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Comparison of coarse-resolution rapid methods for assessing fish passage at riverine barriers: ICE and SNIFFER protocols

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Abstract

Man-made barriers have led to river fragmentation, restricting fish migrations to critical habitat. Fragmentation is relevant to the Water Framework and Habitats (Annex II fish) Directives of the European Union. SNIFFER (Water Framework Directive 111) is a United Kingdom-developed fish passability assessment method with passability scores based on published data describing the physiological abilities of different fish species/life stages. SNIFFER is an objective protocol, but final scores require assessor opinion on specific nonquantified elements. The French ICE fish passability assessment protocol covers a larger number of fish species/life stages and removes the requirement for velocity readings (except in a few situations) and expert opinion with assessors following a decision tree process. In most situations, fewer direct measurements are required for the ICE protocol, and the evaluation process is quicker and simpler. Both protocols utilize a similar passability scoring system (0 = total barrier, 0.3 = high impact, 0.6 = low impact, 1 = no risk). Comparison of outcomes for species categories for both protocols was made in paired comparisons for 112 transversal sections (fish passage routes) recorded at 52 barriers (in-river structures) of varying complexity in Irish rivers. Overall scores were found to be in high agreement for species groups at impassable (Score 0) and no risk (Score 1) barriers. Protocol agreement dropped significantly for high-impact (Score 0.3) and low-impact (Score 0.6) barriers. Results are discussed in the context of barrier passability at the 52 structures examined, primarily in the context of Atlantic salmon (*Salmo salar* L.) and of sea lamprey (*Petromyzon marinus* L.). In total, 22 of the structures had one or more fishways or fish passage solutions built into them as part of the original design. Both protocols identified substantial problems for sea lamprey and adult salmon at the majority of the fish passage solutions surveyed. The merits and shortcomings of both protocols, for managers assessing fish passability at complex riverine structures, are discussed.

KEYWORDS

Atlantic salmon, hydromorphology, river connectivity, sea lamprey

1 | INTRODUCTION

Most river networks in developed countries are fragmented by man-made barriers (Nilsson, Reidy, Dynesius, & Revenga, 2005). Fragmentation of habitats has been identified as one of the five main factors of biodiversity loss along with pollution, overexploitation of natural resources, invasive species, and climate change (Fahrig, 2003). The main cause of connectivity loss for migratory fish species (diadromous and potamodromous) in riverine systems are man-made structures, such as dams, weirs, and culverts for road crossings, which act as physical barriers to both fish passage and sediment transport (Doehring, Young, & McIntosh, 2011; Hall, Jordaan, & Frisk, 2011;

Gargan et al., 2011; Drouineau et al., 2018). Although many of these barriers can be eliminated (De Leaniz, 2008) or mitigated by modification (Dodd, Cowx, & Bolland, 2017), this process can often be expensive, and budgetary constraints tend to restrict the amount of restoration that can occur (Poplar-Jeffers et al., 2009). Another issue facing fishery managers is the problem of identifying and prioritizing barrier mitigation work within a catchment (King & O'Hanley, 2016; O'Hanley, 2011; O'Hanley, Wright, Diebel, Fedora, & Soucy, 2013) especially when barrier numbers within catchments can exceed many hundreds. Thus, a robust understanding of the scale of the ecological impacts of potential barriers is essential to prioritize restoration efforts and to focus funding and mitigation works to key obstructions (King, O'Hanley, Newbold, Kemp, & Diebel, 2017).

Under an ideal scenario, where time and budget are not limiting factors, the impact of one or several barriers on the movement of fish can be evaluated empirically via direct methods such as hydroacoustic sonar technology (Burwen, Fleischman, & Miller, 2010) or with fine-resolution telemetry using passive integrated transponder (Aarestrup, Lucas, & Hansen, 2003; Lucas, Mercer, Armstrong, McGinty, & Rycroft, 1999), radio (Newton, Dodd, Barry, Boylan, & Adams, 2018; Rooney, Wightman, Ó'Conchúir, & King, 2015; Winter, Jansen, & Bruijs, 2006), or acoustic tags (Steig, Skalski, & Ransom, 2005; Tummers et al., 2016). The outcomes from these techniques tend to be site specific, and it is generally not financially or logistically feasible to employ these types of techniques when scaling up to barrier passability at the whole-catchment scale. As a result, low-cost coarse-resolution rapid methods provide managers with a probability estimate of barrier passability for a range of fish species, and a number of protocols are in existence in Europe (U.K. SNIFFER protocol, SNIFFER, 2010; French ICE protocol, Baudoin et al., 2015; Spanish ICF protocol, Solà et al., 2011) and in America (the FishXing model; Furniss et al., 2008—and protocols developed by Coffman, 2005). Coarse-resolution rapid methods encompass physical measurements (e.g., drop height and depth of water over structure) paired with peer-review published data on the physiological capacities of the given fish species (e.g., max. swimming speed and jumping heights), allowing for passability scores to be estimated (Kemp & O'hanley, 2010).

The impacts of barriers can be variable, from short delays to complete obstruction, depending on barrier type, hydraulic conditions, species swimming capabilities, and timing of migration. The most pressing issues faced by managers are complete barriers, which can reduce or fragment species distributions completely, resulting in diminished populations that are increasingly genetically isolated and at greater risk of extinction (Sheer & Steel, 2006; Wofford, Gresswell, & Banks, 2005).

The impetus to restore connectivity within European rivers is driven, in part, by various European Union (EU) regulations—the Habitats Directive, Water Framework Directive, and the EU Eel Regulations. The Habitats Directive requires designation of Special Areas of Conservation (SACs) in Member States for conservation of specific species and habitats. Within SACs, Conservation Objectives, specific to the species, are developed. Impaired passage is a significant issue for migratory fish species listed in the Habitats Directive, for example, Atlantic salmon, twaite and allis shad, and the sea and river lamprey

(Castro-Santos, Shi, & Haro, 2016; Drouineau et al., 2018; Lucas, Bubb, Jang, Ha, & Masters, 2009) and also nonmigratory fish species (Benitez, Matondo, Dierckx, & Ovidio, 2015). The Water Framework Directive identifies the importance of longitudinal connectivity for ecological quality in rivers, both for upstream and downstream movement of aquatic organisms and for sediment transport and renaturalization of constrained rivers. With this considerable focus on river connectivity, it is clear that there is a need for the development of accurate coarse-resolution rapid assessment methods.

