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Accuracy of coarse-resolution protocols for assessing fish passability at river infrastructure

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A B S T R A C T

River infrastructure can present a major barrier to fish movement. While mitigation can be achieved through infrastructure removal or modification, e.g. construction of fish passes, prioritising this work to maximise ecological benefit within budgetary and other constraints remains a substantial management challenge. Several coarse-resolution rapid barrier assessment protocols have been developed to estimate fish passability at river infrastructure to aid decision making in relation to catchment scale barrier management. The outputs of these protocols are rarely validated against empirical data, such as that provided by telemetry or other methods of tracking fish, limiting confidence in whether they provide realistic estimates of fish passability. In this study, the accuracy of two barrier passability assessment protocols yet to be validated against empirical data, SNIFFER and ICE, developed in the UK and France, respectively, was assessed by: 1) collating available empirical multi-species fish passage data at river infrastructure, 2) undertaking field surveys at each structure to quantify SNIFFER and ICE passability scores, and 3) comparing the fish passage data with the estimated passability scores. Fish passage data were obtained for four species (*Salmo trutta, Cottus gobio*, *Lampetra fluviatilis* and *Thymallus thymallus*) and five barrier types (sloped weir, culvert, rock ramp, nature-like bypass, and some classified as 'complex') at thirteen sites in England. Both protocols suggest these barriers are a major impediment to upstream moving fish as a classification of 'impassable' was the most common. However, agreement between protocols was low for barriers considered 'high impact', 'low impact' or 'easily passable'. When compared with empirical fish passage data, there was a positive relationship with the passability scores predicted by SNIFFER, but the protocol tended to be conservative. There was no relationship between the empirical fish passage data and the passability scores predicted by ICE, although field surveys were undertaken outside of the recommended discharge range which may have influenced accuracy. This study provides the first partial validation of two barrier passability assessment protocols and suggests that further detailed validation is needed to calibrate the passability scores and enhance confidence in the planning tools (e.g. optimisation models) that utilise their outputs.

1. Introduction

Freshwater ecosystems cover <1% of the Earth's surface yet approximately 10% of all known animal species inhabit them (Strayer and Dudgeon, 2010). They are the most threatened of all ecosystems (Albert et al., 2021; WWF, 2020), reflecting the high demand for the numerous ecosystem services they provide, including water supply, power generation, navigation and commercial, subsistence and recreational fisheries. Several persistent and emerging threats (Reid et al., 2019) are responsible for rapid population decline and elevated extinction risk for many species (Collen et al., 2014), including fish (Deinet et al., 2020). One of the greatest threats, particularly for rivers, is the construction of infrastructure, such as dams and weirs, water off-takes, culverts and road crossings, that can degrade and fragment habitat and create barriers to the critical movement of fish (Thieme et al., 2023).

Mitigating the negative ecological impacts of river barriers on fish movement can be achieved through infrastructure removal (Birnie-Gauvin et al., 2018) or modification, e.g. construction of fish passes or easements (Armstrong et al., 2010; Franklin et al., 2018). For this to be effective, however, there is a need to recognise the interconnectedness of multiple barriers within a catchment, rather than focus on individual

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structures in isolation; failure to do so can result in substantial inefficiencies and waste of resources (Kemp and O'Hanley, 2010). Several barrier prioritisation methodologies have been developed to inform planning decisions when faced with a network of infrastructure. These include approaches that use optimisation modelling to accommodate spatial relationships between (known or theoretical) barriers, magnitude of ecological impact, benefits likely to be gained through implementation of actions (e.g. removal or modification), and how optimal solutions vary with differing levels of investment (King et al., 2017). There are major challenges in applying these catchment-scale planning tools, however, including the poor and often patchy geospatial information available for the river barrier network, lack of basic information such as barrier type, condition and size, and limited, if any, understanding of ecological impacts such as how much of an impediment the structure is to the movements of fish (Belletti et al., 2020; Jones et al., 2019). Catchment-scale barrier planning and environmental impact mitigation tools will likely play an important role in efforts to enhance the ecological status of rivers in the future. As such, improvements in the quality of data used to underpin these decisions is needed to maximise their efficacy.

Robust information on fish passage at river barriers is required to inform the prioritisation of mitigation work aimed at reconnecting fragmented rivers. Ideally, standardised empirical data relating to real life fish passage metrics (Kemp, 2016), such as attraction, entrance and passage efficiency and length of delay, for multiple species and barrier designs would parameterise prioritisation models that inform decision-making. Such high resolution data is typically obtained using mark-recapture (Franklin et al., 2024; Tummers et al., 2016a) or telemetry techniques (Cooke et al., 2013) that are both financially and logistically costly, and typically unfeasible when applied to coarse resolution catchment-scale analysis (Barry et al., 2018). Therefore, alternative barrier assessment protocols are needed to infer passability for a range of fish species, life-stages and barrier types.

