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REVIEWS

The status of fishways in Canada: trends identified using the national CanFishPass database

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Abstract The disruption of river connectivity through the construction of barriers used for hydropower development and water control purposes can severely damage river ecosystems, reduce the quality of fish habitat, and prevent the upstream migration of fishes. Fishways function as a means of passage around barriers for fish migrating both upstream and downstream. In 2009, the CanFishPass project was initiated in a partnership with Fisheries and Oceans Canada and Carleton University to create a searchable database containing specific information on fishways in Canada built to enable upstream passage. In this paper we evaluate the information gathered in the CanFishPass database to identify trends concerning fishways and fish passage in Canada, yielding, we believe, the first national-scale trend analysis related to fishways anywhere in the world. Although CanFishPass may not include all fishways in Canada, our analysis identified 211 which are primarily located along the coasts and along major rivers and water bodies such as the Great Lakes. British Columbia has the largest number of fishways in Canada (62) and Prince Edward Island has the fewest (2). The most popular type of fishway is the pool and weir fishway (85), followed by vertical slot (37) and Denil type fishways (23). Fishway construction has proceeded at a steady rate since the 1970's, although there has been an increase in the number of nature-like fishways since the year 2000. The majority of fishways are installed to pass salmonids in Canada, although some fishways on warmwater systems pass large components of the fish community. Only 9 % of the fishways in Canada have been studied using methods that enable proper evaluation of biological effectiveness. We recommend that evaluations be carried out at new and existing fishways and that these evaluations enable the determination of attraction and passage efficiency. Additionally, we recommend that future fishway projects and evaluations in Canada be advised to submit details of their work to CanFishPass so that knowledge of these fishways is centralized. Similar efforts on a global scale could lead to opportunities to identify patterns in fishway design and biological effectiveness that would ultimately inform decision making and improve connectivity where deemed necessary.

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Introduction

The disruption of river connectivity through the construction of barriers used for hydropower development and water control purposes (irrigation, flood control, and drinking water structures) can severely damage river ecosystems, reduce the quality of fish habitat, and prevent the upstream migration of fishes (Dynesius and Nilsson 1994; Poff et al. 1997; Malmqvist and Rundle 2002). Worldwide, over 45,000 large dams (>15 m) exist (Nilsson et al. 2005) and an estimated 160–300 large dams are constructed every year (Acreman 2001). Barriers regulate 85 of the 113 (77 %) large rivers (discharge before human alteration of $\geq$350 m^3/s) in Canada, the United States, Europe and the former USSR (Dynesius and Nilsson 1994). Migration delays, habitat loss (e.g. spawning and rearing habitat), habitat fragmentation, flow alteration, changes in temperature, ice regime, morphodynamics and water quality, as well as increased exposure to predators are all negative effects that barriers impose on migratory fish populations (Drinkwater and Frank 1994; Larinier 2001; Katopodis and Aadland 2006). The regulation of rivers through anthropogenic activities has led to the decline and even extinction of populations of migratory fish on almost every continent including Europe, Asia, Australia, North America (Larinier 2001) and South America (Oldani et al. 2007).

In an attempt to restore river connectivity and mitigate the effects of dams on fish populations, barriers are often equipped with fish passage facilities, also known as fish ladders or fishways (Clay 1995). Fishways function as a means of passage around barriers for fish migrating both upstream and downstream (Clay 1995). While the engineering aspects of fishway design have been previously explored (see bibliography of Katopodis 1992; Clay 1995; Thorncraft and Harris 1996; Ead et al. 2004; Khan 2006; Rodriguez et al. 2006; Katopodis and Williams 2011), scientific biological evaluations of fishways, especially in the peer reviewed literature, are generally lacking. Indeed, a global review of peer-reviewed articles on fishway effectiveness yielded only 96 papers (Roscoe and Hinch 2010). Roscoe and Hinch (2010) identified that 58 % of studies focused on the passage of salmonids, while comparatively little information exists on fishes that are not commercially or recreationally important. Moreover, many of the evaluations that examine fish passage base their assessment largely on the presence of fish at the top of the fishway, indicating successful ascent (Roscoe and Hinch 2010). What is unknown is the number of fish (or species) failing to find the fishway or do so but fail to ascend the fishway. This lack of information regarding the effectiveness of fishway designs for a wide variety of species makes it difficult for management agencies involved with fish passage development projects to determine which designs are best suited for a given system and species (but see Katopodis and Williams 2011; Bunt et al. 2012; Noonan et al. In Press). In fact, even determining basic information on the number and types of fishways in a given region is challenging as no repository for such information exists.