Inland Fisheries Ireland (IFI) commenced using the SNIFFER (2010) protocol in 2012 to determine likelihood of fish passage over identified major barriers in SAC-designated rivers (Gallagher, O'Gorman, Rooney, Coghlan, & King, 2017). Publication of the ICE barrier assessment protocol (Baudoin et al., 2015) provided the authors with an opportunity to examine the SNIFFER outcomes against a second coarse-resolution protocol. It was considered that such coarse-resolution protocols provide those tasked with barrier mitigation with options that are consistent and repeatable, in terms of measurement and application of measurements, in order to access river connectivity.

This study examined 52 barriers from a range of rivers in Ireland, generating passability scores for both the SNIFFER and ICE protocols and allowing a direct comparison of each protocol and its outcomes, for the same structure, for three species: Atlantic salmon (*Salmo salar* L.), sea lamprey (*Petromyzon marinus* L.), and brown trout (*Salmo trutta* L.). Both the salmon and sea lamprey are Habitats Directive species with designated SACs in Irish rivers for whom barrier issues arise in their migration (Gargan et al., 2011). The brown trout has diadromous and potadromous populations in Irish rivers. This paper examined (a) convergence in score outcomes, (b) key factors underlying score differences between the ICE and SNIFFER protocols, (c) performance of fishways or fish passage solution as assessed by both protocols, and (d) overall outcomes in the context of Water Framework Directive aspirations and conservation management of target species.

2 | METHODS

2.1 | Data collection

A total of 52 structures were assessed using the SNIFFER protocol for fish passability in the period 2014–2017, in the context of an overall policy aim of IFI to develop a national geographic information system-based layer of river barriers (Figure 1). Where barrier mitigation is being considered, it is IFI policy to undertake SNIFFER surveys on the structure before any works and to submit the passability report as part of the Local Authority planning permission process. Postmitigation resurveys are also required by IFI in order to objectively assess the success of the project.

The availability of the ICE protocol since 2015 has allowed IFI to examine structures using both protocols and to retrofit ICE scores to previously surveyed structures using the measurements from SNIFFER surveys to compute ICE scores. ICE scores were generated from the data recorded while undertaking the SNIFFER assessment. Therefore, this is a paired comparison of protocols under the exact same flow conditions. Data collection has focussed on structures in
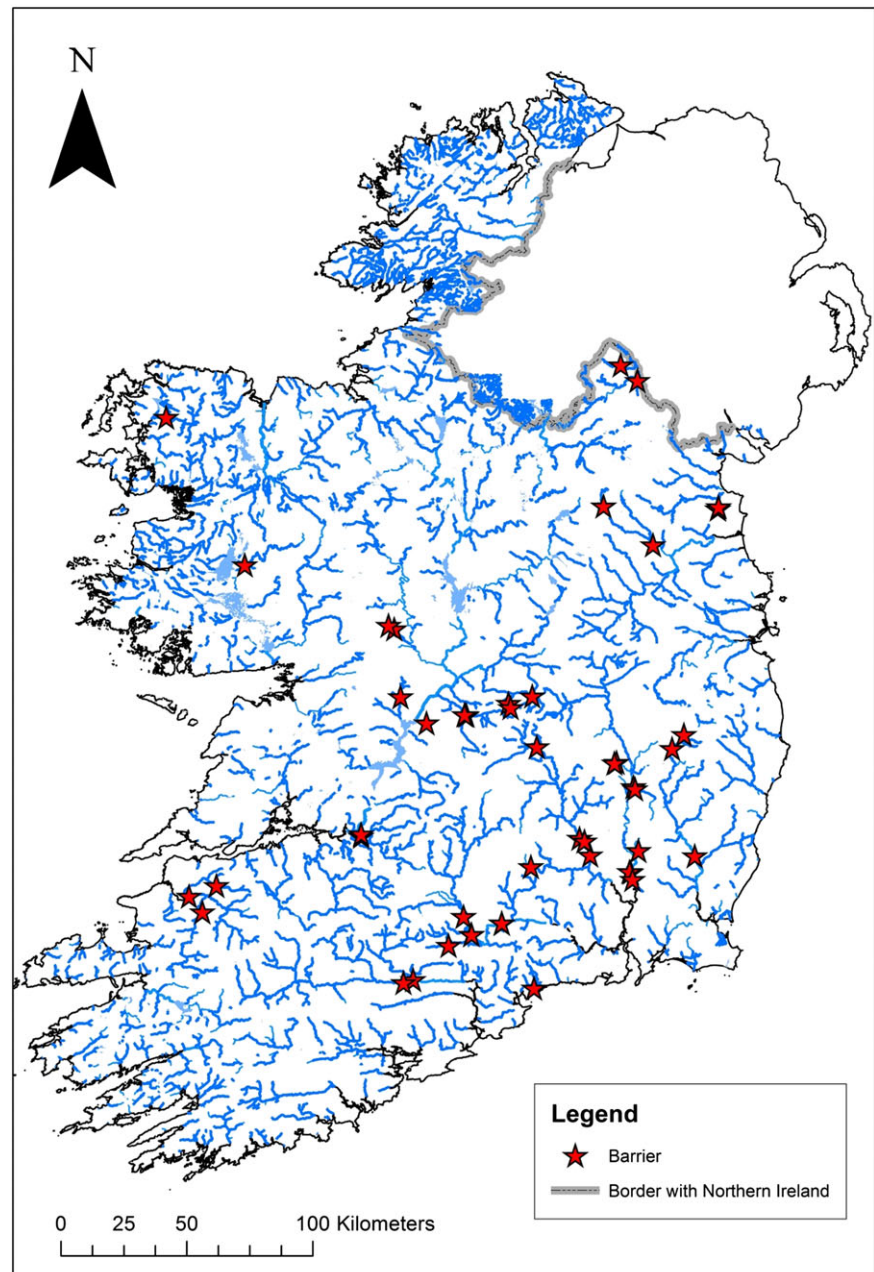
FIGURE 1   Geographic locations of barriers surveyed in this study, 2014–2017 (some overlap due to barrier proximity in some locations) [Colour figure can be viewed at wileyonlinelibrary.com]

main stem rivers designated as SACs for Atlantic salmon and sea lamprey as well as on structures identified by IFI, working in conjunction with other state or local authorities.