Coarse-resolution rapid barrier assessment protocols have been developed to provide a standardised method of surveying a large number of river barriers over a wide geographic area in a cost-effective manner (Kemp and O'Hanley, 2010). Available protocols, such as SNIFFER (developed by the University of Southampton for the Scotland and Northern Ireland Forum For Environmental Research, Kemp et al., 2008; SNIFFER, 2010a) and ICE (developed by Onema and Ecogea in France and the University of Liège in Belgian, Baudoin et al., 2014) require the assessment of topographic and hydraulic conditions, such as head height, slope, water depth and velocity, at potential routes of fish passage at each barrier surveyed relative to known fish swimming and leaping capabilities. They allow for rapid (e.g. assigning scores for a mean of 5.7 structures per day for a range of species, King et al., 2017) and relatively low-cost assessment of barriers providing the data needed to create geospatial inventories of river barrier networks and associated ecological impact. However, these protocols have largely been developed independently, representing the potential for duplication of effort and the inefficiencies of failing to learn from experiences gained and identification of best practice. While levels of agreement between different protocols can be strong at the extremes (e.g. the identification of structures that pose no [1.0 passability score] or a complete [0.0 passability score] barrier to fish movement), they are often weak for intermediate scores (e.g. those that represent high [0.3] or low [0.6] partial barriers) (Barry et al., 2018). Discrepancies are largely caused by differences in the specific threshold criteria used to assign the passability scores, such as minimum depth requirements for certain species or life-stages (Barry et al., 2018). Furthermore, despite extensive field testing (e.g. SNIFFER, 2010b), there is a lack of validation against quantitative empirical (e.g. mark-recapture and telemetry) data. Validating barrier assessment protocols is essential if the prioritisation methods that depend on the information they provide are to be trusted and the most appropriate management decisions are to be adopted.

This study evaluated the accuracy of two commonly used European barrier assessment protocols, SNIFFER and ICE by: 1) identifying and collating available empirical fish passage data obtained using mark-recapture or telemetry at riverine barriers, 2) undertaking field surveys at each barrier to quantify SNIFFER and ICE passability scores, and 3) comparing the fish passage data with the estimated passability scores.

2. Materials and methods

2.1. Empirical fish passage data

Twenty-eight river barriers for which quantitative fish passage data (mark-recapture and/or telemetry) are available were identified from the literature and through consultation with researchers in England. Modification of the barrier since fish passage evaluation took place or restrictions in access to the sites (e.g. lack of landowner permission) resulted in 15 of these barriers being excluded, leaving 13 remaining (Fig. 1), comprising five different barrier designs. The barriers were located on mid- to low-order rivers in the North of England where gradients ranged from relatively low (e.g. River Derwent, 0.3 m km^{-1}; Tummers et al., 2016b) to high (Chipping Brook, 42.6 m km^{-1}; Forty et al., 2016) with all experiencing substantial flow variation driven by a rapid response to rainfall. Habitat is mostly characterised by the presence of pool-riffle-runs. Substrate is typically dominated by gravel, accompanied by cobble, sand and silt, the former and latter two generally more common in upper and lower river sections, respectively. Channel widths range from approx. 5–15 m (e.g. Swanside Beck, Chipping Brook, Rye, Dove and Costa Beck) to 15–20 m (e.g. River Derwent). For more detailed descriptions of each river, see the source literature (Table 1).

Four of the river barriers were sloped weirs (e.g. Crump or Flat V designs used for gauging flow), three were culverts, one was a rock ramp, one was a nature-like bypass, and four were classified as "complex" (Table 1; Fig. 2). The complex barriers consisted of either a vertical drop leading to several distinct rock ramps (S1), a nature-like easement leading to a culvert (S8) or pool and weir structures consisting of multiple transversal sections (passage routes) with sloped and vertical drops (Pool and Weir 1 and 2) (Table 1; Fig. 2). A comparable diversity of barrier types is logged in the national barrier inventories for both England and France (Belletti et al., 2020). Passage efficiency data were frequently recorded for multiple fish species and size classes at a single structure, resulting in 23 individual data points for comparison against the rapid assessment protocols. The species for which fish passage data were available (Table 1) encompass those that tend to be more (e.g. bullhead [*Cottus gobio*] and river lamprey [*Lampetra fluviatilis*]) and less (e.g. brown trout [*Salmo trutta*] and European grayling [*Thymallus thymallus*]) benthic oriented, and that vary widely in shape, size, and locomotive mode, which are common factors influencing swimming performance and passage at river infrastructure (Jones et al., 2020).

2.2. Coarse-resolution rapid barrier assessment protocols

2.2.1. SNIFFER protocol

In the UK and Ireland, the widely used methodology for rapidly assessing the passability of river barriers for fish is the WFD111 method, commonly referred to as the SNIFFER protocol (SNIFFER, 2010a, 2010b, 2010c). This is because it was commissioned by the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) and funded by the Scottish Environment Protection Agency and Northern Ireland Environment Agency. SNIFFER is used by government agencies, environmental charities/ consultancies and scientific researchers to provide a coarse resolution rapid assessment of potential obstacles to fish migration. The protocol can be used to assess both natural barriers and anthropogenic structures. Species and life-stages considered include adults of Atlantic salmon (*Salmo salar*), brown trout, European grayling, lamprey species, and cyprinid species, and juveniles of salmonids and European eel (*Anguilla anguilla*). The criteria for determining passability

