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Fish passes design discharge requirements for successful operation

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Abstract

Longitudinal connectivity is one of the prime issues addressed in river restoration our days. At the same time, mitigation of climate change impacts by modes of renewable energy increasingly puts pressure on the remaining free flowing river stretches for hydroelectricity production. At the site level, this trade-off manifests in the negotiation of water for upstream and downstream fish passage versus losses for hydroelectricity production. This study has compiled and analysed 193 studies evaluating fish passes designed to provide upstream migration for all species and size classes of the respective river system. The overall assessment of functioning and discharge dedicated to fish pass maintenance, site, and river characters were provided by the studies. The main objective here was deriving general guidance for the minimum amount of water needed for fully functioning upstream fish passage in relation to river size. There was a significant correlation between functionality and design discharge of a fish pass. Fully functioning fish passes (N = 92) had median design discharge of 5% of the mean average discharge of the river, restrictedly functioning of 1.1% and not functioning of 0.22%. A power model could be derived of design discharge needs in relation to river discharge, which is inversely related to river size. In large rivers, a rather small share of mean discharge is sufficient, whereas in small rivers, it cannot be further downscaled due to dimensions. This model might provide first guidance in adjusting needs for both hydroelectricity generation and fish conservation in regulated rivers.

KEYWORDS

design discharge, fish pass, longitudinal connectivity, river rehabilitation

1 | INTRODUCTION

Migration barriers and habitat fragmentation have long been identified as major impacts on riverine aquatic ecosystems resulting in dramatic declines of obligatory migrating fish species (Dugan et al., 2010; Limburg & Waldman, 2009) as well as riverine fish in general (Dugan et al., 2010; Pimm, Russell, Gittleman, & Brooks, 1995; Wilcove, Rothstein, Dubow, Phillips, & Loscos, 1998). Worldwide, there are between 37,626 (ICOLD, 2011) and >45,000 (Nilsson, Reidy, Dynesius, & Revenga, 2005) large dams higher than 15 m registered. Lehner et al. (2011) estimated that about 7.6% of the world's rivers with an average discharge >1 m^3/s (575,900 river kilometres) is affected by a cumulative upstream reservoir capacity that exceeds 2% of their annual flow. However, the number of large dams and reservoirs significantly underestimates the ecological impacts of damming on aquatic organisms, because already barriers >0.2 m in height can form impassable obstacles for some fish and lamprey species, and their number is multiply higher. For example, in the United States, the total number of migration barriers comprises 74,921 dams >2 m high (Graf, 1999) and more than two million smaller dams (Poff & Hart, 2002). In Austrian rivers, 55,135 small dams and weirs were reported (Lashofer et al., 2011), in German rivers, some 200,000 transverse structures (Fehér et al., 2012). Other recent counts of river fragmentation in Europe provided by Fehér et al. (2012) comprise more than 60,000 dams, weirs, and mills on French rivers, over 100,000 artificial barriers with a height >0.5 m in Swiss rivers, 779 barriers on the 3,000 km long priority network of rivers in Belgium, 6,023 barriers >1 m in height in Czech rivers, and 1,688 continuity interruptions in the River Danube. In the Netherlands, approximately 18,000 potential barriers are located in WFD (European Water Framework Directive, 2000/60/EC) relevant water bodies (Brevé, Buijse, Kroes, Wanningen, & Vriese, 2014).

However, despite the already overwhelming global river fragmentation and its well-known impact on aquatic biodiversity, there is an increasing pressure on the last free flowing river sections for hydroelectricity production, especially in Southeast Asia, South America, and Africa (Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015). The Paris Agreement to combat climate change and to accelerate actions for a sustainable low carbon future of December 12, 2015, has now been ratified by 175 parties. It requires the parties to lower their greenhouse gas emissions and to meet their growing energy demand from renewable sources. This will drive further development of hydropower as one source of renewable energy, especially because its technically feasible potential has been estimated exploited by 22% only globally (ICOLD, 2011). Correspondingly, in the United States, rising energy consumption in coming decades in combination with improving renewable energy production has been projected to increase the annual water withdrawn or manipulated especially for hydropower by 18–24% (McDonald et al., 2012). In Europe, the European Commission proposed a Renewable Energy Directive (2009/28/EC) aiming to increase the level of renewable energy—among others from hydropower—in the EU energy mix to 20% by 2020. Accordingly, National legislations like the German Renewable Energy Act have been amended setting incentives to increase the amount of renewable energies, for example, higher feed-in tariffs for energy generated from small hydropower and other renewable sources. By stimulating renewable energy production from hydropower and the full exploration of the hydropower potential of rivers (Anderer, 2011; Anderer, Dumont, Heimerl, Ruprecht, & Wolf-Schumann, 2010), the implementation of Renewable Energy Directive worsens the ecological status of rivers. Increasing hydroelectricity production will compromise the biodiversity conservation goals.