The criteria or dimensions to be compiled at barriers, in respect of the SNIFFER and ICE protocols, are summarized in Tables 1 and 2. A series of linear measurements are common to both. SNIFFER requires

TABLE 1   Key characteristics of SNIFFER and ICE protocols

Characteristic	SNIFFER	ICE
Number of species/life stages	9	47
Measurements needed	10	4
Scoring method	0, 0.3, 0.6, 1	0, 0.3, 0.6, 1
Time per barrier[a]	90 min	20 min

[a]Time based on average barrier after gear has been set up (30-m sloping weir, 2 × transversal section) with appropriate gauging staff and velocity meter.

the collection of a substantial body of data on depth–velocity paired data at a series of locations. In addition, SNIFFER requires a judgement on degree of turbulence present and on standing waves. A subjective assessment on the impact these factors have on passability may influence the final SNIFFER score. In effect, the surveyor is scoring each point of the transect on its suitability in terms of depth and water velocity for the particular species/guild to be able to either hold station or make swimming progress upstream. The passability scores are then calculated on the basis of the known swimming abilities of the species in question.

Both methods require an initial examination of the structure to determine the number of "transversal sections" (TSs) or potential fish passage routes, in the prevailing conditions, across the structure, in common with previous studies (Ovidio, Capra, & Philippart, 2007). The term, transversal section, is used in both protocols examined here. A TS is a portion of a riverine structure used in the assessment of

TABLE 2 Criteria measured or recorded for SNIFFER and ICE protocols

Measurement	SNIFFER	ICE
Drop height	✓	✓
Slope	✓	✓
Depth through structure	✓	✓
Plunge pool depth	✓	✓
Water velocity	✓	✗[a]
Turbulence	✓	✗
Standing wave	✓	✗
Debris blocking structure	✓	✗
Fish passes	✓	✗[b]
Downstream migration	✓	✗

[a]ICE protocol in general does not need flow velocities; however, there is an option to produce passability scores based on flow velocity data for culverts. [b]ICE does not provide a passability score for fish passes; it gives a positive or negative rating based on sizing criteria.

passability at riverine obstacles. When viewed from downstream, a barrier is visually fragmented into a series of potential fish passage routes or TSs for crossing the structure, each being distinguished by having discrete water velocity and depth conditions across its width. Fishways or "fish passage solutions" may be present in a barrier and will constitute a discrete potential passage route or TS. Many barriers will not have such a fishway. Each TS in a riverine structure is assessed separately to examine passability at riverine obstacles. A TS can consist of several features longitudinally (e.g., a vertical jump and then a swim feature for fish) but generally provides a possible direct route for fish passage across the structure. In the present study, all 52 structures were surveyed by one or more of the authors, 28 surveyed by two of the team, and 10 being surveyed by three of the team. Surveyors had received training from University of Stirling, Scotland, where the final SNIFFER protocol was developed. In addition to these data, 22 of the structures had one or more fish passage solutions (fishway) of different types, and a separate examination of SNIFFER versus ICE passability outcomes was undertaken using this set of TSs for upstream migration only. The ICE protocol does not accommodate downstream movement, so this was not considered for this assessment.

All surveys reported here were conducted in low flow conditions, with water and weather conditions that provided optimum safety to operators. The term fish passage solution is used as a generic expression to cover structures or fishways specifically designed or installed to facilitate fish passage at riverine barriers (terminology in line with the current development of a CEN standard for assessing fish passage via telemetry).

2.2 | SNIFFER protocol

The Water Framework Directive 111 or SNIFFER (Scotland and Northern Ireland Forum for Environmental Research) protocol was developed for U.K. use (Kemp, Russon, Waterson, O'Hanley, & Pess, 2008; SNIFFER, 2010). Commonly referred to as the "SNIFFER" protocol, the barrier assessment methodology examines the structure

and identifies the number of TSs that fish species could use to pass over the structure. At each TS, velocity measurements at 0.6D (D = water depth) and bed level are required at five points across each of three transects perpendicular to the flow: (a) at the inlet or entry point, (b) midpoint, and (c) at the foot or outlet of the TS (see Supporting Information). The hydraulic head is recorded along with "natural" river width, length of the structure, plunge pool depth, and so on. In addition to measurements, the SNIFFER requires the recording of certain "subjective" elements including the presence of standing waves and the degree of turbulence associated with each TS.

The passability for a given species is ranked as either 0 (complete barrier), 0.3 (partial barrier high impact), 0.6 (partial barrier low impact), or 1 (no barrier). The overall passability score for each TS is the lowest score or the most detrimental obstacle to passage at the TS (e.g., barrier height and velocity). The overall passability score for the entire structure is equal to the TS with the highest score, that is, most passable TS. To calculate scores, a series of criteria are applied at each TS, based on the species and/or life stage being considered. These criteria are based on published data describing the swimming and leaping abilities of a discrete set of fish species/life stages recorded in Britain, including six species and various life stages. In effect, the surveyor is scoring each point of the transect on its suitability in terms of depth and water velocity for the particular species/guild to be able to either hold station or make swimming progress upstream. The passability scores are then calculated for the whole TS based on the scores generated at each point measurement.

The SNIFFER protocol considers passability in the context of both upstream (adult salmon, adult lamprey, juvenile eel) and downstream migrations (salmon smolts; adult silver eel). The protocol also facilitates passability performance of fish passage solutions.

2.3 | ICE protocol

In France, ONEMA (Office National de l'Eau et des Milieux Aquatiques) developed the ICE protocol in collaboration with the University of Liège (Belgium) for assessing the passage of obstacles by fish (Baudoin et al., 2015). As with the SNIFFER protocol, ICE is based on an examination of the topographical and hydraulic characteristics of barriers combined with the published physiological capacities (swimming, jumping, or crawling) of the fish species. The protocol also requires the identification of the potential passageway(s) in each barrier through which fish can pass, in the same manner as the TSs utilized in the SNIFFER protocol. Long profiles of each potential passageway are recorded by obtaining specified measurements for each specific point in a structure corresponding to a significant change in the profile (e.g., a drop or step). Velocity readings are rarely required as hydrodynamic equations and modelling have been used to set specific physical thresholds (e.g., head height and slope) above which velocity is estimated to restrict passage (Baudoin et al., 2015).