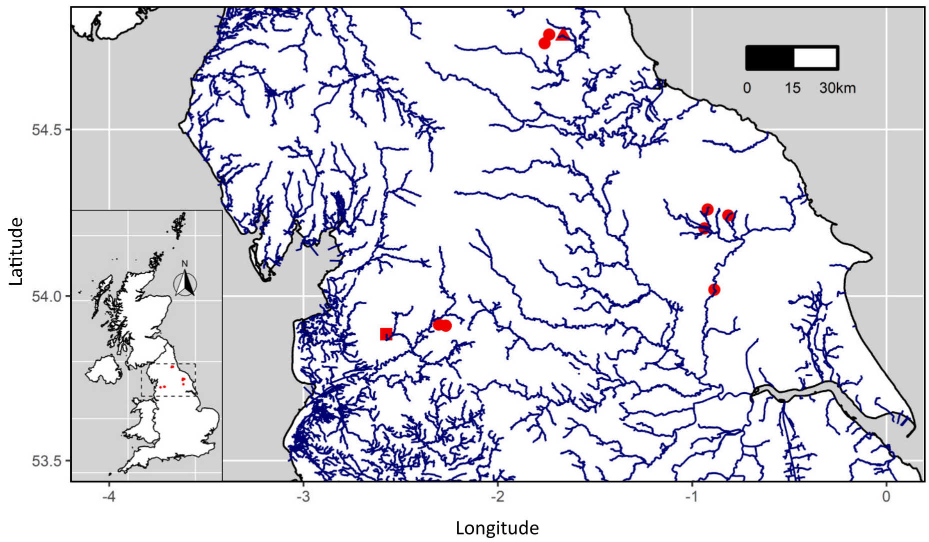

Fig. 1. Location (red points) of river barriers with existing data on the ability of fish to pass the structure and that were evaluated using the SNIFFER and ICE coarse-resolution barrier assessment protocols. Due to close proximity of some barriers, the square and triangle symbols represent the location of three and two barriers, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scores are based on published data describing the swimming and leaping abilities of multiple species and life-stages.

It is recommended that the SNIFFER protocol be conducted under low flow conditions to promote ease of access and safety, so that assessments are undertaken during the most severe conditions for fish passage, and to maximise the chance that most data be collected by measurement rather than estimation (SNIFFER, 2010a). Non-uniform structures are broken up into hydraulically distinct "transversal sections" (TS) which present different passage routes for fish (SNIFFER, 2010a). Each TS is assessed independently. Five physical measurements (of water velocity and depth) are recorded along three lateral transects at each TS (crest/ inlet, mid-point and foot/ outlet) to inform on passability. At its simplest the assessment protocol requires each velocity and depth measurement location within a TS to be assessed in relation to a fish's swimming capabilities and ranked as either 0 (complete barrier), 0.3 (high impact partial barrier), 0.6 (low impact partial barrier) or 1 (no barrier). The overall passability score for each TS is the lowest score that makes up the easiest route to ascend. The overall passability score for the entire barrier is equal to the TS with the highest score.

Depending on the type of barrier, additional data (e.g. step height, pool depth, gap dimensions) must be recorded and assessed alongside generic factors such as the presence of debris, standing hydraulic waves and levels of turbulence. Although the protocol is largely objective, the influence of these additional factors on fish passage are subjective. The protocol categorises three broad barriers from the perspective of the fish (a jump, swim or depth barrier) enabling flexibility in the types of river infrastructure assessed.

2.2.2. ICE protocol

The ICE (Informations sur la Continuité Écologique) protocol is extensively used across the French territory, with data frequently included in the French national river barrier database (https://geobs.brgm.fr/). Furthermore, specific studies have also used it in Belgium and Portugal (Michael Ovidio, University of Liège, pers. comm.). The protocol requires the identification of the potential passageway(s) through which fish can move at each barrier (similar to transversal sections in the SNIFFER protocol) and categorisation of their geometric features and hydraulic conditions. Long profiles of each potential passageway are recorded by collecting altimetric data for each specific point in a structure corresponding to a significant change in the profile, e.g. a break in a slope. Although velocimetric data is occasionally required, hydrodynamic equations and modelling are typically used to set specific physical thresholds (e.g. head height and slope) above which velocity is estimated to restrict fish passage based on data of the swimming and leaping capabilities of given species.

A strength of ICE is its multispecies focus, accounting for 47 separate species/ life-stages arranged into 11 groups and 20 sub-groups according to swimming capabilities. Barrier passability is defined in a similar way to SNIFFER with possible scores being 0 (total barrier), 0.33 (high impact partial barrier), 0.66 (medium impact partial barrier), or 1 (low impact passable barrier). Generally, passability scores are assigned based on the threshold physical values (e.g. depth, velocity, slope etc.) measured at the barrier compared to the minimum, average and maximum swimming abilities assigned to each fish group. For example, if the velocity is lower than the minimum swimming speed then passability is equivalent to 1, if it is between the minimum and average, then passability is assigned a value of 0.66, if it is between average and maximum, passability is 0.33, and if it is above the maximum then passability equals 0. To reduce time in the field, extreme thresholds are highlighted whereby the barrier is instantly classed as impassable and no further measurements are required.

The ICE protocol uses decision trees to determine the overall passability of five barrier types: 1) vertical or sub-vertical barriers (slope $>$ 150%); 2) weirs with inclined downstream face (slope $\leq$ 150%); 3) rock weirs; 4) barriers comprising gates or where underflows occur; and 5) road/ rail structures. The protocol also provides guidance on assigning a passability score for complex structures consisting of more than one of these barrier types. It is recommended that the ICE protocol be carried out under the hydrological conditions most common during the migratory period of the focus species (Baudoin et al., 2014).

2.3. Data collection and analysis

SNIFFER and ICE assessments for the 13 English river barriers (Table 1) were conducted between 19 and 23 August 2019. Data for both protocols were collected simultaneously at each barrier using an automatic level, 20 m tape measure, metre rule, velocity meter (Valeport Model 801 Flat) and digital camera under summer low-flow conditions. For each barrier, the raw data were post-processed manually (SNIFFER protocol) or using custom software (ICE protocol: Rapid Barrier Passability and Hydropower Assessment Tool - https://amber.international/software/) to generate passability scores for the fish species/ life stages that had previously been considered in passage efficiency assessments. Resource limitations prohibited the protocols being undertaken multiple

Table 1
Infrastructure and study details for the 13 river barriers used to assess the validity of two commonly used rapid barrier assessment protocols (SNIFFER and ICE). Barrier IDs have been maintained from the source literature for ease of reference. Passage Efficiency (PE) method indicates if the score is based on barrier permeability (BP) or proportion passed (PP). Size of *S. trutta* and *T. thymallus* refer to fork length, and "body length" for all other species. A complex barrier type indicates that the structure consists of more than one barrier type. Latitude and longitude positions use the WGS84 coordinate system.

