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Research article

Collaboration between fish passage scientists and engineers: Insights from an international questionnaire

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ABSTRACT

Fish passage science and practice seeks to facilitate the movement of fish around obstacles in their habitat, primarily through the construction of fishways and culverts. Successful implementation of fish passage requires collaboration between groups with very different backgrounds and expertise, including knowledge-producers (scientists who study fish passage and related topics such as fish swimming ability) and knowledge users (engineers who apply that knowledge to design fish passage solutions). To investigate the nature of collaboration between these groups, we surveyed fish passage scientists and engineers from around the world. Respondents were asked about the importance of collaboration, mechanisms of collaboration, potential barriers to collaboration, and how collaboration can be improved. Both fish passage scientists and engineers reported high importance of collaboration and that they collaborated frequently with the other group. Respondents reported that consultation with other professionals (of their discipline and the other) was the most important means of obtaining and sharing information related to fish passage science and engineering. Both groups also tended to over-estimate their knowledge and use of the other's discipline. While respondents reported high engagement in collaboration, key themes emerged with respect to barriers to collaboration and means of improving collaboration. These included lacking a shared understanding of both disciplines, professional differences, insufficient institutional support, and inadequate sharing of knowledge (e.g., reporting and publishing). Opportunities for improving collaboration identified by respondents included 1) more interdisciplinary opportunities that facilitate interaction (particularly conferences and workshops); 2) promoting collaborative projects and interactions between fish passage scientists and engineers on project teams; and 3) ensuring that information is shared between groups (e.g., through accessible publications). Findings from this research have the potential to enhance collaboration between scientists and engineers, to the benefit of fish passage and fish populations.

1. Introduction

Fish passage involves the creation of structures that allow fish to move freely among habitats (Clay, 1995). Given the complexity of this task, the science and practice of fish passage is inherently interdisciplinary and requires experts in a range of disciplines including, but not limited to, engineering, hydrology, ecohydraulics, fish behaviour, fish physiology, and movement ecology (Silva et al., 2018). While this science and practice of fish passage is still developing, overall, fish passage solutions have failed to fully restore the connectivity associated with that of a pre-impacted, free-flowing river (e.g., Pompeu et al., 2012; Cooke et al., 2020a). Recent reviews on the performance of fishways indicate that both up and downstream passage success through a fishway can be highly variable, but is generally low overall (Bunt et al., 2016; Noonan et al., 2012; Hershey, 2021; but see Keefer et al., 2021). Indeed, there are now hundreds of studies that have been conducted to understand individual-level performance of fish passage systems, and, in many cases, why they are ineffective. Yet, why the accumulation of so much information has not yielded better passage outcomes remains unclear (Kemp, 2016). Few studies have systemically examined fish passage as a science and practice to understand the factors leading to these shortcomings.

Interdisciplinary areas of research and practice provide additional challenges with respect to communication and collaboration among

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individuals of different backgrounds (Campbell, 2005; Cooke et al., 2020b). This can lead to the so-called 'knowledge-action-gap' whereby information is produced that is either not relevant to inform decision-making or decision-makers fail to identify, adopt, and implement the findings of relevant science (discussed in Lauber et al., 2011; Cook et al., 2013). It is widely accepted that decision-making should be based off of the best available evidence, but often conservation decisions remain experience-based (Pullin et al., 2004; Sutherland et al., 2004; Walsh et al., 2015). Further, perceptions on what constitutes 'best available evidence' can differ across organizations with respect to fish passage (Vogel et al., 2020). Although there are likely multiple reasons for poor fish passage outcomes (e.g., weak environmental legislation, lack of context-specific science), it is reasonable to suggest that knowledge movement and collaboration among fish passage professionals is a potential factor. Specifically, fish passage requires collaboration between scientists that generate and apply knowledge to fish passage projects and engineers that use that knowledge to design and build fish passage structures. To be clear, there can also be knowledge generation conducted by engineers (e.g., generating computational fluid dynamic models to understand hydraulics) but by and large these two domains exist with the knowledge generation domain dominated by scientists and the practice domain by engineers. There are many academic and professional differences between scientists and engineers, including in their training, values, and methods of thought (Blade, 1963), and these differences are likely to impact how these groups use information and how they collaborate with one another (Pinelli 1991). Given the complexity of fish passage, it is critical that the collective community of fish passage experts share knowledge and work together (Silva et al., 2018).

To improve the outcomes of fish passage, there is a need to identify barriers to both knowledge exchange and mobilization as well as potential means of overcoming these barriers (Nguyen et al., 2017). We conducted an international questionnaire of fish passage scientists and engineers to better understand the extent of collaboration and knowledge dissemination between these two groups, as well as perceptions on the mechanisms behind, value of, and reasons for these practices. Additionally, perspectives on obstacles to disseminating information and potential means of improving knowledge exchange between these groups were identified. Findings from this work have the potential to decrease the 'knowledge-action gap' with respect to fish passage, to the benefit of aquatic organisms that are dependent on effective fish passage structures.

2. Methods

2.1. Distribution

The online questionnaire was designed using the freeonlinequestionnaires.com platform and was distributed with the goal of reaching fish passage scientists and engineers from around the world. The questionnaire was shared through the Fish Passage conference contact list maintained by the Fish Passage Conference Steering Committee. Fish passage scientists and engineers were also identified through Google searches using the terms *fish passage*, *scientists*, *engineers* and a geographical descriptor such as *Australia* (all search terms in English). Based on this search, we distributed the questionnaire to individuals from 29 different organizations (e.g., American Fisheries Society – Bioengineering Section, International Hydropower Association, International Association for Hydro-Environment Engineering and Research, Kleinschmidt Group). This included a mix of organizations that focused more on the science or engineering aspects of fish passage. The survey was also shared via social media (Facebook and Twitter).