A comprehensive range of 47 separate fish species/life stages, common to mainland northern Europe, are included in ICE. Species are clustered into 11 groups with subgroups according to physical swimming capabilities. Within the ICE protocol, the passability of barriers is defined on a similar scale to the SNIFFER protocol with four possible scores: 0 (total barrier), 0.33 (high-impact partial barrier),

0.66 (medium impact partial barrier), and 1 (low-impact passable barrier) or NC (barrier having indeterminate impact). Generally, passability scores are assigned on the basis of the threshold physical values (e.g., depth, velocity, and slope) present at the barrier compared with the minimum, average, and maximum swimming abilities assigned to each fish group. Thresholds are also outlined whereby the barrier is immediately classed as impassable (extreme values) and no further measurements are required to be recorded.

The ICE protocol is completely objective. No expert opinion is needed, passability scores being derived from the measurements taken on the day of assessment with no observational data (e.g., on turbulence or standing waves) required.

The ICE protocol does not assess the passability of barriers in the downstream direction. In addition, the ICE protocol does not specifically address fish passage solutions or fishway structure. However, it does facilitate "preassessment" examination of fish passage solutions, allowing for rapid identification of those structures "not well suited to the species in question" or for which "more in-depth assessment may be necessary."

2.4 | Data analysis

A generalized linear mixed-effects model was performed with score agreement as response variable (disagree = 0, agree = 1) and protocol scoring as covariate (a four-level factor: 0, 0.3, 0.6, and 1) and TS (fish passage route) as a random effect. The generalized linear mixed-effects model had binomial error distribution and quantified the probability of protocol score agreements (across species) between SNIFFER- and ICE-assessed TSs. Statistical analyses were undertaken using R studio Version 1.1.383 using the lme4 package (Bates, Maechler, & Bolker, 2012; R Core Team; www.r-project.org). The model was assessed for dispersion, and model diagnostics were assessed graphically by examining the residuals for heterogeneity. p values were generated for the fixed effect of "protocol score" using the log likelihood method, by comparing models with and without the term in question.

To further investigate the SNIFFER and ICE results at the species level, Atlantic salmon adults, adult lamprey, salmonids (25–55 cm), and juvenile salmonids (<25-cm salmon and brown trout) scores were examined over the suite of structures. These taxa were chosen in the context of Irish fisheries management and conservation management concerns. The total number of score agreements (%), for each fish group/scoring pairing, between ICE and SNIFFER was calculated. Further analysis examined the reasons for observed differences in paired outcomes for adult lamprey and adult salmon through a paired score output analysis. These data were interrogated for reasons underlying less strict and stricter outcomes based on protocol scorings. The influence of recorder opinion on passability scores in relation to subjective elements of the SNIFFER protocol (e.g., influence of turbulence) was also examined for adult lamprey and Atlantic salmon.

Those TSs representing fish passage solutions, that is, purpose-built fish passage structures or fishways such as Denil passes and pool passes, were excluded from the initial comparison of SNIFFER and ICE scores. ICE does not specifically score for fish passes. However, the ICE protocol does provide a "screening" of fish passage solutions,

and these ICE outcomes were separately compared with the SNIFFER passability scores for the fish pass TSs.

3 | RESULTS

Fifty-two instream barriers, located at a range of river sites across the Republic of Ireland, were assessed using both the SNIFFER and ICE assessment techniques. The majority of structures were categorized as weirs (n = 38) with smaller numbers of bridge aprons (n = 8) and other structure types (Figure 2a). All but two of the structures were on channels of Stream Order 3 or higher with 18 structures in channels of Stream Order 6 (Figure 2b). Structures ranged in drop height (hydraulic head) from 0.2 to 4 m with a mean of 1.3 m (Figure 2c). The barriers, not including fish passage solutions or fishways, were delineated into 112 TSs. There was an average of two TSs per barrier with 40% of the structures having one TS only (Figure 2d). In addition to these data, 22 of the structures had one or more fish passage solution (pool type passes, n = 10), chute (a sloping channel or slide for conveying water to a lower level, n = 10), vertical slot passes (n = 5), Denil passes (n = 3), and rock ramp (n = 2).

3.1 | Level of agreement between protocols

The model revealed a significant effect of score agreement between protocols (χ^2 = 188.7 df = 3, p < 0.05). There was a high probability of score agreement between protocols for TSs with scores of 0 (impassable barrier) and 1 (low-impact barrier) but lower probability of score agreement for TSs with scores of 0.3 (high-impact partial barrier) and 0.6 (medium impact partial barrier; Figure 3).

The initial analysis also examined the degree of concurrence between SNIFFER and ICE scores for the four species/life stages investigated for the 112 barrier TSs (Table 3). Score agreement was generally high for the impassable (score = 0) and "no barrier" (score = 1) TSs, with mean score agreement of 88.4% and 60.2% across species, respectively (Table 3). Score agreement was low for the high- (score = 0.3) and low- impact (score = 0.6) barriers, with mean score agreement of 22.4% and 13.0% across species, respectively (Table 3).

3.2 | Distribution of ICE scores among the four individual SNIFFER categories: A detailed examination for Atlantic salmon and adult lamprey