At the local scale, similar trade-off manifests due to water demands for upstream fish migration and downstream fish protection facilities, which are lost for electricity production. There is a strong interest from the hydroelectricity producers to keep such losses at minimum, which usually results in the provision of no or insufficient ecological connectivity. This study focuses on fish migration as the most often addressed aspect of longitudinal connectivity.

Numerous documents and handbooks provide guidance on how to design and construct a fish pass, where to position it, and how to guide and attract upstream migrating fish (e.g., Clay, 1995; DWA, 2014; Jungwirth, Schmutz, & Weiss, 1998; MUNLV, 2005). There are also several studies and reviews on the assessment of fish pass efficiency, which is generally a function of attraction and passability (e.g., Bourne, Kehler, Wiersma, & Cote, 2011; Bunt, Castro-Santos, & Haro, 2012, 2016). Therefore, this study addresses neither efficiency assessment of fish passes nor construction details. The focus here is on the design discharge assigned for fish passes independent of their type. Many typical failures reported for fish passes like insufficient attraction flow, too narrow slots, too steep slopes causing too high flow velocities, and height differences between compartments of the fish pass are all directly or indirectly related to insufficient water supply assigned already in the planning phase. There are no rules established on the minimum amount of water to supply unhindered fish migration. Therefore, this study aimed to derive a first estimate for fish pass design discharge, that is, for the share of average river flow needed for unrestricted upstream fish migration from existing evaluation studies.

2 | DATA COLLECTION

Scientific and grey literature was searched for fish pass evaluation studies using common search engines with "fish pass*", "longitudinal connect*" and "fish", and "migration facility" and "fish", respectively with the German terms "Fischpas*", "Durchgäng*", and "Fisch" as keywords. The reference lists of obtained work were screened for original data and further sources. In addition, a request for unpublished reports and documents has been sent to the German Federal authorities responsible for water, environmental planning, and nature conservation, because they often request for success monitoring from fish pass constructors.

All texts were screened for information on fish pass details, hydraulic design, dimensions, especially flow over the fish pass, success monitoring, passage rates, constraints, and final assessment. A principal prerequisite for inclusion in the study was that the fish pass was designed to serve all species and age groups corresponding to recent guidance for longitudinal connectivity in Europe and elsewhere, which require for unrestricted passage of all species and age groups including weak swimmers (DWA, 2014; MUNLV, 2005). This approach automatically excluded eel ladders and Denil fish passes, which by design serve only a single species and large salmonids, respectively. A study was retained for further analyses if the following minimum information was provided: (a) a final assessment of the upstream fish passage based on observational data from no to fully functioning, (b) the type of fish pass, (c) the maximum discharge through the fish pass (here considered as design discharge), and (d) the mean discharge of the river at the site or the fish region. Additional information on fish pass design, dimensions, age, slope, depth, flow velocities, and energy dissipation have been compiled when provided together with the information on river and site name, country, and continent.

Our search yielded a total of 79 studies reporting on 193 upstream fish migration facilities. The database is provided as Supporting Information.

The rather low number of evaluable studies is in accordance with former findings (e.g., Bunt et al., 2012; Noonan, Grant, & Jackson, 2012; Pompeu, Agostinho, & Pelicice, 2012; Roscoe & Hinch, 2010). The vast majority of fish passes have never been evaluated and will never be evaluated, although thousands of fish passes exist worldwide and improving longitudinal connectivity is high on the river rehabilitation agenda, for example, in Germany (Kail & Wolter, 2011) and the Netherlands (Brevé et al., 2014),

3 | DATA ANALYSES

The ratio between the reported maximum discharge through the fish pass (Q_{FP}) and the mean river discharge (MQ) was computed. The

Q_{FP}/MQ ratio was arcsin-transformed (arcsin (sqrt(x))) and MQ log (lg(x)) transformed. For fish passes allowing full passage, a regression model was calculated of Q_{FP} in relation to MQ as proxy for river size using the transformed values. A power function fitted best.

