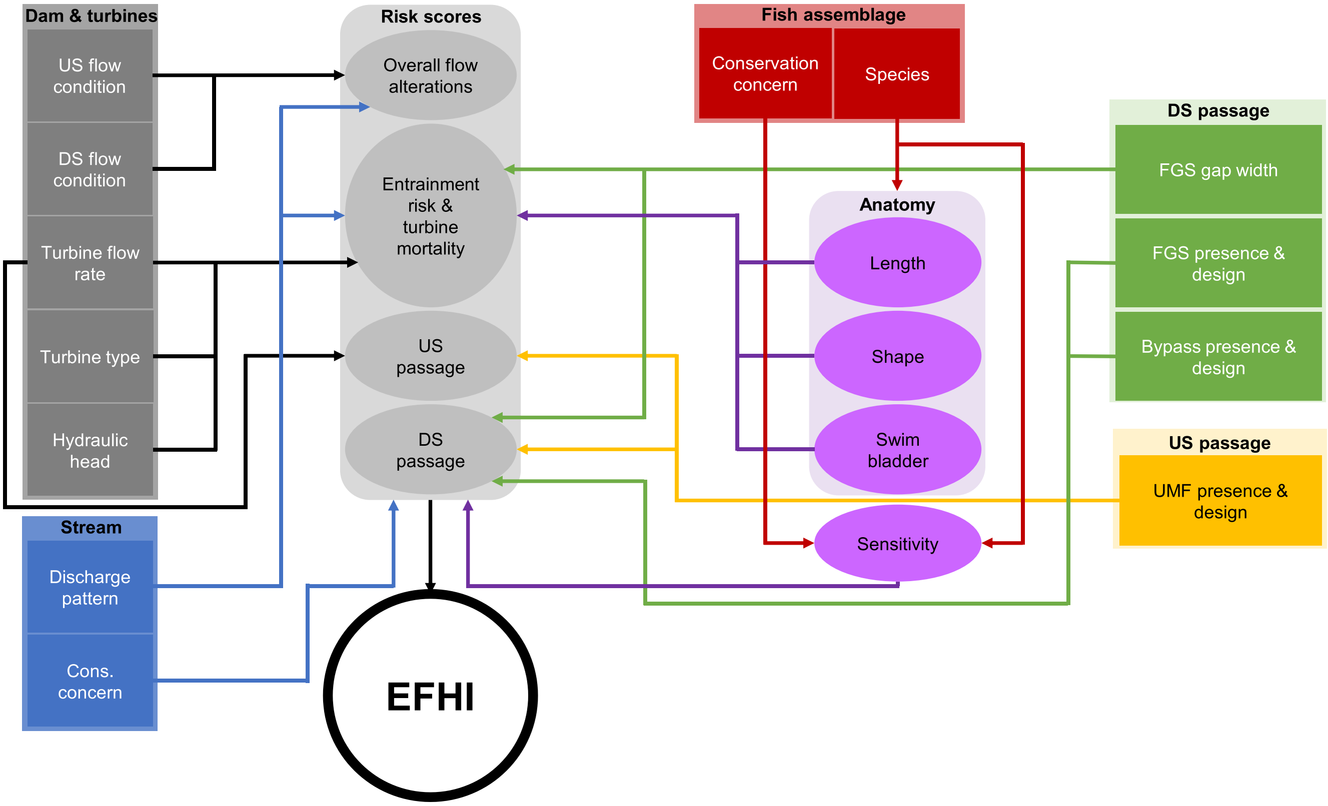

Fig. 2. Mechanistic model of the EFHI parameterized by different groups of input parameters and the four resulting hazard components (light grey) as well as the final EFHI score (open circle). Obtained from van Treeck et al. [29].

Table 1
Data of the seven hydropower plants for EFHI calculations. Except for one case, impoundment capacities of the plants were determined using aerial photographs. If not stated otherwise, turbine specifications and hydraulic head apply to all installed turbines. DAI = daily average inflow; Screw = Archimedes screw turbine; VLH = very low head turbine; VSP = vertical slot pass; HBR = horizontal bar rack; VBR = vertical bar rack; * = approximated; ** = upstream migration facility works bi-directional; ^{1} = run run-of-river setup; residual water discharge was defined equal to annual mean discharge; ^{2} = built into the residual water stretch of a HPP further downstream; discharge in residual stretch was used vicariously as annual average and low stream discharge.