Barrier ID	River	Location (Lat, Long)	Barrier type	Length (m)	Width (m)	Height (m)	PE method	Species	Size	PE score (0.0–1.0)	Source
S1	Deerness	54.773304, −1.649746	Complex	17.1	4.0	1.42	BP, PP, BP.	*S. trutta* *S. trutta* *C. gobio*	Mean (range): 117 (50–338) mm Mean (range): 419 (268–754) mm Mean (range): 73 (52–111) mm	0.44 0.87 0.14	Tummers et al., 2016a
S2	Deerness	54.779182, −1.669066	Nature-like	36.0	2.0	1.11	BP, PP, PP, BP.	*S. trutta* *S. trutta* *S. trutta* *C. gobio*	Mean (range): 117 (50–338) mm Mean (range): 175 (125–273) mm Mean (range): 419 (268–754) mm Mean (range): 73 (52–111) mm	0.58 0.70 0.81 0.32	Tummers et al., 2016a
S7	Deerness	54.756441, −1.758721	Culvert	11.0	5.4	0.34	BP, BP.	*S. trutta* *C. gobio*	Mean (range): 117 (50–338) mm Mean (range): 73 (52–111) mm	0.11 0.00	Tummers et al., 2016a
S8	Deerness	54.782337, −1.735478	Complex	43.9	1.7	0.86	BP, PP, BP.	*S. trutta* *S. trutta* *C. gobio*	Mean (range): 117 (50–338) mm Mean (range): 145 (120–219) mm Mean (range): 73 (52–111) mm	0.46 0.83 0.22	Tummers et al., 2016a
Buttercrambe Weir	Derwent	54.018900, −0.885352	Sloped weir	6.1	20.0	1.31	PP, PP.	*L. fluviatilis* *L. fluviatilis*	Mean ± SD: 389 ± 19 mm Mean ± SD: 370 ± 21 mm	0.14 0.09	Tummers et al., 2016b Tummers et al., 2018
River Rye Flat V Weir	Rye	54.203869, −0.936644	Sloped weir	4.8	12.0	1.20	PP.	*T. thymallus*	Mean (range): 310 (265–421) mm	0.00	Lucas and Bubb, 2005.
Kirby Mills Flat V Weir	Dove	54.260586, −0.919864	Sloped weir	4.0	6.0	0.45	PP, PP.	*T. thymallus* *S. trutta*	Mean (range): ca. 240 (180–310) mm Mean (range): ca. 260 (150–320) mm	0.36 0.84	Lucas and Bubb, 2005.
Costa Beck Crump Weir	Costa Beck	54.242252, −0.813816	Sloped weir	2.0	5.0	0.18	PP.	*T. thymallus*	Mean (range): ca. 250 (174–330) mm	0.96	Lucas and Bubb, 2005.
Culvert 1	Swanside Beck	53.913286, −2.302943	Culvert	20.0	0.5	0.80	PP.	*S. trutta*	Mean (range): 152 (80–294) mm	0.98	Forty et al., 2016.
Culvert 2	Swanside Beck	53.889151, −2.588886	Culvert	63.5	2.2	3.32	PP.	*S. trutta*	Mean (range): 128 (74–206) mm	0.37	Ribble Rivers Trust, 2015.
Pool-Weir 1	Swanside Beck	53.910189, −2.267072	Complex	8.4	6.2	1.16	PP.	*S. trutta*	Mean (range): 131 (80–208) mm	0.76	Forty et al., 2016.
Rock Ramp	Chipping Brook	53.884514, −2.574003	Rock Ramp	4.6	6.8	0.55	PP.	*S. trutta*	Mean (range): ca. 145 (102–326 mm)	0.71	Forty et al., 2016.
Pool-Weir 2	Chipping Brook	53.884514, −2.574003	Complex	7.2	9.6	0.84	PP.	*S. trutta*	Mean (range): 145 (102–326 mm)	0.79	Forty et al., 2016.

times, i.e. also during the peak migration period for each species of interest, as recommended for ICE. However, most prioritisation projects will also have limited resources, and so this scenario likely reflects the reality under which these protocols are used. Specifically, it is unlikely that passability will be routinely assessed multiple times at the same barrier to account for specific migration periods when passability scores for multiple species are required, and so use of data collected outside of periods of peak migration will likely be common (as indicated by the ICE data in the French national database).