We encouraged all recipients of the invitation to share it with others within their fish passage network. This purposive snowball-style recruitment (i.e., encouraging participants to refer the survey to others; Penrod et al., 2003) was necessary as it was not possible to gain access to a single comprehensive list of scientists and engineers involved in fish passage. While some have been critical of online snowball-style surveys (e.g., Duda and Nobile, 2010), there have been many recent efforts to test the validity of this method (e.g., Baltar and Brunet, 2012; Brickman Bhutta, 2012; Kosinski et al., 2015; Forgasz et al., 2018; Schneider and Harknett, 2019). The non-random sampling approach reduces the likelihood that the questionnaire respondents are representative of a larger population (Szolnoki and Hoffmann, 2013). However, online snowball-style surveys can be highly effective for accessing subpopulations that may be missed with random or stratified-random sampling (Brickman Bhutta, 2012; Schneider and Harknett, 2019) such as fish passage scientists but especially engineers.

The survey was available from October 6th, 2020 until January 6th, 2021. The survey was only available in English which undoubtedly introduces bias into an international survey. We did not have the resources to properly translate the survey and responses into other languages. We acknowledge this shortcoming which is common in such studies and suggest that an international consortium of researchers could undertake such a survey in the future. A research ethics application was completed and submitted to the Carleton University Research Ethics Board B (CUREB-B), and the project was granted ethical clearance on July 22, 2020 (Project #113204).

2.2. Questionnaire questions

The questionnaire first asked respondents to identify as a fish passage scientist or a fish passage engineer, with corresponding definitions to inform this response. Each group was then asked a similar, but distinct, set of questions pertaining to collaboration with the other group on fish passage projects. The questionnaire consisted of 18 questions (with one additional question for scientists related to methods of knowledge sharing), which included two demographic questions, all of which were optional. Most of the questionnaire consisted of Likert-style or close-ended questions pertaining to the frequency of collaboration, reasons for collaboration, knowledge and use of the other group's discipline, and methods of knowledge transfer. When applicable, respondents were provided with an open-ended 'other' option. The final four questions of the questionnaire were open-ended and sought perspectives on obstacles to disseminating information and methods of improving understanding and knowledge exchange (for all questionnaire questions and summary tables of results see Appendix A1).

2.3. Statistical analysis

Two questions were identified after distributing the questionnaire that lacked clarity or included a typographical error. Question 11) "At what stage of a fish passage project are fish passage engineers [scientists] consulted?". This question allowed respondents to select all that apply, but this was not clearly indicated in the question. We present these results given this uncertainty, and analyze the responses of the subset of the respondents that selected multiple responses (and therefore knew that they could select all answers that applied). The second question pertained to question 10) for engineers, who were asked to rate the importance of the following; "Collaborating with fish passage **engineers** results in higher quality outcomes", which should have read "Collaborating with fish passage **scientists** results in higher quality outcomes". Given the theme of collaboration between scientists and engineers throughout the questionnaire, we suspect responses to this question reflect engineers' perspectives on collaboration between these two groups and present this information below. Irrespective of the response to this question, we believe responses to other questions within the questionnaire (Q7, 8, and 9) indirectly indicate whether fish passage engineers tend to value collaboration with fish passage scientists.

Free responses to questions pertaining to barriers to collaboration and means of improving knowledge exchange were analyzed in NVivo

12 using inductive thematic coding, as in Thomas (2006). Codes were first designated by identifying recurring themes in a subset of questionnaire responses, these codes were then added to and refined upon reviewing further responses (ie. inductive coding). This process was repeated until a final list of codes was created, which was then applied to the full list of responses to each question. Each response could contain more than one reference (i.e., unique points), and each of these references were coded independently by two study authors. After an initial scoring by both authors, score consistency was moderate (~50%). Similar codes were then combined, and the remaining references that were scored inconsistently were rescored by both reviewers. Prior to the second round of scoring, authors discussed the code structure to ensure codes were interpreted consistently. Scoring consistency improved (~85%), and all remaining references scored inconsistently were assigned to both codes. Separate multinomial regressions were completed with *barriers to disseminating fish passage information* and *potential means of improving knowledge exchange* as dependent variables and *age* and *number of professional years in fish passage* as independent variables. For these analyses, responses of scientists and engineers to both questions pertaining to *barriers to disseminating fish passage information* were pooled, as were their responses to the question pertaining to *improving knowledge exchange.* Only codes comprising more than 5% of the total responses to those questions were included, and p-values were corrected for false discovery rate. Differences in these two dependent variables were then compared across continents using a Chi-square test. Only Europe and North America had enough references to be included in these analyses, with most responses coming from the United States, Canada, and Germany. Statistical analyses were conducted in 'R' Statistical Software (R Core Team, 2021). Summary statistics are presented as mean ± standard deviation unless otherwise specified. Standard deviation values should be interpreted as a relative measure of dispersion in the dataset rather than an absolute measure given that the upper bound of the Likert-scale (5) may be surpassed by the sum of the mean and standard deviation.

3. Results

3.1. Overview

There was considerable diversity in age and experience amongst fish passage scientists (n = 123) and engineers (n = 60) responding to the questionnaire (Table 1). Respondents included fish passage professionals from 23 countries including those in North and South America, Europe, Oceania, and Asia (Table A1), though most fish passage scientist (47%) and engineer (62%) respondents were from the United States.

3.2. Collaboration

Scientists and engineers were similar with respect to self-reported frequency of collaboration with various groups (Table 2; Table A2). Both scientists and engineers reported almost 'always' collaborating with government on fish passage projects, followed by collaboration 'occasionally' or 'often' with the private sector. Scientists reported collaborating with academics more frequently than engineers did.

Table 1
Demographic information for fish passage scientists (n = 123) and fish passage engineers (n = 60). Data are presented as median (min-max).

Group	Age	Year in fish passage	Peer reviewed publications	Fish passage projects
Scientist	46 (25–82)	15 (1–35)	3 (0–50)	10 (0–300)
Engineer	49 (27–81)	12 (1–39)	1 (0–20)	20 (1–1000)

Table 2
Comparing mean ± SD responses of fish passage scientists (n = 124) and engineers (n = 59) with respect to the frequency of collaboration with various groups on fish passage projects.

How often do you collaborate with the following groups on fish passage projects? Never (1), rarely (2), occasionally (3), often (4), always (5).

Group	*Scientists*	*Engineers*
Government	4.21 ± 1.01	4.64 ± 0.74
Private	3.51 ± 1.10	3.62 ± 1.04
Academia	3.41 ± 1.10	2.90 ± 1.20
Industry	3.34 ± 1.33	3.03 ± 1.33
NGO	2.99 ± 1.06	3.13 ± 1.29
Community groups	2.82 ± 1.09	2.81 ± 1.17

Overall, it was reported that the least frequent fish passage collaborations occurred with NGOs and community groups, which were reported to occur 'occasionally'.