Fully functioning and not functioning were used as provided by the various studies, whereas all reported limitations (size or species selectivity and insufficient numbers of upstream migrants) were considered restricted passability.

Fish pass types were classified according to their principal construction into pool type, vertical slot, bottom ramp passes, and bypass channels, to mention the most common types.

Significant differences in mean Q_{FP}/MQ ratios between types of fish passes and fish passage functionality classes were tested using one-way ANOVA with post hoc Dunnet-T3 test due to variance inhomogeneity. The comparison between fish pass types was limited to bottom ramps, bypasses, pool, and vertical slot fish passes, because of low numbers of replicates for other types (9 V stepped passes, six meander fish passes, four bristles passes, three fish lifts, and three fish locks). To assess the impact of Q_{FP}/MQ ratio on upstream fish passage function, a median test (Kruskal–Wallis H) was performed with post hoc Mann–Whitney U pairwise comparisons.

All calculations were performed using IBM SPSS Statistics Version 22.

4 | RESULTS

The 193 fish pass assessments were mainly obtained from Europe (176), in particular from Germany (119), Austria (26), and Switzerland (15). Ten studies were found from Australia, five from South America, and one each from North America and Asia. The river systems ranged from small creeks with mean discharge of 0.07 m^3/s to large rivers with 12,000 m^3/s. The fish passes had dotations between 0.04 and 12 m^3/s. The resulting Q_{FP}/MQ ratios ranged between 0.002% and 100% (mean ± standard deviation = 25.8 ± 39.4%, median = 2.61%).

The majority of fish passes evaluated were pool type fish passes (51), followed by bottom ramps (45), bypass channels (38), and vertical slot passes (34). Pool type fish passes performed significantly less than other fish passes (one-way ANOVA, $p < 0.01$).

Most of the evaluated fish passes were reportedly fully functioning, about one third restrictedly, and 33 not at all (Figure 1). Bottom ramps, bypass channels, and vertical slot passes had the highest share fully functioning migration facilities (Table 1). The fully functioning fish passes received discharges between 0.068 and 6.5 m^3/s (min-max) and were situated in a broad variety of rivers ranging from 0.106 to 1,910 m^3/s MQ (Supplementary Information). The group of fish passes reportedly not functioning received significantly lower Q_{FP} (one-way ANOVA, $p < 0.01$). The median Q_{FP} was 5% of the river's MQ for fully functioning fish passes, 1.1% for restrictedly functioning, and only 0.22% for not functioning fish passes. These differences were highly significant between all three groups (Kruskal–Wallis H, $p < 0.001$, Mann–Whitney U, $p < 0.05$).

Bottom ramps received significantly higher Q_{FP}/MQ ratios than bypasses and vertical slot passes (one-way ANOVA, $p < 0.01$, Figure 2); however, their reported performance in fish passage did not significantly differ (one-way ANOVA, $p > 0.2$). Pool type fish passes were maintained with significantly lower Q_{FP}/MQ ratios

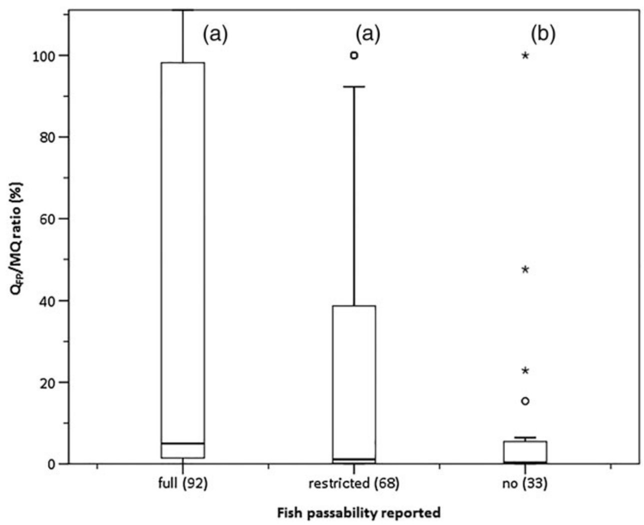

FIGURE 1 Reported fish pass functionality for upstream migration in relation to the Q_{FP}/MQ ratio (number of samples in parentheses). Same superscripts refer to homogenous subgroups (Kruskal–Wallis H Test, *df* = 2, χ^2 = 11.097, p < 0.001, post hoc Mann–Whitney U)