Category	Parameter	Au	Baierbrunn	Baiersdorf	Eixendorf	Heckerwehr	Höllthal	Lindesmühle
Stream discharge parameters	Impoundment capacity	<DAI	<DAI	<DAI	>DAI	<DAI	<DAI	<DAI
	Impoundment current speed (m/s)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
	Annual mean/low discharge (m^3/s)	46.6/ 9.45	19/8^2	34.8 /15.1	4.32/ 1.33	3.17/0.87	51.5/ 19.3	12.3/2.97
	Discharge residual water stretch (m^3/s)	46.6^1	19^1	9.1	4.32^1	3.17^1	12	12.3^1
Turbines	Number and type	2x VLH	1x VLH	2x Kaplan	1x Kaplan	1x Screw	2x Screw 1x Kaplan	1x Kaplan
	Design flow rate (m^3/s)	2x 27	14.5	2x 16	4.5	5	2x 9 1x 18	10.8
	Hub/outer diameter (m) (Kaplan only)	–	–	0.76/2	0.38/1	0.53/1.5	0.95/2.5	0.53/1.5
	Rotational speed (RPM) (Kaplan only)	–	–	150	333	212	100	212
	Number of blades (Kaplan only)	–	–	4	4	3	4	3
	Hydraulic head (m)	2	4	2.3	5	2.5	2	2.8
Fish protection and fish passage facilities	Upstream passage type	VSP	Pool pass Rocky ramp	VSP Pool pass	–	Screw	Pool pass	Nature-like
	Upstream passage discharge (m^3/s)	1*	4.2 0.3	1	–	0.015	1*	0.33*
	Protection screen type	HBR	–	VBR	VBR	–	–	HBR
	Screen bar spacing (mm)	270	120	15	20	120	2x 150 1x 20	15
	Downstream bypass	No	Yes	Yes	Yes	No	No	Yes**
	Bypass fully accessible	–	No	No	No	–	–	No

and weak swimming species. In addition, the rocky ramp provides habitat for rheophilic species [44–49].

Assemblage-specific calculation of EFHI

For each of the seven hydropower sites final EFHI scores and scores of EFHI's four hazard components FLOW, ETM, US and DS were calculated in three treatments, comprising the same physical parameters but three different sets of fish species:

1. The five most dominant (relative abundance $\geq$ 5%) yet sensitive species of the actual, fish-faunistic reference community ("reference set"; Supplement Table S1). When two species were equally sensitive in the reference assemblage, we prioritized that of higher dominance. Because a risk assessment based on an already degraded biological component does not provide meaningful management recommendations towards the "good ecological status/potential" demanded by the Water Framework Directive, the reference assemblage is used by default with the EFHI. This treatment was used to establish the ultimate risk ranking of the seven HPPs and the results were analyzed in context of Mueller et al.'s [34–40] empirical impact assessments.
2. The five most abundant species of the actual fish assemblage determined by electrofishing ("sample set"; Supplement Table S2). These species were evaluated regarding their mortality rates in turbine entrainment events and therefore, comprise a baseline of the HPP risks for the current fish assemblage. The sample sets were used to comprehend fish-ecological observations in the EFHI and juxtapose them with results of the reference sets. Further, they were used to determine the difference in HPP risk level for the reference compared to the current fish assemblage, and to calculate the single contribution of the target fish sensitivity on the final EFHI score.
3. Species used in the standardized fish release experiments ("release set"; Supplement Table S3). This set comprises the eight most frequently used species in each standardized release experiment by Mueller et al. [34–40], European eel (*Anguilla anguilla*), common nase (*Chondrostoma nasus*), brown trout (*Salmo trutta*), common perch (*Perca fluviatilis*), European grayling (*Thymallus thymallus*), common barbel (*Barbus barbus*), common roach (*Rutilus rutilus*) and Danube salmon (*Hucho hucho*), of which the five most abundant were used in the EFHI. The EFHI results of the release set were compared to the results of the standardized release turbine mortality experiments by Mueller et al. [34–40].

Data analysis

To estimate whether the EFHI reflected the environmental conditions around the seven HPPs, the results of the reference set were interpreted and compared with the comprehensive reports on the empirical fish mortality estimates by Mueller et al. [34–40].

Paired two-sample permutation tests (asymptotic general independence tests, AGIT [50]), were used with a p-value adjustment that controls for false discovery rate (FDR [51]) to test for differences in EFHI hazard scores and average fish sensitivities between the sets. Pearson correlation coefficients were calculated for the entire data set and separately for the single sets to quantify pairwise relationships of EFHI's hazard components. In addition, multiple factor analysis (MFA, R-package 'FactoMineR', [52]) was used to analyze the multivariate characteristics of the EFHI hazard scores dataset and to visualize potential multicollinearity between single hazard scores. MFA is a generalization of the principal component analysis [53] to reduce the multidimensional attribute space of the variables EFHI, FLOW, ETM, US and DS, which were calculated with three sets of species, into a smaller set of principal components. Observed mortality estimates were extracted from the field studies by Mueller et al. [34–40] and their correlation coefficients determined with the EFHI results of the release and sample sets. To explore the impact of species sensitivity on the risk scores linear models were calculated and tested against a null model by means of ANOVAs.