Most fish passage scientists (92.8%; n = 125) and engineers (91.5%; n = 59) reported having contacted the other group to seek their expertise. Fish passage scientists (2.94 ± 0.77) and engineers (3.24 ± 0.79) reported that they 'often' collaborated with the other group on fish passage projects (Table A3). When asked to select all that apply, fish passage scientists reported seeking out collaborations with fish passage engineers because *fish passage engineers can help shape research questions* (38%), *fish passage engineers can help produce interdisciplinary research* (55%), and *collaboration may increase the likelihood that research findings are adopted by fish passage engineers* (58%). Most fish passage engineers reported seeking out collaborations with fish passage scientists because *fish passage scientists can provide information on local species relevant to fish passage (e.g., fish behaviour)* (72%), *fish passage scientists can provide insight on the effectiveness of various design alternatives* (70%), and *fish passage scientists can conduct post-design monitoring* (70%).

Both fish passage scientists and engineers reported a high frequency of agreement that *collaborating with fish passage engineers results in higher quality outcomes,* that both groups *know who and where to contact* individuals of the other discipline, and that *funders encourage collaboration* (Table 3). Both groups tended to self-report higher levels of understanding of the other group's discipline than the other group reported

Table 3
Comparing mean ± SD responses of fish passage scientists (n = 123) and engineers (n = 57) with respect to collaboration on fish passage projects.

Please indicate the degree to which you agree/disagree with the following statements. Your answer choice should most accurately reflect your view of each statement. Strongly disagree (1), disagree (2), neutral (3), agree (4), strongly agree (5).

Scientists			*Engineers*
Fish passage engineers understand the ecology and biology of fish	3.02 ± 0.94	4.35 ± 0.94	I understand the biological aspects of fish passage science such as fish ecology and biology
I understand the engineering aspects of fish passage design such as hydraulics and construction	4.12 ± 1.02	3.62 ± 1.04	Fish passage scientists understand fish passage engineering and construction
Fish passage engineers are using fish passage science/research to design fishways	3.96 ± 0.95	3.92 ± 1.11	Fish passage scientists use principles of fish passage engineering in their research
Collaboration would delay project completion	1.92 ± 1.02	2.05 ± 1.05	Collaboration would delay project completion
I know who and where to contact fish passage engineers	4.33 ± 0.93	4.45 ± 0.75	I know who and where to contact fish passage scientists
My funders encourage collaboration	4.29 ± 1.02	4.17 ± 1.12	My funders encourage collaboration
Collaborating with fish passage engineers results in higher quality outcomes	4.58 ± 0.67	4.73 ± 0.58	Collaborating with fish passage engineers results in higher quality outcomes

them understanding. Both scientists and engineers tended to agree that the other group uses principles of fish passage engineering and fish passage science (respectively) during fish passage projects. Both groups reported disagreement with the statement *collaboration would delay project completion.* Almost all fish passage scientists reported collaborating with fish passage engineers during the earliest stages of research (95–98%; n = 124) and similarly almost all engineers reported collaborating with fish passage scientists during the earliest stages of fish passage construction (93–95%; n = 59). Scientists collaborating with engineers during multiple stages of research tended to collaborate a similar amount during data collection (87%; n = 45) and post-data collection stages (84%; n = 45). Engineers collaborating with scientists during multiple stages of research tended to collaborate less with scientists during the construction phase (70%; n = 30) than during the post-construction phase (90%; n = 45). These estimates of collaboration in the latter stages of fish passage projects are most likely overestimates given the error in question phrasing (see *Statistical Analysis* section), but nonetheless indicate that collaboration is most common during the earliest stages of fish passage projects, and least common during the construction phase.

3.3. Sources of knowledge transfer

Overall, both fish passage scientists and engineers reported high importance of several sources of information (Table 4). Both groups reported that the most important means of learning about a discipline was through consultations with professionals of that discipline. However, fish passage scientists did tend to report slightly higher importance of consultations with other fish passage scientists than engineers when seeking information about fish passage engineering. Both groups tended to agree that technical reports are a more important source of engineering information than peer-reviewed manuscripts. Scientists reported greater importance of peer-reviewed manuscripts when seeking information on fish passage science than engineering. Both groups reported that personal experience had similar importance to technical reports and had higher importance than fish passage science conferences. Fish passage science conferences were reported as the least important source of information (though most respondents still agreed these conferences were an important source of information). Fish passage scientists reported high importance of multiple different means of sharing information with fish passage engineers (Table 4). Consultations with fish passage engineers and technical reports had the highest reported importance, with conference or workshop presentations having the lowest reported importance.

Table 4
Comparing mean ± SD responses of fish passage scientists and engineers with respect to fish passage information seeking.

	When you do seek information about fish passage science, how important are each of these sources of knowledge? Very unimportant (1), unimportant (2), neutral (3), important (4), very important (5).		When you do seek information about fish passage engineering, how important are each of these sources of knowledge? Very unimportant (1), unimportant (2), neutral (3), important (4), very important (5).	
Source	*Scientists (n = 124)*	*Engineers (n = 58)*	*Scientists (n = 121)*	*Engineers (n = 58)*
Consultations with fish passage scientists	4.48 ± 0.63	4.67 ± 0.63	4.54 ± 0.64	4.58 ± 0.86
Consultations with fish passage engineers	4.00 ± 0.93	4.42 ± 0.83	4.44 ± 0.73	4.71 ± 0.53
Peer-reviewed manuscripts	4.48 ± 0.67	4.44 ± 0.82	3.94 ± 1.01	4.22 ± 0.83
Personal experience	4.35 ± 0.74	4.33 ± 0.90	4.38 ± 0.84	4.65 ± 0.63
Technical reports (local to international)	4.25 ± 0.70	4.45 ± 0.70	4.36 ± 0.73	4.53 ± 0.60
Attendance at a fish passage science conference	4.08 ± 0.92	4.02 ± 0.89	3.98 ± 0.92	3.98 ± 1.02

If you did a **fish passage science study**, how important do you think each of these strategies is for sharing your work with **engineers**? Very unimportant (1), unimportant (2), neutral (3), important (4), very important (5).