TABLE 1 Average Q_{FP}/MQ ratios of reportedly fully to not functioning fish passes per fish pass type (in parentheses number of observations)

Fish pass type	Fish passability reported		
	Full	Restricted	No
Bottom ramp	0.733 (28)	0.978 (14)	0.418 (3)
Bristles pass	0.539 (2)	0.048 (2)	
Bypass	0.139 (20)	0.200 (11)	0.108 (7)
Fish lift	0.045 (1)	0.000 (1)	0.001 (1)
Fish lock	0.031 (1)	0.004 (2)	
Meander pass	0.031 (3)	0.108 (3)	
Pool pass	0.071 (7)	0.008 (23)	0.017 (21)
Vertical slot	0.170 (21)	0.072 (12)	0.021 (1)
V-stepped	0.149 (9)		

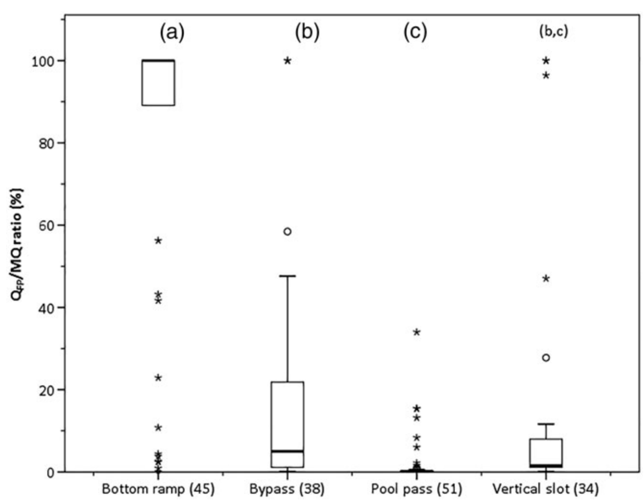

FIGURE 2 Relative design discharges (Q_{FP}/MQ ratios) reported for different fish pass types (number of samples). Same superscripts refer to homogenous subgroups (Kruskal–Wallis H Test, *df* = 3, χ^2 = 32.33, p < 0.001, post hoc Mann–Whitney U)

(Kruskal–Wallis H, $p < 0.001$) compared with other fish pass types (Figure 2), which coincides with their significantly lower performance.

The median Q_{FP}/MQ ratio of the fully functioning fish passes was 5% of the average river discharge (range 0.04–100%, mean ± standard deviation = 32.6 ± 42.4%). Over all types of fish passes, their functionality in terms of fish passage was positively correlated to the Q_{FP}/MQ ratio (Figure 1); however, this relation is highly significantly, inversely correlated to river size (Figure 3). Meaning in large rivers, a rather small share of the mean discharge is sufficient to provide successful upstream fish passage, whereas this proportion exponentially increases in small rivers. In contrast, in small rivers, the absolute minimum size of a migration facility in terms of depth, slot width, and flow necessary to attract a fish and let him pass through cannot be further downscaled and thus requires higher shares of the available discharge for maintenance.

5 | DISCUSSION

Despite tremendous efforts and a huge amount of projects to improve longitudinal connectivity of rivers for fish, there were surprisingly few studies evaluating the efficiency of upstream fish passage for a variety of species and size classes in relation to discharge. Similar deficits were reported by Roscoe and Hinch (2010); Bunt et al. (2012, 2016), Noonan et al. (2012), and Pompeu et al. (2012). This study compiled and analysed a representative data set of 193 fish pass assessments covering a broad range of river types from small creeks to very large rivers (Supplemental Information). There is a spatial bias by studies from Europe, which is less related to accessibility of studies rather than the longer tradition of providing fish passage for all species and size classes. For example, in North America, fish passes are primarily designed for salmons and to a lesser degree for shads and sturgeons, whereas coarse fish migration needs are not addressed (Katopodis & Williams, 2012; Roscoe & Hinch, 2010). This analyses on purpose focused on the fish assemblage as a whole.