At each barrier, passage efficiency had been previously quantified as

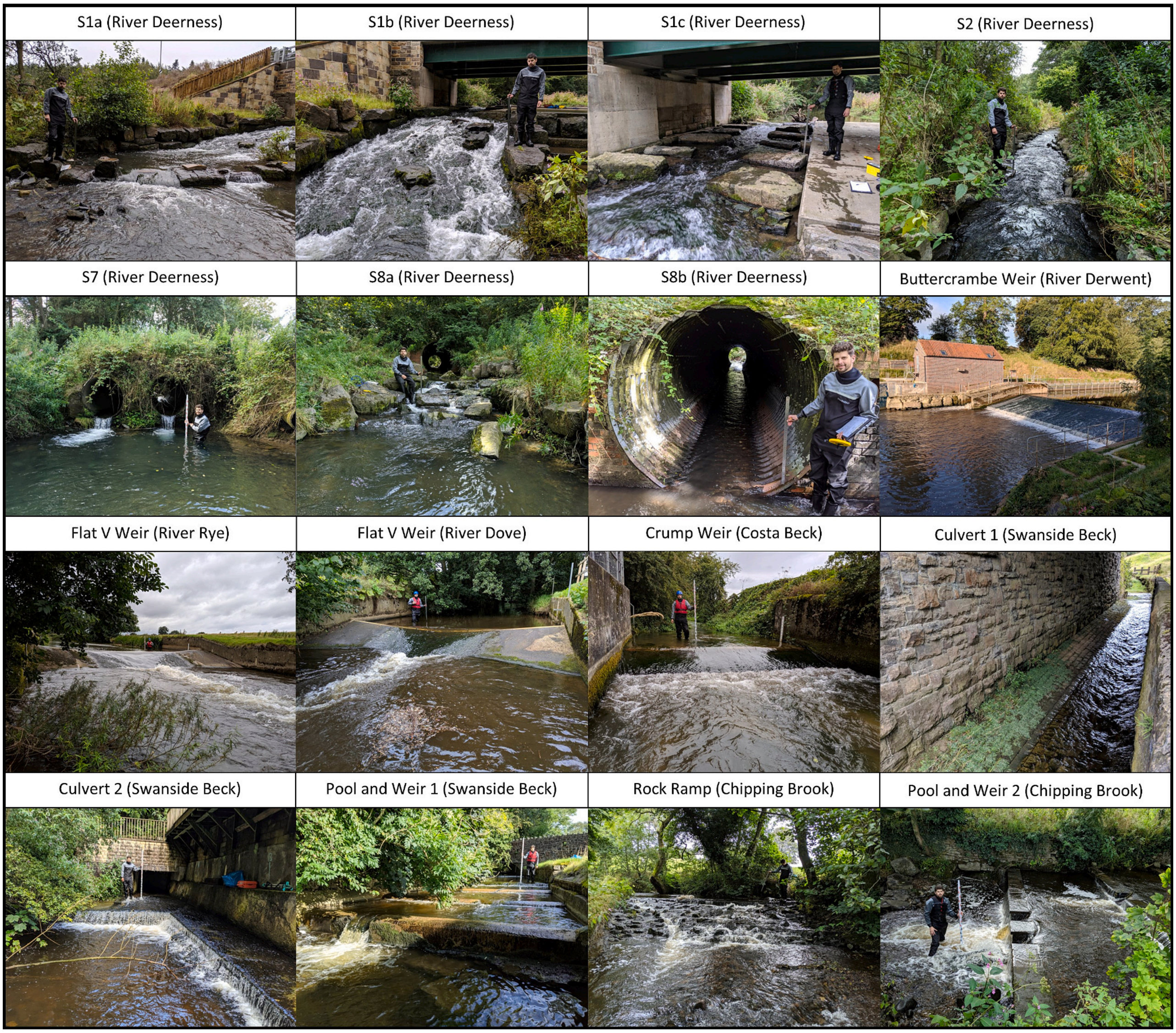

Fig. 2. Photographs of the 13 river barriers used to assess the validity of two commonly employed rapid barrier assessment protocols (SNIFFER and ICE). Barrier IDs have been maintained from the empirical fish passage source literature for ease of reference. Multiple photographs are shown for S1 and S8 to illustrate the distinct sections to these "complex" barriers.

either: 1) a measure of barrier permeability (BP) calculated using mark-recapture techniques and Laplace kernel analyses (e.g. Tummers et al., 2016a), or 2) a measure of the proportion of fish that passed (PP) the structure out of those that attempted using telemetry (Table 1). The size range of fish for which passage efficiency data were available did not always match that for which the protocol passability scores were generated. For example, the ICE protocol divides the passability score for *S. trutta* into: 1) brown trout [150–300 mm], 2), brown or sea trout [250–550 mm], or 3) brown or sea trout [500–1000 mm], whereas the passage efficiency data for that species might only be available for a broader size range of fish (e.g. Barrier S1; *S. trutta*: 268–754 mm, Table 1). Where this occurred, the mean score of the protocol groups for which telemetry data were available was used in the analysis. For the ICE protocol 23 fish passage data points were available for comparison with protocol scores. For SNIFFER, 19 data points were available due to the protocol not producing scores for bullhead of which there were 4 observations. As model residuals did not meet the assumption of normality, the relationship between passage efficiency and head height and passage efficiency and fish length were analysed using a Spearman Rank correlation. Due to the ordinal nature of some of the data, the relationship between passage efficiency (e.g. mark-recapture and telemetry results) and the rapid barrier assessment protocol scores was analysed using Spearman Rank correlation.