To identify hydropower components and sites of particularly high risk for the reference community, the numerical divergence of each pair of risk scores between the reference and sample set within sites was calculated. The result was then correlated with both the sensitivity of the sample and the reference set to test whether high calculated risks were related to a high divergence (e.g., degradation) of the current fish assemblage compared to the reference, or to disproportionally sensitive reference communities, respectively.

All EFHI calculations were conducted using the European Fish Hazard Index EFHI, version 2.1.8 (https://zenodo.org/record/4686531, [29]). Statistical analyses were conducted in R, version 4.0.4 [54]. For calculating pairwise permutation tests the package ‘coin’, version 1.4–1 [50]) was used. Linear models were calculated using the package ‘lme4′ [55]. The statistical significance threshold for all analyses was $p = 0.05$.

Results

Among all studied HPPs, the final EFHI score ranged between 0.27 (low risk; Baiersdorf; sample set) and 0.75 (high risk; Eixendorf; reference set, Table 2 and Table 3). EFHI scores varied substantially between the three species sets as indicated by a paired permutation test (two-sided asymptotic general independence test AGIT, $maxT = 3.26$, $p < 0.01$). Pairwise post hoc tests revealed significant differences in the final EFHI score between the sample set (mean $EFHI = 0.47$) and the release set (mean $EFHI = 0.60$; AGIT, $Z = 2.36$, adjusted $p < 0.05$) and between the sample set and the reference set (mean $EFHI = 0.59$; $Z = 2.43$, adjusted $p < 0.05$). Differences in EFHI scores between reference and release sets were not significant ($Z = 0.40$, adjusted $p > 0.1$).

Scores of the four hazard components varied considerably between the different sets, too (Table 2 and Table 3). Statistically significant differences between species sets were found for FLOW (AGIT, $maxT = 3.38$, $p < 0.01$), US ($maxT = 3.35$, $p < 0.01$) and DS ($maxT = 3.35$, $p < 0.01$). Differences in ETM were not statistically significant between the three sets of species used ($maxT = 1.37$, $p > 0.1$).

Correspondingly, the average sensitivity of species differed among the three sets (AGIT $maxT = 3.36$, $p < 0.01$, Fig. 3). Average sensitivity of the species set in release sets ($mean = 3.5$) deviated clearly from that in the sample sets ($mean = 2.7$; $Z = 2.55$, adjusted $p < 0.05$), but was similar to those of the reference sets ($mean = 3.4$; $Z = 1.36$, adjusted $p > 0.1$). Generally, sensitivities of species of the release sets were more similar to those of the reference sets compared to sensitivities of the sample sets (Fig. 3).

An ANOVA comparing linear models of risk scores of FLOW against the null model revealed a dependence on average species sensitivity across all sets ($F = 10.28$, $p < 0.01$). In contrast, scores of ETM, US, DS, and the final EFHI score did not improve the explanatory power of the null model ($F = 0.03$, $p = 0.87$; $F = 0.78$, $p = 0.39$; $F = 3.35$, $p = 0.08$; $F = 2.93$, $p = 0.1$, respectively).

Table 3

Calculated results of reference runs for overall flow alterations (FLOW), entrainment and turbine mortality (ETM), upstream fish passage (US), downstream fish passage (DS), and the final EFHI score (EFHI), and average species sensitivity.

Site	FLOW	ETM	US	DS	EFHI	Average sensitivity
Au	0.55	0.3	0.55	0.8	0.55	3.08
Baierbrunn	0.6	0.35	0.28	0.48	0.43	3.38
Baiersdorf	0.6	0.3	0.35	0.6	0.46	3.30
Eixendorf	0.8	0.86	0.8	0.55	0.75	3.17
Heckerwehr	0.6	0.6	0.85	0.85	0.73	3.27
Höllthal	0.6	0.53	0.6	0.85	0.65	3.38
Lindesmühle	0.65	0.56	0.52	0.52	0.56	3.75

A strong positive correlation was found between EFHI and US scores in all species sets (all $R > 0.97$; $p < 0.01$, Fig. 4) and between EFHI and ETM scores in the reference species set ($R = 0.86$, $p < 0.05$, Fig. 4). Among the single components, significant pair-wise correlations were detected between ETM and FLOW ($R = 0.86$, $p < 0.05$) and ETM and US ($R = 0.78$, $p < 0.05$) in the reference sets (Fig. 4). The MFA indicated similar patterns of (multi)-collinearity across the four hazard components and the final EFHI score with ETM and US scores rather contributing to the first axis (56% explained variance) and the DS to the second axis (30% explained variance, see Supplement Fig. S3 and Table S4).

Final EFHI scores were not significantly correlated with observed mortalities ($p > 0.1$) and similarly, ETM scores did not correlate with observed mortalities either (all $p > 0.1$). However, some pronounced, yet statistically insignificant trend was found between the ETM score, and the mortality rates observed in the standardized release experiments, particularly when compared to the index values based on the sample species set ($R = 0.57$, $p = 0.18$).