Source	*Scientists (n = 126)*
Consultations with fish passage engineers	4.16 ± 0.76
Peer-reviewed manuscripts	3.95 ± 0.94
Technical reports (local to international)	4.06 ± 0.80
Conference or workshop presentations	3.90 ± 0.84
Co-producing research together	4.13 ± 0.85

3.4. Barriers to disseminating information

There was high consistency between scientists and engineers with respect to the barriers to disseminating information on fish passage science and engineering (Table 5; Table A6). Barriers to disseminating fish passage science and engineering information were also similar. Overall, responses referring to collaboration barriers were more common than those referring to communication and knowledge exchange barriers. Engineers more commonly referred to knowledge exchange barriers than scientists while scientists more commonly referred to collaboration barriers as an obstacle to disseminating fish passage science. Respondents most often referred to a lack of shared understanding of both disciplines, followed by professional differences (methodology, endpoints, priorities), lack of willingness to collaborate/mutual respect, and lack of support (time, funding) as specific collaboration barriers influencing the dissemination of fish passage science and engineering information. The most common communication barrier referred to within responses was the 'choice of terminology and the use of jargon', while the most common knowledge exchange barrier was a 'lack of information sharing (e.g., reporting, publishing)'.

3.5. Improving understanding

Fish passage scientists most often reported that sharing information on 'fish passage biology' (34% of all scientist references) and 'general fish biology' (20%) with fish passage engineers would be the most beneficial to improving their understanding of fish passage scientists' approach to addressing river connectivity issues (Table 6; Table A7). Examples of 'fish passage biology' included understanding of fish behaviour in fishways and recognition that passage performance is context-specific. Examples of 'general fish biology' included understanding of life-history events and swimming capacity of fishes. Scientists also reported that sharing information on 'design principles' (10%) and on the 'variability of biology' (8%; ie. biology is difficult to study, and much is unknown). Fish passage engineers most often reported that sharing information on 'engineering constraints' (40% of all engineer references), 'general engineering principles' (26%), and 'fish passage engineering principles' (23%) would be the most beneficial to improving their understanding of fish passage engineers' approach to addressing river connectivity issues. Examples of 'engineering constraints' included understanding that designs need to be constructible and that money allocated to fish passage is dependent on the project budget. Examples of 'general engineering principles' and 'fishway engineering principles' included understanding of hydraulics and the fishway design and validation process. A small number of fish passage scientists and engineers reported that increasing recognition that fish

Table 5
The percentage of all fish passage scientist and engineer references pertaining to various codes related to the topic of barriers to disseminating information about fish passage.

Similarly, what obstacles, if any, are there to disseminating information about fish passage science from fish passage scientists to fish passage engineers?

Code	Scientists (n = 160)	Engineers (n = 65)
Collaboration barriers	**67%**	**48%**
•lack of shared understanding *(lack of knowledge pertaining to the other discipline)*	24%	20%
•professional differences *(methodology, endpoints, priorities)*	16%	11%
•lack of support *(insufficient time, money)*	6%	5%
•lack of willingness to collaborate and/or mutual respect *(lack of respect/interest for others discipline or no effort to collaborate)*	11%	6%
•lack of shared workspaces *(separation in terms of working spaces, projects, or project phases)*	4%	
•networking issues (*difficulty knowing and reaching members of the other profession*)	2%	2%
Communication barriers	**16%**	**14%**
•complex terminology and use of jargon *(use of complex language and use of shared terms with different meanings)*	8%	3%
•scientific recommendations not being framed in engineering contexts	2%	3%
•lack of language translation *(information not available in native language)*	1%	3%
Knowledge exchange barriers	**14%**	**29%**
•lack of information sharing (e.g. *reporting, publishing)*	5%	12%
•interdisciplinary opportunities (events, platforms)	4%	5%
•knowledge gaps *(where information has yet to be produced that would help inform fish passage decision-making and/or engineering)*	2%	6%
•literature access barriers	2%	3%
None	**3%**	**9%**

Similarly, what obstacles, if any, are there to disseminating information about **fish passage engineering** from **fish passage engineers** to **fish passage scientists?**

Code	*Scientists (n = 130)*	*Engineers (83)*
Collaboration barriers	**57%**	**52%**
•lack of shared understanding *(lack of knowledge pertaining to the other discipline)*	19%	25%
•lack of support *(insufficient time, money)*	5%	6%
•lack of willingness to collaborate and/or mutual respect *(lack of respect/interest for others discipline or no effort to collaborate)*	11%	8%
•professional differences *(methodology, endpoints, priorities)*	11%	5%
•networking issues (*difficulty knowing and reaching members of the other profession*)	5%	2%
•shared workspaces *(separation in terms of working spaces, projects, or project phases)*	4%	1%
Communication barriers	**22%**	**22%**
•complex terminology and use of jargon *(use of complex language and use of shared terms with different meanings)*	11%	8%
•lack of explanation for engineering design choices	4%	1%
•engineering ideas not linked to biology	3%	6%
•lack of language translation *(information not available in native language)*	1%	1%
Knowledge exchange barriers	**15%**	**23%**
•lack of information sharing (e.g. *reporting, publishing)*	4%	16%
•interdisciplinary opportunities (events, platforms)	6%	2%
•literature access barriers	3%	–
•knowledge gaps *(where information has yet to be produced that would help inform fish passage decision-making and/or engineering)*	1%	4%
None	**6%**	**3%**

Table 6
The proportion of all fish passage scientist (n = 137) and engineer (n = 43) references pertaining to various codes related to improving understanding of their respective field's approach to addressing river connectivity issues.

If you were talking to a fish passage engineer that knows little about fish passage science, what one piece of information would you like them to know about your field that would improve their understanding of your approach to addressing riverine connectivity issues?