Further analysis looked at the number of structures scoring 0, 0.3, 0.6, and 1, as scored by SNIFFER. For each of the SNIFFER categories, the distribution of ICE scores across the four passability categories was examined. This was undertaken for Atlantic salmon and for adult lamprey (Figure 4). This procedure again indicated a very high degree of concurrence in outcome between the two protocols for structures classified as impassable (score = 0) via SNIFFER. Concurrence levels were substantially lower for structures yielding a SNIFFER score of "0.3" (high risk) or "0.6" (low risk) with protocol disagreements yielding both more strict and less strict outcomes when compared (Figure 4).
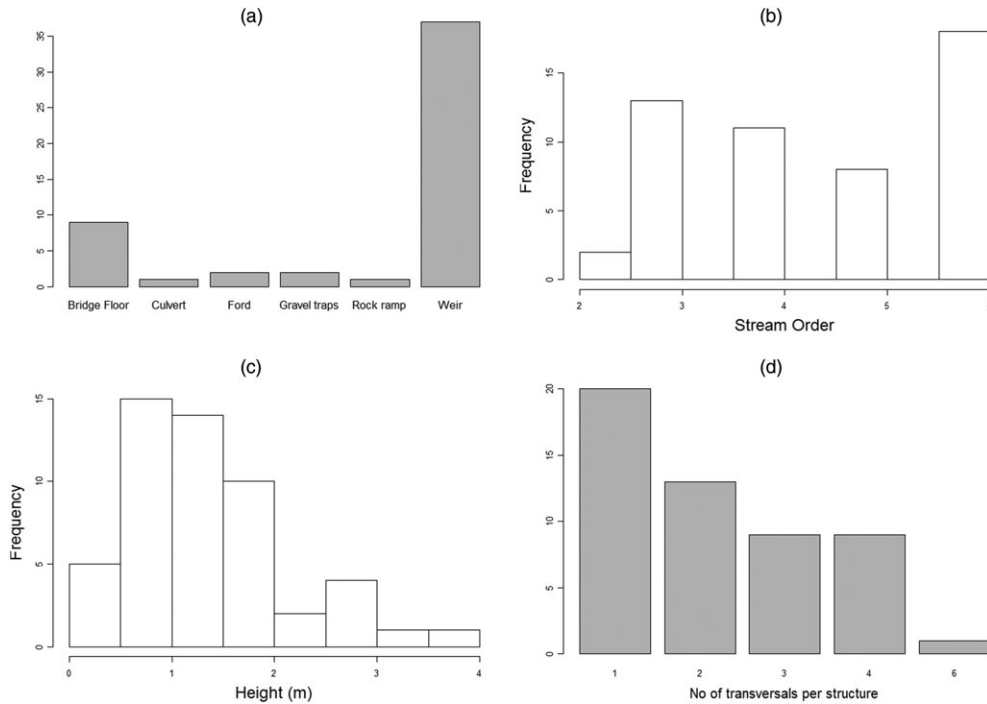
FIGURE 2 (a) Barrier types surveyed. (b) Frequency of barriers across stream orders. (c) Histogram of barrier height (metres). (d) Number of transversals across structures
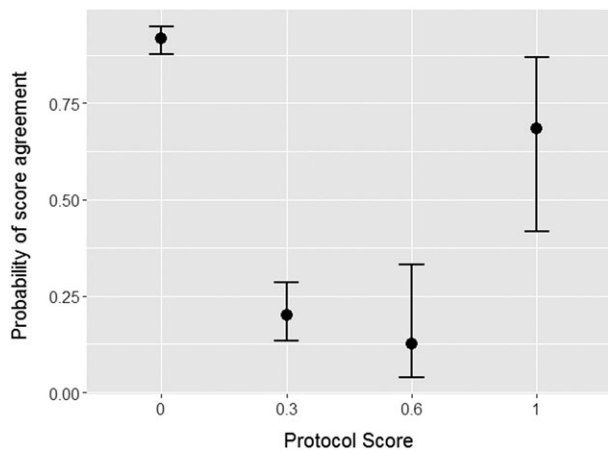

FIGURE 3 Probability of protocol score agreement between SNIFFER and ICE

3.3 | Paired score output analysis; reasons for observed differences

The reasons for stricter and less strict scorings for adult salmon and adult lamprey score outputs were individually assessed to aid in the interpretation of protocol score discrepancies. In each case, the SNIFFER score was used as a "reference" and the ICE decision matrix followed sequentially, identifying the first variable that created the discrepancy in score outcomes.

3.3.1 | Atlantic salmon adults

There were 46 paired comparisons where score discrepancies were observed for Atlantic salmon (Figure 5a). ICE was found to be stricter (ICE score lower than SNIFFER score) in 31 cases (67%) due to the following reasons: (a) not meeting the minimum required depth over the

TABLE 3 Differences in paired comparisons of protocol outputs for different species groups

Fish species (protocol score)	SNIFFER	Paired ICE score	% score agree
(Score = 0)			
Adult salmon (0)	61	60	98.4
Sea lamprey (0)	88	72	81.8
Juvenile salmonids (0)	77	65	84.41
Salmonids 25–55 cm (0)	50	47	93.75
(Score = 0.3)			
Adult salmon (0.3)	36	3	8.3
Sea lamprey (0.3)	19	3	15.8
Juvenile salmonids (0.3)	28	9	32.1
Salmonids 25–55 cm (0.3)	51	15	29.4
(Score = 0.6)			
Adult salmon (0.6)	10	0	0
Sea lamprey (0.6)	4	0	0
Juvenile salmonids (0.6)	5	1	20
Salmonids 25–55 cm (0.6)	4	2	50
(Score = 1)			
Adult salmon (1)	5	3	60
Sea lamprey (1)	0	0	0
Juvenile salmonids (1)	2	1	50
Salmonids 25–55 cm (1)	8	5	62.5