Divergence between risk scores of the reference set vs. sample set were highest at Baiersdorf (cumulated divergence of 0.99) and lowest at Baierbrunn (0.23). With the exception for ETM, divergence was significantly negatively correlated with the respective sensitivity of sample sets (FLOW: $R = -0.79$, $p < 0.05$; US: $R = -0.82$, $p < 0.05$; $DS = 0.82$, $p < 0.05$ and EFHI: $R = -0.76$, $p < 0.05$; Fig. 5) but was not related with the sensitivity of the reference sets.

Discussion

The expected expansion of hydropower and the ongoing decline of freshwater biodiversity require a standardized, transparent, and evidence-based assessment of its impacts [6]. Therefore, the assessment of potential risks of HPPs for fishes is paramount to its sustainable development. This study exemplarily demonstrates at seven small hydropower plants in Germany how the European Fish Hazard Index EFHI

Table 2

Results of the seven hydropower plants using the same species as in the standardized release experiments (“release”) and species caught upstream of the plant (“sample”). Displayed are the hazard scores for the single EFHI-components: overall flow alterations (FLOW), entrainment and turbine mortality (ETM), upstream fish passage (US), downstream fish passage (DS), final EFHI score (EFHI), and the related observed mortality rates.

Site	Set	FLOW	ETM	US	DS	EFHI	Observed mortality	Average sensitivity
Au	Release	0.65	0.40	0.65	0.90	0.65	5.7	3.8
	Sample	0.50	0.25	0.50	0.75	0.50	44	2.9
Baierbrunn	Release	0.60	0.35	0.28	0.48	0.43	19.3	3.5
	Sample	0.55	0.30	0.24	0.44	0.38	31	3
Baiersdorf	Release	0.63	0.45	0.38	0.63	0.52	20	3.6
	Sample	0.35	0.26	0.10	0.35	0.27	50	2.5
Eixendorf	Release	0.80	0.59	0.80	0.55	0.69	24.6	3.3
	Sample	0.65	0.71	0.65	0.40	0.60	NA	2.5
Heckerwehr	Release	0.60	0.60	0.85	0.85	0.73	12.8	3.4
	Sample	0.45	0.45	0.70	0.70	0.58	28	2.7
Höllthal	Release	0.60	0.42	0.60	0.85	0.62	6.8	3.4
	Sample	0.45	0.47	0.45	0.70	0.52	29	2.9
Lindesmühle	Release	0.63	0.58	0.50	0.50	0.55	42	3.6
	Sample	0.45	0.64	0.36	0.36	0.45	69	2.6

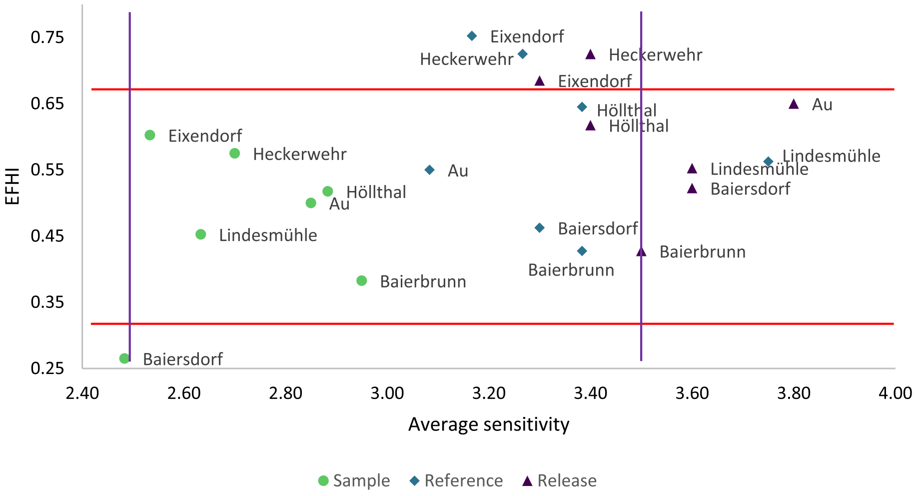

Fig. 3. Average species' sensitivity in release sets (purple), sample sets (green) and reference sets (blue) vs. the respective final EFHI scores (n = 7 each). Red horizontal lines indicate thresholds to moderate and high-risk classes, respectively, purple vertical lines indicate thresholds of moderate and high species' sensitivity.