Code	Scientists
Improved understanding of fish biology and passage	**82%**
•fish passage biology *(links between fish biology and passage)*	34%
•general fish biology *(fish biology, not relating to fish passage)*	20%
•design principles *(foundations of effective design)*	10%
•fishway purpose *(reasons for and goals of fishways)*	6%
•fish passage is imperfect *(fish passage is imperfect, not all fish pass)*	6%
•benefits of river connectivity	5%
Improved understanding of general biology	**10%**
•biology is variable *(biology is difficult to study, and much is unknown)*	8%
Interdisciplinary teams	**4%**
Information sharing	**3%**
None	**1%**

If you were **talking to a fish passage scientist** that knows little about **fish passage engineering**, what one piece of information would you like them to know about your field that would improve their understanding of your approach to addressing riverine connectivity issues?

Code	*Engineers*
Improved understanding of engineering	**89%**
•engineering constraints *(recognition of the constraints that engineers face in doing their job;* e.g. *funding, timing, building constraints)*	40%
•general engineering principles	26%
•fishway engineering principles *(*e.g. *hydraulics of fishways)*	23%
Interdisciplinary teams	**9%**
Improved understanding of fish biology	**2%**

passage requires interdisciplinarity was most important to improving understanding.

3.6. Improving knowledge exchange and communication

Fish passage scientists and engineers had similar responses pertaining to improving knowledge exchange and communication between the two groups. Improvements pertaining directly to knowledge exchange were most frequently reported by scientists (44% of all scientist references) and engineers (54% of all engineer references), followed by improvements relating more so to collaboration and communication. More specifically, both scientists (25%) and engineers (39%) most frequently reported a need for interdisciplinary opportunities which included conferences (16%), workshops (5%), and webinars (3%). Other responses related to the formation of collaborative projects and interdisciplinary teams (20%), improving publishing efforts (10%), and more frequent communication (10%), training (7%), and professional appreciation (5%), among others (Table 7; Table A8). Neither the *barriers to disseminating fish passage information* nor the potential means of *improving knowledge exchange* reported tended to vary across respondents of different ages or based on their number of professional years working in fish passage (all $p > 0.19$; Table 8). The responses pertaining to *barriers to disseminating fish passage information* did not vary significantly between respondents from Europe and North America ($\chi^2 = 11.07$, n = 208, P = 0.09), though 'choice of terminology and the use of jargon' was more frequently mentioned by respondents in North America (19% vs. 9% of responses) while 'professional differences' were more frequently mentioned by respondents in Europe (25% vs. 13% of responses). Similarly, there was no significant difference in responses pertaining to potential means of *improving knowledge exchange* between respondents from Europe or North America ($\chi^2 = 8.07$, n = 114, P = 0.09), though 'conferences' were more frequently mentioned by respondents in North America (30% vs. 7% of responses) while 'collaborative projects and formation of interdisciplinary teams' were more

Table 7
The proportion of all fish passage scientist (n = 158) and engineer (n = 59) references pertaining to various codes related to improving knowledge exchange and communication between fish passage scientists and engineers.

What can be done to improve knowledge exchange and communication between fish passage scientists and fish passage engineers?		
Code	Scientists	Engineers
Improving collaboration	**42%**	**37%**
•collaborative projects and formation of interdisciplinary teams	20%	22%
•training *(training or education to learn about the other profession)*	8%	5%
•professional appreciation *(respect and trust for the other profession)*	5%	5%
•time and funding	4%	–
•knowledge of professional network	3%	5%
Improving communication	**14%**	**9%**
•more frequent communication	11%	9%
•use of simple language	2%	–
Improving knowledge exchange	**44%**	**54%**
•interdisciplinary opportunities (events, platforms)	25%	39%
•publishing information	9%	12%
•improving monitoring	4%	–
•addressing knowledge gaps	2%	2%

Table 8
P-values for the relationships between age and number of professional years in fish passage with various coded responses of fish passage scientists and engineers related to *barriers to disseminating fish passage information* and potential means of *improving knowledge exchange and communication* between the two groups.

Barriers to disseminating fish passage information	Intercept	Age	Professional fish passage years
•lack of information sharing (e.g. *reporting, publishing)*	0.71	0.93	0.71
•professional differences *(methodology, endpoints, priorities)*	0.68	0.71	0.19
•complex terminology and use of jargon	0.59	0.93	0.19
•lack of understanding of engineering constraints and principles	0.59	0.71	0.93
•lack of understanding of scientific and biological principles	0.59	0.71	0.93
•lack of willingness to collaborate and/or mutual respect	0.59	0.93	0.59
Improvements to knowledge exchange and communication	**Intercept**	**Age**	**Professional fish passage years**
•conferences	0.93	0.93	0.71
•more frequent communication	0.68	0.71	0.59
•publishing information	0.71	0.71	0.59
•training	0.71	0.99	0.93

frequently mentioned by respondents in Europe (48% vs. 29% of responses).

4. Discussion

4.1. On the extent and value of collaboration

Collaboration describes joint effort towards a shared goal (Briggs et al., 2006) during which teams go through periods of knowledge generation, reduction, clarification, organization, and evaluation to build consensus (Kolfschoten et al., 2014). Engineers and scientists differ in their professional approaches, which can influence the way they seek, use, and generate information, and ultimately, collaborate (Pinelli, 1991). From a hydraulic structures engineering perspective (e.g. fishways), there have been calls to improve collaboration by increasing interactions between engineers and other water experts/scientists across organizations (Erpicum et al., 2021). In our study, collaboration between fish passage scientists and engineers was reported to be frequent and of high value, and many interesting perspectives on the state of collaboration in the discipline were shared (Box 1). Both fish passage scientists and engineers agreed that they knew who and where to contact individuals of the other group, that collaboration did not yield delays, that collaboration resulted in higher quality outcomes, and that funders encouraged collaboration. It was also reported that almost all scientists and engineers engaged with members of the other group during the earliest stage of fish passage projects, and commonly throughout all stages of projects. Early collaboration is key to the success of interdisciplinary projects as it allows all sides to present and explore the full range of possible approaches to the problem including any assumptions related to the issue and assumed objectives (Campbell, 2005).