structure (n = 26), (b) swim length through structure (n = 3), (c) slope exceeds threshold (n = 1), and (d) not meeting the required plunge pool depth (n = 1). SNIFFER scores were found to be stricter than ICE scores for Atlantic salmon in 15 cases (33%) due to the following: (a)
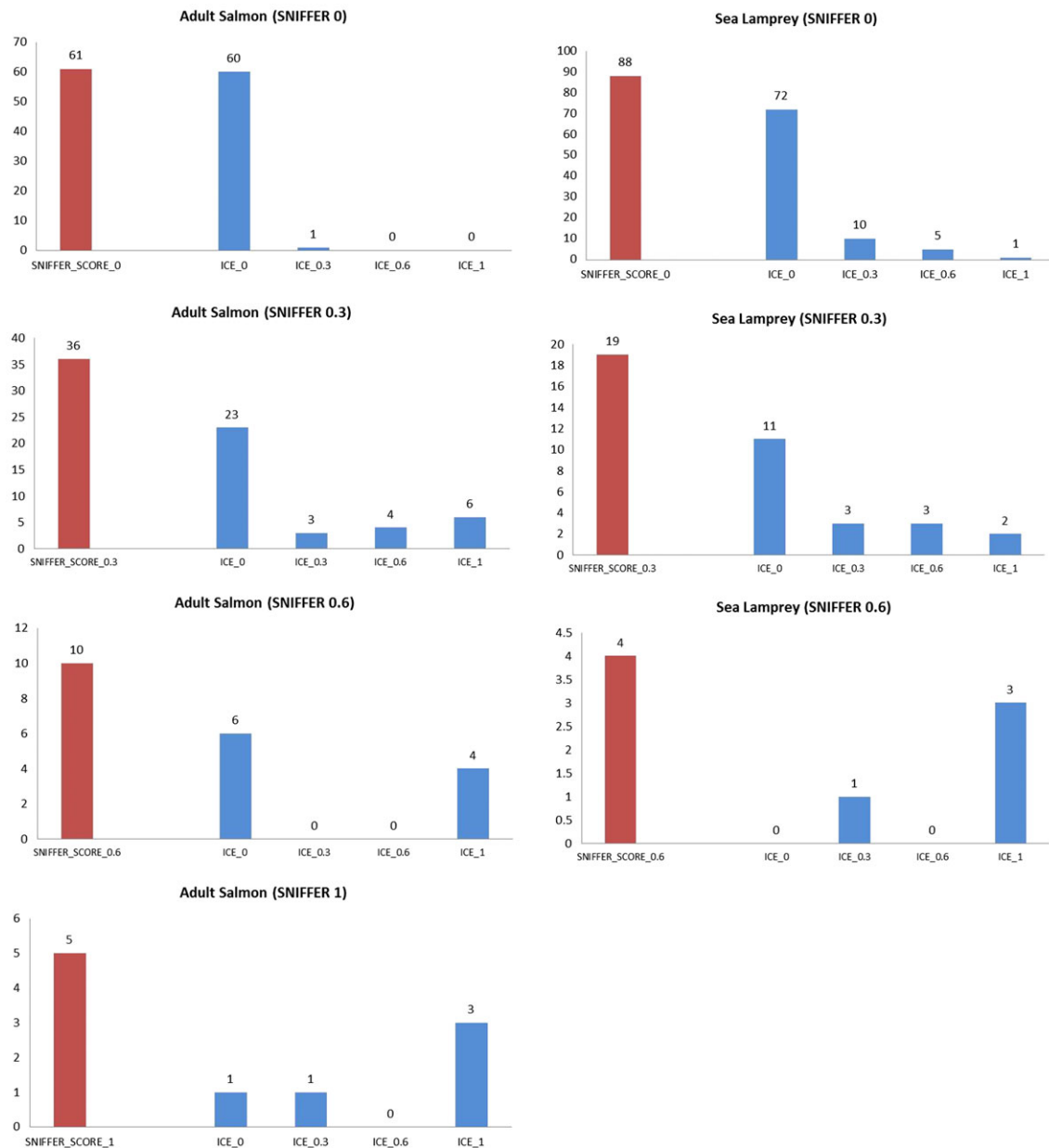
FIGURE 4   Distribution of ICE scores in relation to SNIFFER scores for adult salmon and sea lamprey within the different passability categories (0, 0.3, 0.6, and 1) [Colour figure can be viewed at wileyonlinelibrary.com]

water velocity (n = 6), (b) swim length through structure (n = 3), (c) slope (n = 1), (d) turbulence (n = 3), (e) effective resting location (n = 1), and (f) lip (n = 1).

3.3.2 | Adult lamprey

There were a total of 34 paired comparisons where score discrepancies were observed for adult lamprey (Figure 5b). ICE was stricter (ICE score output lower than SNIFFER score) for 11 paired comparisons (32%), due to the following reasons: (a) not meeting the minimum required depth mover the structure (n = 7), (b) swim length through structure (n = 3), and (c) hydraulic head (n = 1). SNIFFER scores were found to be stricter than ICE scores for adult lamprey in 23 paired comparisons (68%) due to the following reasons: (a) water velocity (n = 7), (b) turbulence (n = 6), (c) swim length through structure (n = 4), (d) slope (n = 4), (e) effective resting location (n = 1), and (f) lip (n = 1).

3.4 | Impact of the recorder opinion in SNIFFER final scoring

A review indicated that the nonquantified elements or recorder opinion items, collected during the SNIFFER scoring process, impacted on final SNIFFER scores in a small proportion of cases only.

In total, 112 TSs were investigated for Atlantic salmon to examine the influence of recorder opinion on protocol passability score obtained in SNIFFER. The final SNIFFER score was thus altered on 14 occasions (12.5%), due to turbulence (n = 8), standing wave (n = 3), lip (n = 2), and effective resting location (n = 1). Of these 14 occasions, the final SNIFFER score remained less strict than the ICE score in 10 cases (71%).

The influence of recorder opinion on protocol passability score was reviewed for adult lamprey at 111 TSs. The final SNIFFER score was altered on eight occasions (7.2%), due to turbulence (n = 6), lip
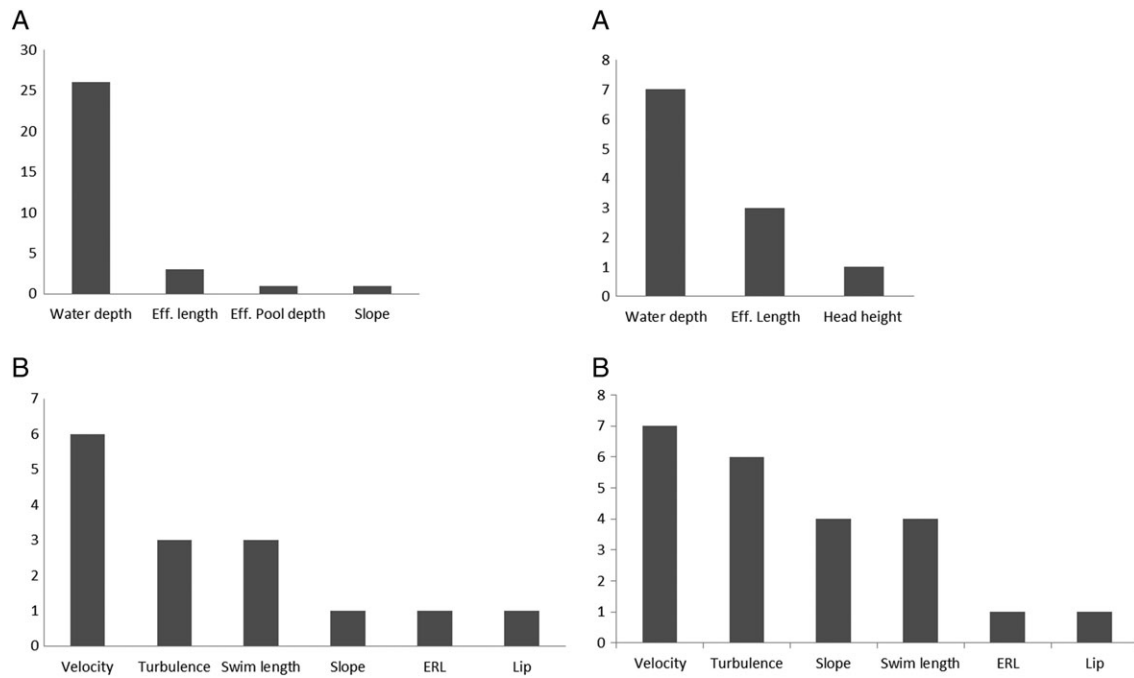
FIGURE 5 (a) Atlantic salmon outcomes: A, barrier attributes highlighted by ICE protocol, which lead to ICE score being stricter than paired SNIFFER scores for salmon (*n* = 31); B, barrier attributes highlighted by SNIFFER protocol, which lead SNIFFER score being stricter than paired ICE score (*n* = 15). (b) Sea lamprey outcomes: A, barrier attributes highlighted by ICE protocol, which lead to ICE score being stricter than paired SNIFFER score for adult lamprey (*n* = 11); B, barrier attributes highlighted by SNIFFER protocol, which lead to SNIFFER score being stricter than paired ICE score (*n* = 23). ERL = effective resting location