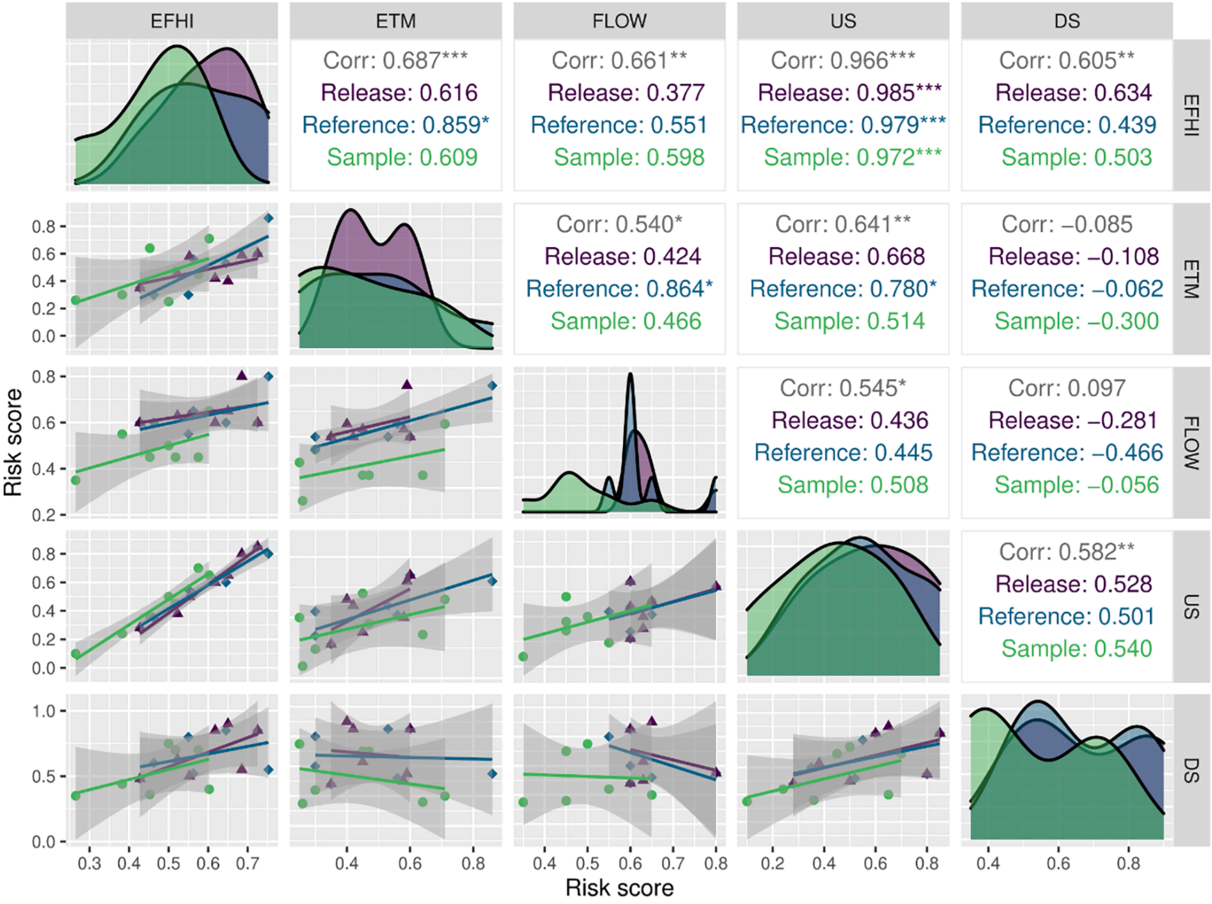

Fig. 4. Correlation metrics, scatter plots and histograms of hazard components, final EFHI scores and observed mortalities of release (purple), reference (blue) and sample (green) treatments.

by van Treeck et al. [29] can facilitate and augment such risk screening. We tested how accurately the final EFHI and its hazard components FLOW, ETM, US and DS reflect the results of the empirical impact assessments on-site and explored mechanistic, framework-related, and ecological factors when they did not. Overall and to a great extent, the tool captured risks that have been documented in detailed, prior on-site impact assessments by Mueller et al. [34–40]. In addition, the application of the EFHI also identified key areas for further adjustments of its mechanistic behavior.

Results of EFHI calculations

Final EFHI scores and scores of the hazard components FLOW, ETM, US and DS strongly differed across sites, with the overall lowest