It is also important to recognize the diversity of organizations involved in fish passage collaborations, and that scientists and engineers are just two of the many actors involved in the process. Scientists and engineers both reported collaborating with other groups either occasionally or often, which included government, the private sector, academia, industry, NGOs, and community groups. Both groups reported the lowest frequency of collaboration with community groups (e.g., anglers, Indigenous groups), which is troubling given that these are typically the primary users of fisheries' resources. Given the value of collaborative community-driven restoration (Lenhart, 2003; Reyes-García et al., 2019; Baumgartner et al., 2021) and the moral imperative (see the UN Declaration for the Rights of Indigenous Peoples) to engage Indigenous peoples it seems prudent that both groups seek to collaborate with community groups and rightsholders more often than 'occasionally' on fish passage projects.

4.2. Fish passage information sources

Both fish passage scientists and engineers reported that all sources of information were at least 'important' when it came to learning about fish passage science and engineering. Both fish passage scientists and engineers reported that consultation between the two groups was the best source of seeking fish passage science and engineering information and scientists also felt this was the most important means of sharing fish passage science information with engineers. This is consistent with findings from a UK survey on information-seeking behaviours that found both scientists and engineers most frequently used colleagues and internal documents as a source of information (Wellings and Casselden 2019). Consultations may be particularly important for engineers, as they prioritize the accessibility of information when choosing information sources (Gerstberger and Allen, 1968; Young and Harriot, 1979). Previous research has found engineers have high reliance on other people and internal documents to obtain information, and that people are a critical source of information because they can outline the rationales underlying certain engineering decisions (Hertzum and Pejtersen, 2000). Indeed, consultation is a valuable means of sharing information provided that the shared information avoids personal biases (Dale, 2015) and is based on scientific evidence (Pullin et al., 2004). Scientists tended to undervalue the importance of peer-reviewed papers and technical reports when it came to sharing their science, compared to the importance engineers assigned to these sources when seeking information about fish passage science. Previous research has suggested that engineers rely less on literature and more on informal sources of information than scientists (Brinberg, 1980), though there was little evidence for this in our study as both groups reported high importance of consultation and personal experience. This may be related to the highly applied nature of 'fish passage' as a discipline, as it has been suggested that applied scientists also rely more on informal information sources (Herner, 1954).

Box 1
Select quotes from fish passage scientists and engineers on the state of collaboration and knowledge exchange between the two groups.

Scientists	Engineers
"… mitigation is not expensive. Loss of ecosystem deliveries is expensive. And the solution lies in collaboration across disciplines and interests."	"In my experience, the largest barrier is culture/politics/money. I often spend my time and resources trying to explain the value of environmental sustainability and fish passage, and spending time on that during a project outside the "typical". Many times it's treated as a regulatory checkmark and not a component to be fully defined and evaluated during design. Often, fish friendly innovations are rejected out of what appears to be fear in favour of conventional, better understood solutions."
"The field of fish passage has too much established dogma, much of which doesn't apply well. Too much emphasis is placed on concrete & steel and not enough on using natural or inducible features such as hydraulics in the way that fish normally behave. Riverine fish live by hydraulics. Engineers tend to work against the fish's natural responses more than with them. For example, the hydraulics around a screening structure can do more to guide fish than screens themselves, as demonstrated by historically fish-safe water withdrawals. Yet the engineers continue to push for criteria of the screen alone, such as approach velocity, through-screen velocity, and pore/slot diameter, which may be minor contributors to fish exclusion. But as a biologist I have had reviewers (engineers) essentially tell me I have no business discussing hydraulics–that's their business. Sad."	"We have found that it really speeds the permitting process to have scientists involved in the design, regulators are much more comfortable approving projects when they know this is occurring."
"There is a woeful lack of options for scientists interested in fish passage to get an education and very little support for academics. To move forward there needs to be more joint education beginning at the undergraduate level so that mutual knowledge, respect and collaboration is incorporated into peoples working style from the beginning of their careers …"	"National guidelines often lag 10 years behind scientific findings and therefore new knowledge cannot be applied as it becomes available."
"I don't think the issue in this field of study is scientist/engineer communication. As state above, the extreme control by agencies and energy companies around this topic, and the need for litigation to prompt actions is almost always the obstacle or limitation on fish passage actions."	"A fish passage engineer is someone who can lead an effort for fish passage in a inter-disciplinary way. For example, fish passage requires integrating disciplines including fisheries/biological science, fish behaviour, hydrology, hydraulics, structural engineering, sometimes mechanical and electrical engineering, etc. A fish passage engineer is not an expert of all these but rather an integrator. Consider it analogous to "Systems Engineering"
"I don't fine as much a separation among fields as 15–20 years ago. I feel like the respect in the importance in multidiscipline collaboration is an accepted part of the practice."	"Collaboration between not only engineers and scientists, but also with resource agencies and public stakeholders starting as early as possible in the design process does not slow a project down, it actually makes it go quicker and more smoothly."
"The best project outcomes that we've achieved have occurred through early and often communication between scientist, natural resource managers, engineers, and the asset owner."	
"The science of fish passage is constantly evolving, and so should we. The distinction between "fish passage scientist" and "fish passage engineer" should at least be deconstructed to a stage where both sides have a basic understanding of what the other is working with (concepts, formulas, ideas) to be able to quickly identify and mitigate arising problems."	
"Our efforts to pass fish have largely failed, so we cannot keep thinking the same way and expect success."	

4.3. Overcoming barriers to disseminating information

Fish passage scientists and engineers reported similar barriers to disseminating information between the two groups. Respondents primarily reported barriers related to collaboration, though communication barriers and knowledge exchange barriers were also mentioned. Further, both groups reported similar approaches to improving knowledge exchange and communication. Shared identification of problems and solutions is critical to effective problem solving (Dostál, 2015), and as such, both scientists and engineers within the fish passage community appear to be well-positioned to improve the state of collaboration, communication, and knowledge exchange within the field.