3. Results

3.1. Empirical fish passage data

Combining data for all species/ life-stages, median passage efficiency was highest at the rock ramp (0.71), a little lower at the nature-like (0.64) and complex barriers (0.61) and lowest at the sloped weirs (0.25) and culverts (0.24) (Fig. 3a). Brown trout were the most frequently studied species with passage efficiency data (ranging from 11 to 98%) available at 10 (76.9%) of the river barriers assessed. Passage efficiency data for bullhead were available at 4 barriers and ranged from 0 to 32%, for grayling at 3 barriers (0–96%), and for river lamprey at one barrier (9–14%) (Table 1, Fig. 3b). Twelve of the thirteen barriers had a head height of <1.5 m (exception: Culvert 2, h = 3.32) (Fig. 3c), there was no relationship between head height and passage efficiency ($r_s = -0.20$, $p = 0.35$). Mean fish lengths ranged from 73 (bullhead) to ca. 400 mm (lamprey and large trout/ grayling). There was no relationship between fish length and passage efficiency when data were combined (r_s

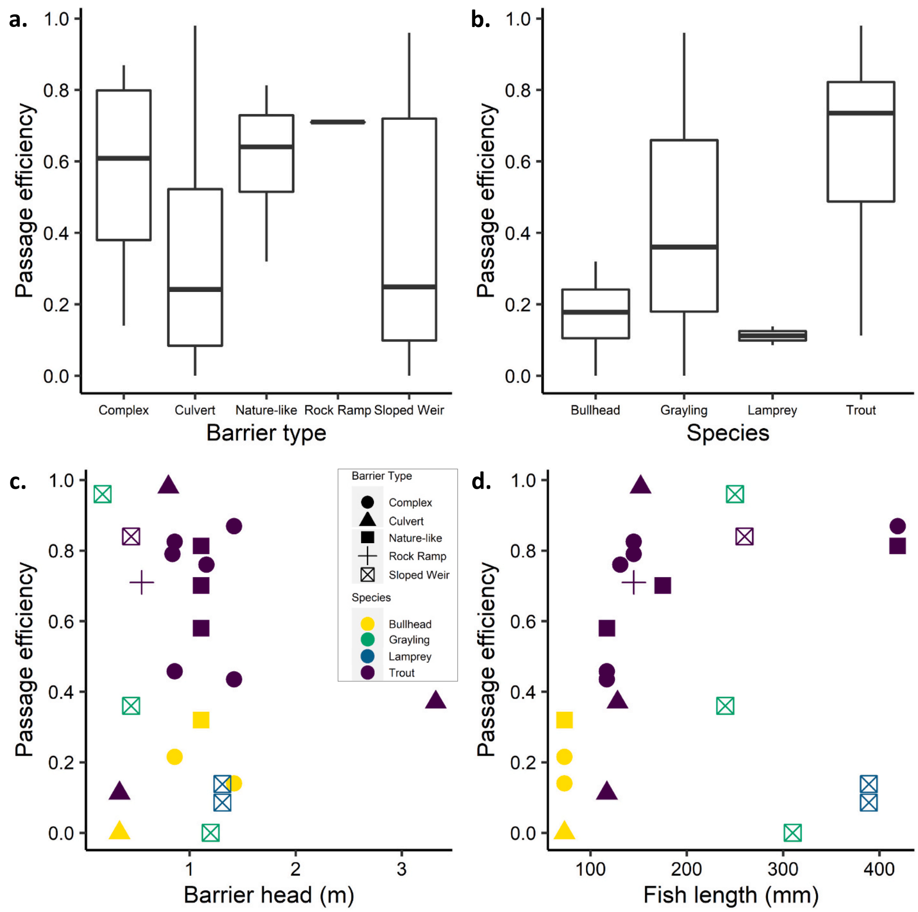

Fig. 3. Relationship between passage efficiency and **(a)** barrier type, **(b)** species, **(c)** barrier head height, and **(d)** fish length for the 13 river structures used to assess the validity of two commonly used rapid barrier assessment protocols (SNIFFER and ICE).

= 0.34, $p = 0.11$; Fig. 3d). For trout, passage efficiency appears to drop when body length is less than approx. 120 mm, although interpretation is difficult due to the low number of observations per barrier type (Fig. 3d).

3.2. Coarse-resolution rapid barrier assessment protocols

Combining data for all species, SNIFFER identified most of the river barriers as impassable (passability score of 0; 50.0% [$n = 26$]), with the remaining being high impact (passability score of 0.3; 38.5% [$n = 20$]), followed by low impact (passability score of 0.6; 9.6% [$n = 5$]) and then easily passible (passability score of 1; 1.9% [$n = 1$]) barriers. Similarly, ICE identified most river barriers as impassable (63.5% [$n = 33$]), with the remaining being easily passable (15.4% [$n = 8$]), low impact (11.5% [$n = 6$]) or high impact (9.6% [$n = 5$]).

The mean level of agreement between SNIFFER and ICE passability scores for all species was low (28.8%; 15/52) (Table 2). The highest probability of agreement (50.8%) was for impassable barriers, with very little agreement, 0, 12.5 and 0% for high impact, low impact and easily passible barriers, respectively (Table 2). Disagreement in passability score was not limited to just one category (i.e. ± 0.3; frequency: 40.4%), but was often two (i.e. ± 0.6) or even three (i.e. ± 1) categories different between protocols (frequency: 21.2% and 9.6%, respectively) (Fig. 4).

3.3. Comparison of coarse-resolution rapid barrier assessment protocol scores and empirical fish passage data

There was a positive relationship between the SNIFFER ($r_s = 0.62$, $p < 0.01$; Fig. 5a) but not ICE ($r_s = 0.09$, $p = 0.67$; Fig. 5b) protocol scores and empirical fish passage efficiency data. The fitted linear regression line (TS = 0.37SS + 0.008) between the fish passage data and SNIFFER scores (TS and SS, respectively) indicated that the protocol tended to be conservative, underestimating passage (Fig. 5a).

Table 2
SNIFFER and ICE observations per species/ life-stage (AT: adult trout; AG: adult grayling; AL: adult lamprey; JS: Juvenile salmonid) for each protocol score category at 13 river barriers where empirical fish passage data were available with number and percent of paired ICE scores in agreement.