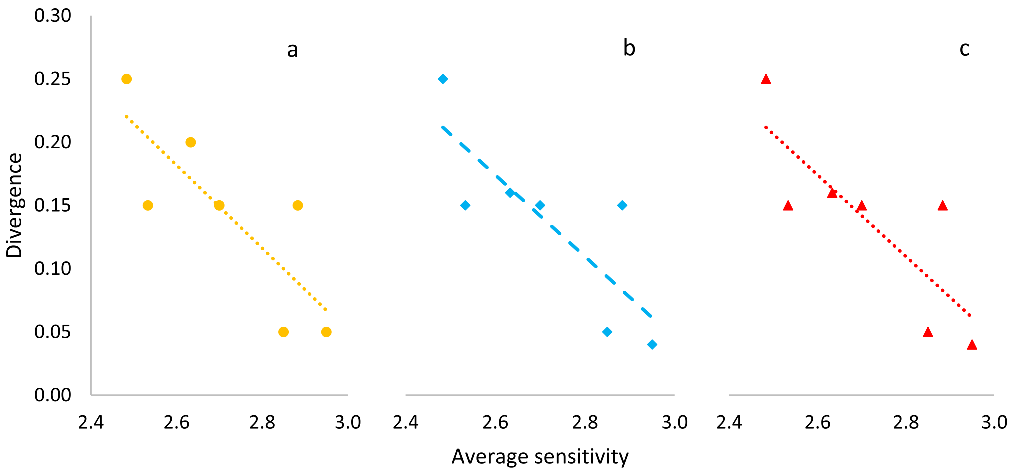

Fig. 5. Correlation of the divergence of FLOW (a), US (b) and DS (c; n = 7 each) between reference and sample sets and the average species' sensitivity of the sample set.

("moderate") risk calculated at Baierbrunn and the overall highest ("high") risk at Eixendorf. Because the final EFHI score is calculated by aggregating the scores of the four hazard components, we discuss their scoring results individually.

Highest FLOW scores (0.8) were calculated for Eixendorf, which is the only HPP with an upstream storage exceeding daily average inflow, and slow current speeds through the impoundment. Since hydromorphological mechanisms downstream cannot compensate a high upstream risk and vice versa, the higher risk class of the two components determines the final FLOW hazard. Indeed, Eixendorf's FLOW classification matched field observations conducted in 2015, when the hydropower plant was built on top of an existing weir. Fish samplings upstream and downstream of the plant before and after construction, showed lower than expected abundances of rheophilic fish species including common gudgeon (*Gobio gobio*), European dace (*Leuciscus leuciscus*), common nase (*Chondrostoma nasus*) and common barbel (*Barbus barbus*), as well as of rheophilic invertebrates [37]. Furthermore, comparative analyses of the aquatic assemblages up- and downstream of the dam revealed no significant change after construction of the HPP, indicating a persisting, detrimental effect of the impoundment caused by the weir [37]. Downstream of Eixendorf the presence of ubiquitous fish species like common perch (*Perca fluviatilis*) indicate ecological degradation [56]. The reasons for that are closely related to the ecological deficits upstream and downstream: a lack of shallow littoral zones as fish nurseries and heavy embankments. In addition, the reservoir traps sediment (i.e., gravel) that is subsequently missing downstream [37]. This leads to habitat displacement and ecological degradation [57–61], which cannot be fully captured by the EFHI, because it assesses downstream risks based on stream discharge and turbine flow rate patterns and ratios only.

The lowest FLOW scores (0.55) were calculated for Au. At this site, the original weir was replaced by an inflatable rubber weir [34]. Its specific design allows for more dynamic management of high and low flows and permits the downstream transport of sediment and dead wood. The improved hydro-geomorphological conditions support a range of rheophilic species and their reproduction [34]. Despite the presence of rheophilic and lithophilic species, the assemblage still deviates from the reference community, with some reference species such as European dace (*Leuciscus leucisucs*), common nase (*Chondrostoma nasus*) and common gudgeon (*Gobio gobio*) still absent. The difference in average sensitivity between sample set (2.9) and reference set (3.1) was small. Given that rheophilic and lithophilic guilds are commonly more sensitive than eurytopics or phytophilics [33] we conclude that Au's FLOW scores accurately describe prevalent conditions.

The highest US score (0.85) was calculated for Heckerwehr. Studies show that one of the most important metrics mediating the upstream passage success of a fish way is the amount of water going through it [62]. At Heckerwehr, the installed upstream fish migration screw is supplied with only 0.3% of the flow rate of the installed Archimedes screw, which is<15 times the recommended EFHI value for a stream of that size. A standardized assessment of the screw's passage performance following Ebel et al. [63] confirmed the screw's insufficiency, even if not explicitly attributed to disproportionally low discharge [38].

The lowest US risks (0.28) were calculated for Baierbrunn. The risk rating was driven by the high proportion of the turbine flow rate (29%) supplied to the passage facilities, the ecological benefit of the additional rock ramp and its improved downstream fish passage [44–49]. The beneficial effect of the rock ramp was also directly confirmed by Mueller et al. [35] at Baierbrunn. However, due to EFHI's properties, potential performance issues regarding excessive discharge or current speeds in passage facilities as observed by Mueller et al. [35] were not reflected in the framework.