(*n* = 1), and effective resting location (*n* = 1). Of the eight, one occasion (12.5%) resulted in a less strict final score than ICE, and seven occasions (87.5%) resulted in a stricter score than ICE.

3.5 | Assessment of fish passage solutions

The fish passage solutions examined here included pool type passes (*n* = 10), chute (a sloping channel or slide for conveying water to a lower level, *n* = 10), vertical slot passes (*n* = 5), Denil passes (*n* = 3), and rock ramp (*n* = 2). Issues of passage related primarily to excessive step height between pools and inadequate water depth through the structures. Of the 30 fish passage solutions assessed using the SNIFFER protocol for Atlantic salmon, 33.3% (*n* = 10) scored 0 (impassable), 40% (*n* = 12) scored 0.3, 20% (*n* = 6) scored 0.6, and 6.7% (*n* = 2) scored 1 (Figure 6). The ICE protocol found 86.6% (*n* = 26) to have sizing criteria unsuitable to pass adult Atlantic salmon. Reasons included not having minimum depth in pool (42.3%, *n* = 11), not having minimum length of pools (11.5%, *n* = 3), exceeding maximum head drop (30.7%, *n* = 8), plunging jet flow (3.8%, *n* = 1), and three Denil passes exceeding recommended slopes (*n* = 3). Both protocols had a strong concurrence on the general unsuitability of the fish passage solutions or fishways examined. Of the four structures identified by ICE as having suitable sizing for Atlantic salmon, two of these structures had a SNIFFER score of 1 (no barrier), one structure had a SNIFFER score of 0.6, and one had a SNIFFER score of 0.3.

Of the 30 fish passage solutions assessed using the SNIFFER protocol for adult lamprey, 80% (*n* = 24) scored 0 (impassable), 13.3% (*n* = 4) scored 0.3, 6.6% (*n* = 2) scored 0.6, and 0% (*n* = 0) scored 1 (Figure 6). The ICE protocol found 90% (*n* = 27) to have sizing criteria
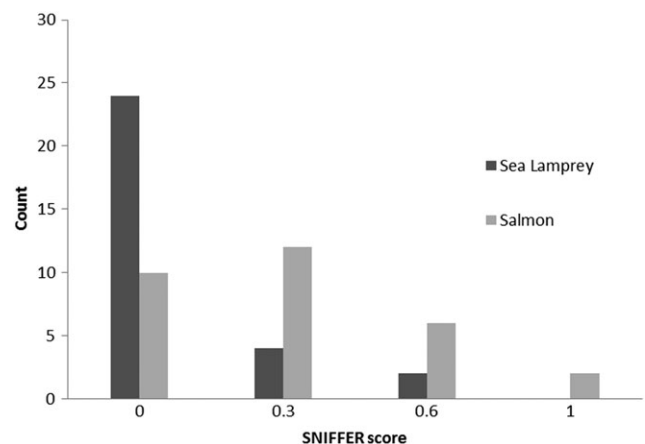

FIGURE 6 SNIFFER scores at fish passage solutions (*n* = 30) for sea lamprey and Atlantic salmon

unsuitable to pass adult lamprey. Reasons included not having minimum depth in pool (40.7%, *n* = 11), exceeding maximum head drop (29.6%, *n* = 8), not having minimum length of pools (11% *n* = 3), plunging jet flow (7.4%, *n* = 2), and the three Denil passes exceeding recommended slopes (*n* = 3). Of the three structures considered "suitable" under ICE, two structures had a SNIFFER score of 1, and one structure had a SNIFFER score of 0.3.

4 | DISCUSSION

The restoration of river connectivity has been recognized as a major conservation target and is a major component in the EU Water

Framework Directive. As a result, new methods have been developed to measure the alteration of connectivity induced by anthropogenic barriers in lotic systems. Common to methods is the inherent difficulty in assessing barrier passability—the dynamic component of river connectivity (Bourne, Kehler, Wiersma, & Cote, 2011; Kemp & O Hanley 2011; Nunn & Cowx, 2012; Drouineau et al., 2018), and in particular the difficulty in developing cost- and time-effective coarse-resolution methods that can be implemented at the catchment scale or larger.

The present study identifies the level of commonality of outcome between recently developed barrier assessment methods for fish in U.K. (SNIFFER) and French (ICE) rivers (SNIFFER, 2010, and Baudoin et al., 2015, respectively). The two methods use similar physical measurements to assess barrier passability and thereafter differ in their processes to generate a passability score. Both make use of peer-reviewed scientifically generated data on fish "performance" or "capacity" to cope with physical dimensions (height, slope, length, etc.) and with hydraulic elements (depth of water available for swimming or for leaping, etc.). A high degree of concurrence was observed in outcome between the two protocols for structures classified as impassable (score = 0) by SNIFFER. Concurrence levels were significantly lower for structures yielding a SNIFFER score of "0.3" (high risk) or "0.6" (low risk) with protocol disagreements yielding both more strict and less strict outcomes when compared. As a result of differing choice processes within each of the protocols, score discrepancies are inevitable. One of the most important factors for successful fish passage is the depth of water over the structure (Bourne et al., 2011; Diebel, Fedora, Cogswell, & O'Hanley, 2015). The threshold minimum water depth for adult salmon in SNIFFER is 0.07 m as opposed to an ICE value of 0.2 m. Similarly, the threshold water depth for adult lamprey is 0.04 m in SNIFFER compared with 0.10 m in ICE.