Scientists and engineers both reported that the most common barrier to the dissemination of fish passage science and engineering information was a lack of shared understanding of both disciplines. Indeed, when asked about barriers to disseminating information about fish passage engineering and science, respectively, references from 20% of engineers and 19% of scientists described the other group lacking knowledge of their discipline or lacking necessary specialized education. Both groups tended to be over-confident in their knowledge of the other's discipline, particularly engineers who 'agreed' they understood fish passage science while scientists were 'neutral' when asked whether they felt engineers understood fish passage science. A lack of shared knowledge is likely to influence collaboration, as common knowledge shared between groups supports further knowledge gain (Hershkowitz et al., 2007). Both groups highlighted particular knowledge gaps that would be most beneficial for the other group to fill to better understand the other groups approach to addressing connectivity issues. Fish passage scientists recommended that engineers learn more about fish passage biology, general fish biology, fish passage design principles, and appreciate that biology is variable and difficult to describe in absolute terms. Scientists mentioned that sometimes engineers "want very specific answers that biology does not always provide easily" and that "engineers tend to want one single set of guidelines with little uncertainty and are generally uncomfortable with the shifting recommendations that ongoing research produces." Fish passage engineers recommended that scientists acknowledge engineering constraints, and improve their knowledge on general engineering and fishway engineering principles. Some of this material could be taught during training courses or through specialized education, both of which were highlighted as important by scientists and engineers. One respondent specifically mentioned a need for "more programs like the one at Umass Amherst-a real fishway engineering program".

Relatedly, fish passage scientists and engineers reported that professional differences (e.g., in methodology, endpoints, and priorities) were an obstacle to collaboration. Indeed, professional differences have been noted as a key barrier to interdisciplinary work in other contexts (Lélé and Norgaard, 2005; Siedlok and Hibbert, 2014). The training, values, and methods of thought can differ between engineers and scientists (Blade, 1963) influencing knowledge dissemination. Pinelli (1991) discussed how the information produced by scientists is not always perceived as useful to engineers. This sentiment was expressed in our questionnaire, as one engineer mentioned "engineers generally operate in the realm of definitives and empirically derived design criteria, which does not mesh well with the broad and often variable nature of biological preferences". It was also stated that "scientists have the difficult task of taking their findings, which are often biological and ecological in nature, and ensuring that the information can be easily interpreted by engineers and potential adjustments to fishway design and operation can be made with relative ease."

Communication approaches by each group were also reported to influence the dissemination of information, such as the use of jargon, which is known to increase risk perceptions and reduce the likelihood that information is adopted by the end-user (Bullock et al., 2019). Many respondents also reported that there was a different 'language' between the two groups, and some noted that shared words often had a different meaning. For example, one scientist stated that "… differences in education/language makes it hard to relate from one field to the other. For example, the entrance of a passage for a fish passage scientist is often the exit of the fish passage for the fish passage engineers". Different technical lexicons can confuse interdisciplinary collaboration (Bruce et al., 2004) and it can take a year or more of collaboration before team members recognize the same definition for words (Naiman, 1999). Several scientists also felt that the priorities of engineers differed, focusing on profit, rather than biological effectiveness. As one scientist stated "engineers don't need to publish and they can build unfunctional fishways and still get new projects from investors. Investors don't care about functionality, so engineers just do whatever, to make the investor happy and get money. The engineers are not held accountable if the fishway does not function. They don't need to listen to scientists." Engineers, however, mentioned that scientists are often unaware of the constraints engineers face, with respect to timing, risk management, constructability, and costs. Part of the problem may also result from an inability for these groups to identify and value the contributions of multiple fields to complex problems (Richter and Paretti, 2009). Indeed, some respondents from both groups felt there was a 'lack of willingness to collaborate', and overall, across both disciplines and groups, respondents more often reported engineers as less willing to collaborate. In general, individuals who are committed, flexible, and agreeable are most likely to successfully undertake interdisciplinary work (Aboelela et al., 2007).

A lack of shared workspaces was also listed as a barrier (primarily by scientists), and often institutional barriers were mentioned. For instance, it was stated that "at some projects, scientists and engineers have to manage different step [sic] of the study and are kept separated by the project holder" and that "at my organization, we use to have several biologists working in our group and then we were re-organized into separate groups based on discipline. This "siloing" approach in some organizations puts up barriers to communication and understanding." Co-locating of fish passage scientists and engineers could be a useful approach for enhancing collaboration (Hesjedal 2022) although practically this is likely to be most achievable for organizations where both professionals work (e.g. government). Many scientists and engineers also suggested that improved and more frequent communication would contribute to improved knowledge exchange, making specific mention to shared meetings, newsletters, and workspaces. Formation of interdisciplinary teams and completion of collaborative projects were also seen as an important means of overcoming barriers to knowledge exchange. For instance, one scientist stated that "project collaboration is far and away the best way to increase communication. The more projects people work on, the more exposure they get to the other end of the discipline". Repeated interaction can build trust in the people and principles of the other discipline, increasing participation in interdisciplinary projects (discussed in Siedlok and Hibbert, 2014). Further, one scientist stated that "in England we have a formal approval process, where a fish pass design has to be approved by a panel of expert fish pass scientists. This ensures communication and cooperation between the designing engineer and fish pass scientist as well as more frequent communication, time, and funding." Legislative models like this (see Armstrong et al., 2010 for more details) are likely to prove useful across other countries.

4.4. Overcoming barriers to knowledge exchange

Fish passage engineers more frequently reported knowledge exchange barriers for both fish passage science and engineering information, and in particular that information was not being shared (e.g. reports, publications). Indeed, it seems as though most fish passage projects that are completed fail to be shared as peer-reviewed publications. For instance, scientists reported having worked on a median of 10 fish passage projects but had a median of just 3 publications. This pattern was even more pronounced for engineers who reported having worked on a median of 20 projects, with just 1 publication (though engineers have less of an expectation to publish information than scientists). Some engineers reported that information was not being produced (ie. no follow-up monitoring), was not reported upon, or was reported but only shared internally. For example, one engineer stated "there are little to no publications made about any passage I'm currently working on. Data is only used for internal review of the passage". As one scientist reported, "There are undoubtedly hundreds of fish passage projects completed a year across North America and Europe, but finding publications is challenging". This issue of producing knowledge but not sharing it has been reported previously for research and development professionals, who tend to have much lower levels of support for knowledge transfer than knowledge production (discussed in Pinelli, 1991). For engineers, the result of their work is a physical structure (that is sometimes documented in written form), whereas for scientists a written publication is the end product (Allen, 1988). It has even been suggested that for engineers, publication of results is the least valued of goals (Ritti, 1971). Engineers mentioned various reasons for this including “a lack of financial/performance incentive for fish passage engineers to produce reports about their work” and mentioned that “It is very difficult to share case studies of projects in private industry given that every phase of the project has some sensitive nature. Whether study, negotiation, design, construction, commissioning, testing, or operations, Owners are rarely ‘comfortable’ discussing the project. Many are even reluctant to celebrate successes if any stakeholder is less than satisfied. We do great work developing elegant solutions to complex interdisciplinary problems, but very little of it is available to present at conferences.” For engineers, there can be norms against free exchange or open access to knowledge for those outside of the organization, in part because of security and proprietary claims to this knowledge (Holmfeld, 1970). In contrast, Holmfeld (1970) argues that scientists have well developed communication systems, providing unrestricted access to information because scientists are rewarded for professional (collegial) recognition. However, some scientists expressed similar sentiments as engineers, stating that “sometimes the information is confidential and/or privileged (particularly when funded by non-government owners and operators of dams or hydroelectric projects).” Herner (1954) mentions that more applied researchers may engage less with those outside their organization and with the scientific literature.