There are no general standards or agreements in fish pass assessment on when a fish pass is fully functioning (Bourne et al., 2011; Roscoe & Hinch, 2010) illustrated by recent debates (Bunt et al., 2012, 2016; Kemp, 2016; Williams & Katopodis, 2016). The various studies applied different methods to assess fish pass functionality, but all had in common that the evaluation based on direct observations or catches. They probably differed in scoring the numbers of successfully upstream migrating specimens observed, but we did not analyse how substantiated the reported assessment results were. However, corresponding to a recent evaluation of differences in expert judgement of habitat suitability for fish (Radinger, Kail, & Wolter, 2017), we might assume that the agreement in assessing a fish pass as fully or not passable between the studies is very high, whereas the assessment of selectivity and sufficient migration rates might vary. The latter variation will not influence our results much, because we did not further differentiated between restrictedly passable fish passes in our analyses.

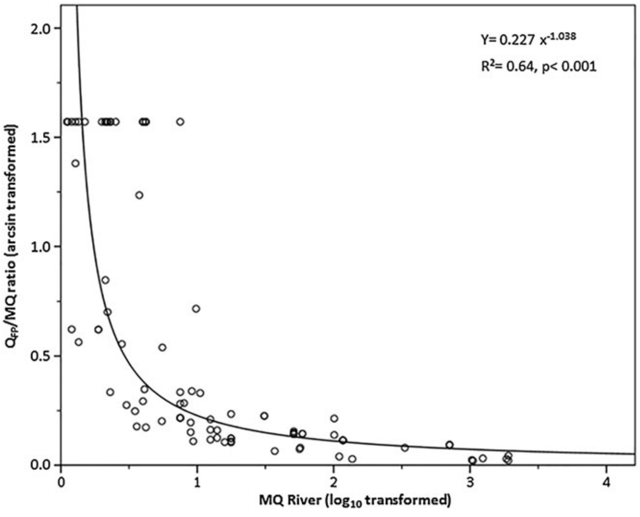

FIGURE 3 Regression (power model) of fish pass design discharges (%MQ, arcsin-transformed) in relation to mean river discharge (m^3/s, log-transformed) for fish passes reported fully functioning (N = 92)

Corresponding to the different scoring systems, also the variety of potential failures, which were reported for about one third of the studies, was not further analysed. Individual construction failures like larger height differences between pools, too high flow velocities in slots, too shallow flows over bars, too small pools or insufficient energy dissipation or even wrong location of the fish pass entrance, and lack of attraction flow can impede successful fish passage (Clay, 1995; DWA, 2014; MUNLV, 2005; Williams, Armstrong, Katopodis, Larinier, & Travade, 2012). All these aspects alone or in combination apply also for the fish pass evaluations analysed, but still Q_{FP}/MQ ratio emerged as significant predictor of fish pass efficiency.

Therefore, despite all limitations, the result obtained seems rather robust. The study yielded clear evidence for the positive relation between functioning and the maximum discharge through the fish pass. The overall Q_{FP}/MQ ratio of a functioning fish pass compared with the river size was unexpectedly low, but plausible. For example, the minimum dimensions of a fish pass needed for brown trout are determined by the size of a mature specimen (DWA, 2014; MUNLV, 2005), so that with decreasing river size and discharge, the Q_{FP}/MQ ratio increases. In contrast, in large rivers, even a rather low Q_{FP}/MQ ratio may result in significant absolute discharge causing expensive constructions. Higher absolute Q_{FP} is also needed to mimic the typical flow conditions of a river, especially of large lowland rivers. Fish species used to migrate and spawn in large, low-energy river corridors, as, for example, shads and smelt, will behaviourally resist and avoid entering high-energy fish passes. This became, for example, obvious with the opening of the new, much larger fish pass at weir Geesthacht, River Elbe, Germany, which now facilitates upstream migration of smelt, little flounders, stick-lebacks, and other potamal fish species (Adam et al., 2012).

The findings presented here provide some guidance for determining Q_{FP}/MQ ratio of fish passes at about 5% of the mean flow of the river, with higher proportions in smaller rivers and vice versa. Further research is needed to adjust the balance between the maximum Q_{FP}/MQ ratio feasible and full fish passage for different river types.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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