Fish mortality in turbines and risks for fish due to flow alterations or upstream fish passage are physically isolated from each other and therefore, mechanistically independently implemented in the tool. In contrast to other components, this does not apply to ETM and DS because turbine passage comprises one (albeit the most dangerous) downstream route for fish [1]. However, substantial research was devoted to the development of turbines that are safer for fish (e.g., [12,20,23,25,26,28,64]). In HPPs running such improved turbines, dedicated downstream bypasses might become partly superfluous if fish can safely migrate through the turbines [19]. If this was universally true, it would principally annul the need for narrow spaced protection screens and dedicated downstream bypasses at the turbine intake. However, so far there is too little evidence from only few installations of these novel turbine types regarding the safety for fish under routine operation. Despite lower fatal blade strike rates in larger or more advanced turbines, fish may still experience significant physiological impacts like barotrauma and other injuries that are not easily detectable or manifest with delay only [65–68]. Populations may also suffer from elevated mortalities due to predation of potentially highly disoriented fish post-passage [15,65,69–73]. Four of the seven studied HPPs were equipped with more advanced turbines like VLH (Au and Baierbrunn [34,35]) and Archimedes screws (Heckerwehr and Höllthal, although the latter also operated a Kaplan runner [38,39]). Neither of these setups featured dedicated downstream bypasses, and all screws were only protected by coarse trash racks with bar spacing between 120 and 270 mm. The missing protection screens and bypasses caused high DS scores that ultimately, resulted in negative relationships with ETM scores. This, in turn, caused relatively high final EFHI scores for HPPs with otherwise low ETM scores.

This risk equality highlights the necessity to interpret EFHI results in the context of its sub scores, but it also shows how EFHI goes beyond empirical mortality estimates. Even at low mortality rates, the absolute mortality caused by a turbine can become high if fishes are not additionally prevented from entering. Accordingly, a large Kaplan turbine equipped with a very fine screen and operating at high load but with only a moderate flow rate compared to the stream discharge, could yield the same ETM score as a highly advanced VLH turbine with documented mortality rates of $\leq$ 4% [23,28,29]. Only if passage through a particular turbine would indeed be the safest downstream route, final EFHI scores would overestimate the total risk of the plant. To date, however, operational and accessible bypasses are considered the safest downstream route for fishes and risks of turbine passage remain dominant [1,11], even in more advanced turbines.

Interpretation of EFHI results in context of observed mortalities

At the seven hydropower plants, the final EFHI score did not significantly correlate with empirically observed mortalities because it aggregates hazards beyond mortality (i.e., FLOW, US, and DS). This was regardless of the assessment methodology, i.e., examining natural entrainment vs. standardized releases of fishes. However, due to the lack of standardization in natural entrainment trials [41] their results are generally less comparable across sites.

Empirical mortality rates higher than expected by the EFHI were observed at Baierbrunn and Baiersdorf which could be attributed to an atypical operation of the installed VLH turbine [35], and the use of arithmetic means of observed mortalities [36], respectively. At Baiersdorf the averaged mortality rate was notably high because of a low number of eels tested with an exceptionally high observed mortality. Unexpectedly high mortality rates of up to 69% were also observed in natural entrainment experiments at Lindesmühle [40], despite a 15 mm fine screen which should prevent most fishes $\geq$ 15 cm total length from entering the Kaplan turbine. Mueller et al. [40] explained these high mortality rates by an unknown share of already damaged or dead fish, low recapture rates that increase statistical uncertainty, dominance of pressure-susceptible physoclistous species and low turbine loads during the experiments. These are all common challenges of empirical fish mortality investigations at HPPs, but only fish anatomy and turbine load factor into the EFHI score, which might explain some deviation from empirical observations. In contrast, mortality rates in the Archimedes screws at Höllthal and Heckerwehr were lower than expected by the EFHI. In screws, factors like fish length, runner size and rotational speed might have the opposite effect than in Kaplan or Francis turbines, as smaller specimens are more likely to get impinged between runner and trough [12,19,74]. So far, mortality models mainly exist for Francis and Kaplan turbines as well as some Kaplan-derivates (e.g., [64,75–77]), while size and species-specific models of damage rates for other turbine types are yet to be developed. In the EFHI, their risks are only implemented as static, empirical information of low (VLH) and moderate risk (Archimedes screw) and cannot provide the same resolution and accuracy as mortality models.