Engineers also mentioned that most information is only available as grey literature, in part because of difficulty publishing engineering information, “Information about fish passage engineering are not easy to publish in peer-reviewed articles, notably because all proposed design criteria and decisions are not always fully supported by results or existing knowledges. But these decisions are necessary to progress and it would be interesting to be able to share it more widely. Consequently, technical guidance mostly remains as reports (grey literature).” On the other hand, scientists reported that grey literature was often not available or difficult to access, or that the academic community was not fully aware of the information available in the grey literature. Acceptance of interdisciplinary research and creation of more interdisciplinary journal outlets may be a useful approach to improving knowledge dissemination (Campbell, 2005). Fish passage engineers called for publications to include more engineering related material. For instance, one engineer called for publications to “include complete description of the design and hydraulic operation of the studied devices”. It seems likely that creating these links between biological effectiveness and design criteria in scientific publications would increase the value of the literature to fish passage engineers. As reported by some scientists, more ‘time and funding’ is needed and this support could help to overcome these publishing barriers, particularly if the funding is dedicated to publishing information. Indeed, it seems unlikely that project owners/funders will provide this support unless information sharing is mandated through legislation. As mentioned by various scientists, there is a need for “government funding of research to be spread openly and freely” and a need for “funding and government agencies to truly recognize that fish passage is a widespread environmental issue and research challenge”.

With respect to improving knowledge exchange, both scientists and engineers frequently mentioned the need for more interdisciplinary opportunities (events, platforms). In particular, both groups called for more conferences, with one engineer saying “Conference presentations are a great way to exchange information, without necessarily publishing papers.” Given that many engineers felt there were not enough incentives in place to publish, conferences are likely to be particularly important for this group to share information. Another collaborative tool that several respondents mentioned from both disciplines was a shared database to store fish passage reports and monitoring results. Creation of such a tool could also make it easier for engineers and scientists in a non-academic setting to share information without having to navigate the laborious peer-review process. Respondents from both groups also reported that webinars and workshops (with an interdisciplinary focus) are important methods of overcoming barriers to knowledge exchange between fish passage scientists and engineers.

4.5. Limitations

It is possible that the overall high levels and positive views of collaboration reported by questionnaire respondents related to how the questionnaire was distributed (i.e., selection bias). Most of the respondents had been recruited through the Fish Passage Conference contact list, which potentially selected more ‘collaborative’ individuals. As such, it is possible we did not reach a representative sample of the two fields. Social desirability bias (i.e., providing a socially-desirable answer rather than one that reflects one’s feelings) also may have contributed to the high rates of collaboration reported (Grimm, 2010), though we were not able to quantify the degree to which this was the case. However, responses to the free-response sections of the questionnaire suggested that fish passage scientists and engineers believe there are numerous barriers to collaboration and disseminating information within the field. It should also be noted that most respondents were English-speaking and from the United States, while many areas of the world where fish passage science and practice are emerging (Wilkes et al., 2018) were underrepresented in our survey. It is possible that greater inclusion of respondents from these areas would have yielded different perspectives on the state of collaboration. In the future, a greater effort could be made to include non-English search terms.

4.6. Conclusions

We surveyed fish passage scientists and engineers from around the world, providing important insights into the state of collaboration and knowledge exchange in this interdisciplinary practice. We found high levels of engagement with and value for collaboration and knowledge exchange. Nonetheless, we identified several perceived barriers to disseminating information, including a lack of shared understanding, professional differences, and a lack information sharing between these groups. Several means of improving knowledge exchange and communication were reported, and we call for the fish passage community to follow these suggestions to ultimately improve fish passage outcomes. At the individual level, there is opportunity for more willingness to collaborate, for students and professionals alike to try and build their understanding of the other’s discipline, to reach out to individuals of the other group, to consider the needs of the other group and how this can shape personal practice, and to support knowledge coproduction and sharing where possible. At the organizational/institutional level, more support is needed to promote and facilitate collaboration, including more interdisciplinary opportunities (conferences, webinars, shared platforms), direct collaborative opportunities (e.g. shared work spaces, projects), and more recognition that improvements to collaboration and knowledge exchange will likely require legislation or funding mechanisms to be implemented.

Finally, it is important to acknowledge that “the link between fish science and engineers has come on leaps and bounds in the last decade and the gap between the two is reducing” as reported by one scientist. This is highlighted by the fact that a small number of respondents specifically reported that they could not think of a single barrier to collaboration/information exchange between fish passage engineers and scientists. Further, some professionals reported that they identified as both fish passage scientists and engineers, and the mere act of having to choose membership to just one of these groups in this questionnaire led to feelings of alienation. We would like to acknowledge the thoughts expressed by these respondents and hope that a major take-away from this study is the need to improve training so that members of this community can act as true interdisciplinary fish passage professionals.

We hope that findings from this work will help to improve the state of collaboration and knowledge exchange in the fish passage community, to the benefit of fish and aquatic ecosystems the world over. We also advocate for further efforts to advance the discipline (Silva et al., 2018), recognizing that improved collaboration and knowledge exchange are just a few aspects of this endeavour.

Credit roles

WMT: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Visualization; Roles/Writing - original draft; Writing - review & editing. SJL: Conceptualization; Data curation; Investigation; Methodology; Software; Supervision; Validation; Writing - review & editing. SJC: Conceptualization; Methodology; Supervision; Writing - review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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