Protocol score category	SNIFFER observations				ICE observations				No. paired ICE scores				Percent protocol agreement				
	AT	AG	AL	JS	AT	AG	AL	JS	AT	AG	AL	JS	AT	AG	AL	JS	Mean:
0	3	7	9	7	10	8	8	7	1	4	5	4	33.3	57.1	55.6	57.1	**50.8**
0.3	7	5	3	5	0	2	1	2	0	0	0	0	0.0	0.0	0.0	0.0	**0.0**
0.6	2	1	1	1	1	1	2	2	1	0	0	0	50.0	0.0	0.0	0.0	**12.5**
1	1	0	0	0	2	2	2	2	0	0	0	0	0.0	0.0	0.0	0.0	**0.0**

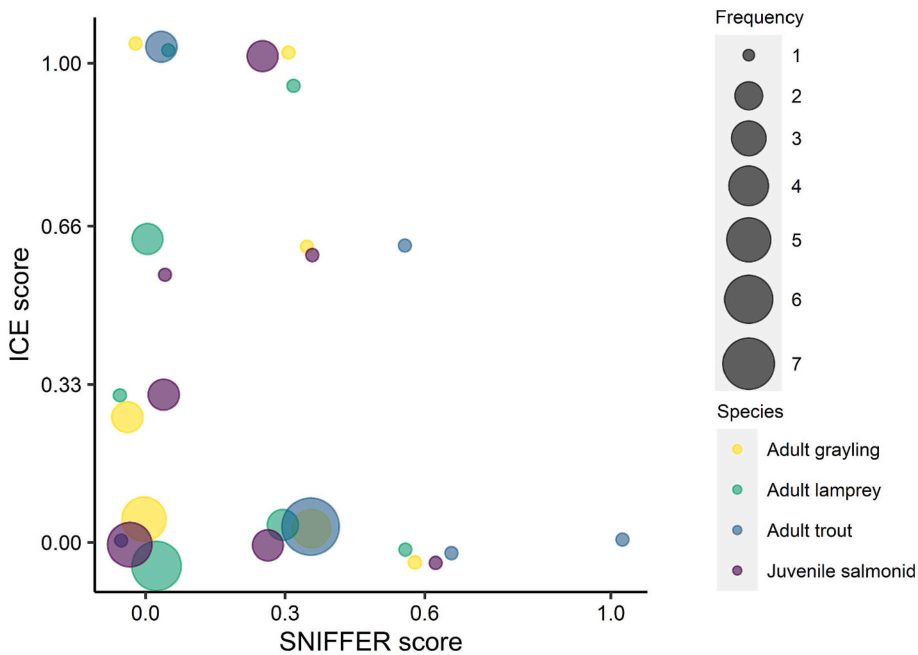

Fig. 4. Paired SNIFFER and ICE coarse-resolution rapid barrier assessment protocol scores of fish passability at 13 river barriers in the north of England, highlighting levels of agreement / disagreement and how frequently these occurred.

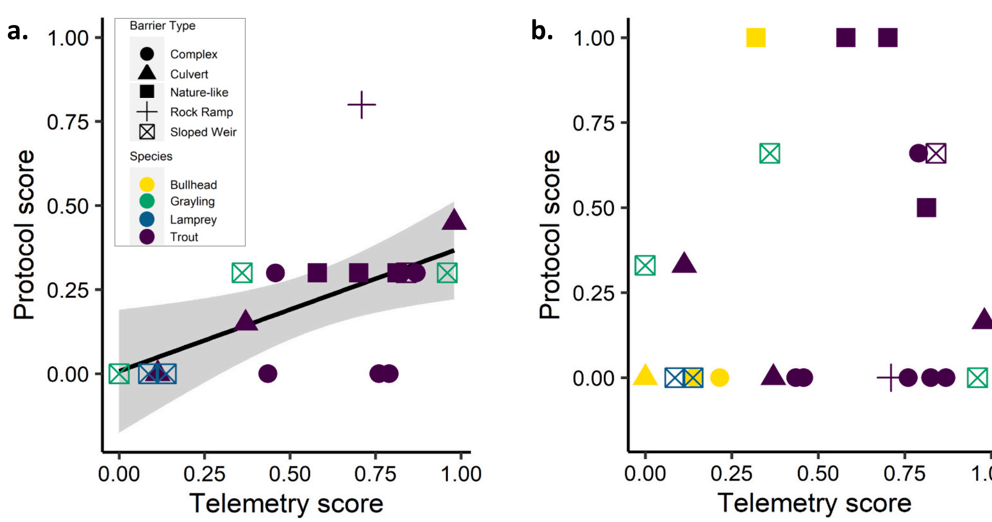

Fig. 5. Relationship between **(a)** SNIFFER and **(b)** ICE coarse-resolution rapid barrier assessment protocol scores of fish passability and existing fish passage efficiency data (obtained from telemetry/ mark recapture studies) at 13 river barriers in the north of England. The relationship in **(a)** is fitted with a linear regression line. Shading represents the 95% confidence interval.

4. Discussion

This study estimated fish passability at 13 river barriers in the north of England using two coarse-resolution rapid barrier assessment protocols (SNIFFER [Kemp et al., 2008] and ICE [Baudoin et al., 2014]) and evaluated them using empirical fish passage data obtained during telemetry and mark-recapture studies. Outputs from both protocols suggest that most river barriers considered represented major impediments to upstream moving fish as passability scores of 0 (impassable) were the most common. However, agreement between protocols was low for barriers considered high impact (scoring 0.3), low impact (scoring 0.6) and easily passable (scoring 1). The positive relationship between SNIFFER estimates of passability and empirical passage efficiency data should provide confidence to regulators, ecological engineers or others tasked with using this information to inform prioritisation efforts aimed at mitigating impeded fish movement at river infrastructure. There was no relationship between the ICE estimates of passability and empirical passage efficiency data, although the location of study was outside of the region where the protocol was developed and assessments were not undertaken during the peak migration period for the species' of interest, as recommended. This study is the first to compare the outputs of these two commonly used rapid barrier assessment protocols against empirical data. Further work is needed to more thoroughly validate them to ensure data used to inform management decisions are appropriate, or at least to emphasise where caution in interpreting the results should be adopted.