Mechanistic diagnosis

We observed that overall, the EFHI framework and its risk scores accurately reflected the environmental conditions of the hydropower constellations investigated. However, the hazard scoring results did not only depend on impact exerting (i.e., hydropower) factors but also on the resilience of fishes against those impacts and the complex interaction between these two factors. This holds true for all EFHI components but particularly for those considering individual life history traits beyond the sensitivity score (the ETM component, for example, considers>10 individual input variables per fish [29]). The relative impact strength of species sensitivity vs. hydropower components is therefore not easily visible. The conducted analyses revealed a strong dependence of FLOW on the respective average species' sensitivity, and significant correlations of the risk score divergence between sample and reference sets on the sample species' sensitivity, with exception for ETM, which is most likely due to its exceedingly complex mechanistic behavior. The role of sensitivity for the risk scoring emphasizes the importance of explicitly considering fish-ecological and fish conservation aspects in context of risk evaluations. Most importantly, however, it highlights the great potential for underestimating hydropower risks in more degraded streams independent from the reference species' sensitivity. The same physical components of a HPP might yield different risk levels for fish, depending on their susceptibility to anthropogenic stress, a phenomenon that was clearly visible when comparing sample and reference sets: The significantly lower sensitivity of the sample (average across all sites 2.7) compared to the reference set (average 3.3) was driven by the lower abundance of sensitive, rheophilic, lithophilic and diadromous species that potentially would occur under natural conditions. This community shift from the reference was generally well-reflected in the reports by Mueller et al. [34–40], and most pronounced in our calculations for Lindesmühle. At this site the specific reference fish community comprises among others European eel (*Anguilla anguilla*), European grayling (*Thymallus thymallus*), brown trout (*Salmo trutta*), common barbel (*Barbus barbus*) and common nase (*Chondrostoma nasus*) and has an average sensitivity of 3.75. The most abundant species in the sample, however, were common roach (*Rutilus rutilus*), common gudgeon (*Gobio gobio*), Eurasian ruffe (*Gymnocephalus cernua*), European dace (*Leuciscus leuciscus*) and common perch (*Perca fluviatilis*), with an average sensitivity of 2.63 (decline of 29.8%). This degradation was partly reflected in low-risk scores of FLOW, US, DS and the final EFHI, but not at all in the ETM score, which was the second highest of all HPP scored. The high ETM risk was caused by high numbers of small species, two of them physoclistous, in the sample set, that could physically pass the deflection screen and enter the turbine, which caused a full weighing of the subsequently high-risk turbine passage with calculated blade strike rates of $>$ 9% [29]. The ETM score was particularly high for common gudgeon (*G. gobio*) and independent of individual sensitivity or calculated blade strike rates and matched the very high observed turbine mortality rates at HPP Lindesmühle discussed earlier. However, often small-scaled HPPs replace existing weirs in already hydro-morphologically degraded stream systems [57], which makes an evaluation of the additional ecological effects of hydropower difficult. While it was beyond the scope of this study to investigate the causes for the diverging species assemblages, it is noteworthy that habitat and up- and downstream flow alterations, as well and limited connectivity, have frequently impacted stream fish species communities, often resulting in a loss of the most sensitive, rheophilic species [78–83].

Future adjustments

Reasons for deviations between calculated in the EFHI and actual impacts found in field surveys can be manifold and often require more detailed follow-up analyses. Besides this, some potential improvements of the EFHI were identified, which might be implemented in future revisions of the tool. This includes further implementation of non-standard turbine configurations and their potential effects on fish mortality rates. For example, a refined turbine selection process issuing warnings when typical turbine installation and operating parameters are exceeded could help fine-tuning the turbine risk scoring. In addition, the turbine risk classification based on empirical data implemented in the EFHI (e.g., for Archimedes screws) should be replaced by modelled fish mortalities, because of their better scoring performance. Therefore, further mortality models for other turbine types should be implemented as soon as they become available.

Finally, the performance of the downstream component DS could be enhanced. If the claimed better performance of the novel, more fish-safe turbine types becomes empirically evidenced under routine operation, these turbines can be implemented as a separate downstream passage route in the DS component. Then it will be reflected in the DS score if passage of a particular fish safer turbine results in lower mortality than alternative downstream routes.

Conclusions

The EFHI performed well in detecting and describing hydropower-related risks such as those exerted by flow manipulations, turbine entrainment and mortality, downstream passage across alternative routes and upstream passage. It was shown that EFHI's resolution is sufficiently high to reliably combine and discriminate its constituent components according to the unique conditions of a given HPP while still considering the sensitivity of the target fish species pool. With its four hazard components and the broad selection of target species implemented (168 native European species), the EFHI can effectively support risk assessment and mitigation of hydropower components and constellations throughout Europe. The EFHI hazard scoring will be further improved by implementing both novel, fish-safer turbine types and mortality models for turbines other than Kaplan and Francis, as soon as they become available.

Author contributions

Ruben van Treeck analyzed the data and led the writing of the manuscript.

Johannes Radinger analyzed the data and participated in writing of the manuscript.

Nicole Smialek provided the reference data and participated in writing of the manuscript.

Joachim Pander provided the reference data and participated in writing of the manuscript.

Melanie Müller provided the reference data and participated in writing of the manuscript.

Jürgen Geist is the responsible PI of the field studies used in this manuscript, provided the reference data, and participated in writing of the manuscript.

Christian Wolter conceptualized the study and participated in writing of the manuscript.

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.2021.101906.

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