A second element that leads to score discrepancies was the recording of actual velocity data. For the ICE protocol, velocity readings are rarely required as hydrodynamic equations and modelling have been used to set specific physical thresholds (e.g., head height and slope) above which velocity is estimated to restrict passage (Baudoin et al., 2015). This is one of the major time constraints in the SNIFFER assessment; therefore, without the need for velocities, ICE is considerably quicker. However, it is possible that ICE may sometimes miss funnelled flows or zones where velocity may increase significantly due to a hydrological anomaly. SNIFFER has the power in these cases to rule the TS impassable due to high velocities, which ICE may fail to do.

Subjectivity was an issue of concern in the initial examination of the two protocols, with SNIFFER requiring recorder assessment of nonquantified elements, such as degree of turbulence and standing waves, which might impact the final passability scoring. On consideration, it is apparent that both protocols employ a degree of subjectivity in the selection or identification of what actually constitute TSs at a structure. It is possible, in the case of many structures, to delineate a large number of potential TSs and to survey each of these. The authors employed a pragmatic approach in identifying TSs, starting with individual visual assessments of the whole structure from a series of viewpoints and following this with discussion of opinion and agreement between the assessors (SNIFFER, 2010, guidelines). TSs at different parts of a structure, but sharing similar or identical hydraulic

or physical attributes, were treated as being the same, from a fish perspective. Any sense of subjectivity in TS selection is considered to be shared equally by both protocols. The outcome of the present study identified a low level of impact of observer bias on the final passability outcome of SNIFFER, with 12.5% (Atlantic salmon) and 7.2% (adult lamprey) of cases being impacted by such criteria. Thus, the initial concerns of reduced objectivity for SNIFFER scores may be put to one side, pending an increased sampling effort for both structures and associated TSs.

4.1 | Measurement time

The two protocols identify the same set of TSs at any barriers and have a common core set of measurements to be taken. Therefore, the time saving relates to time taken in carrying out the key measurements necessary for each of the protocols. Using two surveyors and readily available equipment, King et al. (2017) stated that approximately 5.7 barriers can be surveyed a day using the SNIFFER protocol. However, the SNIFFER protocol can be time-consuming, and on a complex barrier (e.g., >100-m width, ~2-m drop height, and >3 TSs), the number of barriers assessed in a day, in the present study, can be as low as two. The ICE protocol requires fewer measurements, and the lack of flow velocity recording required can significantly reduce the time needed to assess a barrier. There is a considerable time element required in collecting velocity data at two depths (0.6D and bed) at 15 points for each TS identified at a structure. SNIFFER clearly flags the potential for Health and Safety (H&S) issues to arise when working on a structure surrounded by water. Nevertheless, it was possible to collect all relevant data in the vast majority of TSs. In addition to the time element, there is an expense in provision of flow meters as the purchase of instruments can present a high initial investment cost.

4.2 | Fish passage solutions (fishways)

Upstream fish passage solutions must be safe and effective and effect minimal delay in fish migration (Linnansaari, Wallace, Curry, & Yamazaki, 2015); the entrance must be located in such a way that fish will readily find it and enter it without hesitation (Williams, Armstrong, Katopodis, Larinier, & Travade, 2012). In the literature, salmonids were more successful than nonsalmonids at using fish passage mitigation options (Bunt, Castro-Santos, & Haro, 2012). This is principally due to their strong swimming/jumping ability and the fact that most fish passage options are designed to accommodate anadromous salmonid species (Noonan, Grant, & Jackson, 2012). The similarity of outcomes from the SNIFFER assessment of in situ fish passage solutions and those of the ICE preassessment are positive and flag the value of the assessment of the fish pass dimensions provided in the ICE protocol (Baudoin et al., 2015).

The outcome of the analyses, with a demonstration of the unsuitability of many existing in situ fish passage solutions, points to the management relevance of the protocols as well as a clear requirement to address the identified inadequacies. In Ireland, the Fisheries Act of 1842 required weirs to have fishways that effectively passed salmon, although no specifications for fishways were provided. The enactment

of the EU Water Framework Directive (2000) added legal strength for requiring efforts to improve fish passage at dams and diversions across Europe. Although the wording in the Irish legislation does refer to "migration of all fish," it is reasonable to infer that this is a reference to Atlantic salmon. The underlying aspiration was positive, embracing the concept that the design would permit fish movement at any time of year. In practice, the design required a fish passage structure to be incorporated into the overall weir, as opposed to the overall structure permitting passage. The review here, although of a limited number of structures, does point to a high degree of inadequacy to perform the required legal function. The fact that fish passage solutions often do not perform as intended (Silva et al., 2017) identifies the need to monitor and evaluate effectiveness after construction and modify as needed. It is evident that both protocols provide valuable information on whether fishway transversals in existing weirs in Irish "salmon rivers" are fit for purpose or not. By extension, it is apparent that the two protocols may be appropriate to address the success of any barrier mitigation measures involving alteration of, or insertion of, fish passage solutions.

The findings of this analysis reveal that in the context of barrier management decisions, there is a reasonable degree of agreement between these two methodologically different and independently formulated coarse-resolution assessment protocols, particularly for those barriers classed as completely impermeable. River managers need to carefully consider how passability is to be measured. For example, a more in-depth assessment through SNIFFER may be the most appropriate option if mitigation works are planned (e.g., modification to structure). In comparison, the ICE protocol, with fewer measurements and less equipment requirements (i.e., flow meter), can significantly reduce survey time, allowing managers to assess a larger number of barriers. This will be of particular use for catchment-wide stream connectivity studies. ICE also has the advantage of catering for a larger number of species, incorporating those species present in Ireland and the United Kingdom as well as those in mainland Europe. Further work is required to validate these protocols against empirically derived fish passage data for a wide range of species and barrier types, but such assessments are time-consuming and costly. In the meantime, the level of agreement between these two protocols, identified by this analysis, lends support for their validity and will help managers select appropriate assessment tools based on their requirements.

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SUPPORTING INFORMATION

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