Despite extensive field-testing and implementation to identify the degree of impact caused by river barriers on fish movement in the UK, the SNIFFER rapid barrier assessment protocol had not previously been compared against empirical fish passage data. When done so in this study for a range of species that differ greatly in body shape, size and swimming mode, there was a positive relationship between passability scores and empirical fish passage data, although the degree of error was high and the protocol tended to be conservative, underestimating passage. Habitat fragmentation caused by river infrastructure is dynamic, with fish passage influenced by environmental conditions (e.g. in relation to depth, water velocity, discharge, temperature) and endogenous biotic factors (e.g. behaviour, physiological capability, motivational state) and this likely contributed to the observed error in results. Indeed, a perfect assessment of barrier passability is impossible due to the application of a single, transient, assessment of conditions. Multiple assessments under a range of environmental conditions capturing temporal changes in endogenous biotic factors might help resolve the dynamic nature of barrier permeability but this would likely be beyond the scope of most catchment-level barrier mitigation projects. Despite this, the positive correlation identified between empirical fish passage data and the SNIFFER passability scores suggests that the protocol has a role to play in providing valuable information on which to base management decisions, provided limitations are also recognised.

In addition to continuing to validate and refine protocols such as SNIFFER, it would also be advisable to conduct more extensive empirical assessments (i.e. using telemetry) at sites where major mitigation is being considered (e.g. high resource allocation to modification or removal projects). Such an approach would present a compromise between the ability to rapidly assign passability scores to a large number of barriers (e.g. using the SNIFFER protocol) and the ability to more accurately consider biotic and environmental factors influencing fish passage at specific sites. Telemetry studies also provide additional information such as fish space use (e.g. Kerr et al., 2023) and diurnal activity (e.g. Tummers et al., 2018), which can be useful for optimising planned mitigation strategies.

The positive relationship between empirically derived fish passage data and SNIFFER but not ICE passability scores may relate to several factors. First, there are fundamental differences between the protocols in how the passability scores are derived. For example, far fewer physical measurements are required for ICE because hydrodynamic equations and modelling are used to set specific physical thresholds (e.g. head height and slope) above which velocity is estimated to restrict fish passage based on known swimming and leaping capabilities of given species. SNIFFER also requires additional subjective characteristics (e.g. level of turbulence, presence of debris) to be defined, which can have an important influence over the final passability score. Such subjective assessments are not included in the ICE protocol. These factors make the ICE protocol faster to complete but potentially may compromise accuracy. Second, it may be unsurprising that there was no correlation between empirical fish passage data and ICE passability scores because of the geographical location of the river infrastructure assessed in this study. All were located in the UK, which is outside of the region where the protocol was developed and field-tested, which may have biased the results. Although the ICE protocol enables passability scores to be generated for the same species as SNIFFER, intraspecific differences in the swimming performance of different populations of fish do occur (Jones et al., 2020) and might have contributed towards differences in the swimming thresholds used (e.g. adult trout can pass depths 5 cm shallower in SNIFFER than ICE) and hence scores generated by each protocol. Third, the ICE protocol was designed to be undertaken during the peak migration period for each fish species assessed. It is possible that the protocol performs sub-optimally when used outside of these periods (e.g. due to differences in discharge) and that this contributed towards the result obtained in this study. Until further validation, we suggest caution when planning data collection so that the information is collected under the intended conditions as this may reduce the chances of inaccurately informing prioritisation models used by decision makers.

The key conclusion of this study is that the suite of protocols and tools developed to aid catchment-scale river management need to undergo an iterative process of validation and improvement. This is required to ensure that outputs (data) used to underpin decision-making accurately reflect the degree of environmental impact investigated, in this case the impediment to upstream fish passage caused by river infrastructure. To improve the quality of data derived from these protocols, a number of management recommendations are provided as follows:

1. Thorough validation against empirically derived fish passage data should be undertaken for a wider range of species/ life-stages, barrier types, environmental conditions and geographical locations,
2. As rapid barrier assessment protocols undergo iterative validation and improvement, user feedback should be incorporated into the process to improve efficacy and reliability of outputs,
3. Assessment of the reliability of outputs when data are collected under conditions that deviate from protocol recommendations to understand limits of their use,
4. Targeted quantitative assessments (e.g. using telemetry) should complement information obtained by rapid barrier assessment protocols so that biotic and environmental factors influencing fish passage can be understood and factored into decision making at sites where major mitigation is being considered,
5. There should be international collaboration to develop rapid barrier assessment protocols efficiently to enhance the transfer of best practice and reduce the potential for duplication of effort.

CRediT authorship contribution statement

Andrew S. Vowles: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **James R. Kerr:** Writing – review & editing, Visualization, Software, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Paul S. Kemp:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andrew Vowles reports financial support was provided by EU Horizon 2020. Paul Kemp reports no financial or actual ongoing involvement in the use of the SNIFFER Protocol despite being part of the initial development team. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data supporting this article are available from the University of Southampton repository at doi: https://doi.org/10.5258/SOTON/D2953.

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