In 2009, the CanFishPass project was initiated in a partnership with Fisheries and Oceans Canada (a federal government agency with a legal mandate to provide fish passage when needed) and Carleton University to create a searchable database containing as detailed information as possible on as many Canadian fishways as possible built to facilitate upstream passage of fishes. For the purposes of this paper and keeping in line with the goals of CanFishPass the term fishway will refer to passive upstream fish passage facilities. The CanFishPass database was constructed so that it could be continually updated with new information. Where available, the database contains detailed geo-referenced information on engineering and hydraulic specifications as well as the biological effectiveness of fishways (see Hatry et al. 2011). To our knowledge, this is the only such database in the world and therefore serves as a unique resource to understand the diversity of fishways in Canada. In this paper we evaluate the information gathered in the CanFishPass database to identify trends concerning fishways and fish passage in Canada. For example, we detail the geographical distribution of fishways, the types of fishways and species passed, as well as identify information gaps in available fishway information. We conclude by presenting recommendations to strengthen both CanFishPass and fishway science and application in Canada. For the purpose of this paper and the CanFishPass database, it is important to note that culvert-style fish passes have been excluded given that there are thousands of unnamed culverts installed across Canada (Langill and Zamora 2002). The database does cover all other fishway types across a range of barrier sizes.

Methods

Detailed information on the history, design, and structure of CanFishPass is provided in Hatry et al. (2011). As such, we provide only a brief overview of CanFishPass as it relates to populating the database used for the present analysis. Information for CanFishPass was first compiled from an extensive literature search using the following web-based resources: Google Scholar, Fisheries and Ocean Canada (DFO) websites, the WAVES database (DFO online library), American Fisheries Society Infobase, Web of Science, Scopus, Science Direct, hydropower company websites and finally through Google web searches. Searches were not performed with a specifically defined set of search terms; search terms were employed at the discretion of the researcher in a fashion designed to maximize the information returned by the search. Google Scholar searches yielded the highest number of peer reviewed articles while normal Google searches yielded the most grey literature information. Additional information was gathered from a request for information sent out through e-mail to individuals that might have information on fishways in their region. The e-mail was distributed to DFO employees (science and habitat branch), provincial resource management agencies nationwide, environmental consultants, hydropower utilities (directly and via the Canadian Electricity Association), and other government agencies (e.g. Environment Canada, Parks Canada). The database will continue to grow as the database is publicized and new information is forwarded to us. Anyone with knowledge of a fishway in Canada can contribute to the database (after verification by CanFishPass personnel) by providing information to CanFishPass administrators (canfishpass@gmail.com).

For this paper, we included information collected on fishways up to January 1st, 2012. We queried the CanFishPass database to examine patterns in the construction, location, use, and study of fishways in Canada. Our queries included searching the database for fishway location by province (and GPS coordinates when available), fishway type, species passed, date constructed, and type of evaluating study, if any, was conducted. Queries were sorted and basic summary statistics were used to evaluate trends in fishway information. This exercise is largely descriptive and therefore no statistical analyses were conducted.

Findings

Spatial patterns in fishway numbers

In total, the database (as of January 1st, 2012) contained 212 fishways, of which location data (GPS/UTM coordinates) were available for 204. We identified fishways in all of the provinces and territories in Canada except for Nunavut and distinct regional patterns in fishway location are evident (Fig. 1). In the Pacific region many fishways are located on salmon rivers near the coast, particularly concentrated near Vancouver and on Vancouver Island. Further inland fishways are found along Fraser River tributaries as well as along tributaries to lake systems (e.g. Okanagan Lake in the Columbia Basin). A few fishways are located further north in British Columbia on water control structures (for the purposes of this trend analysis the term water control structure refers to a man-made barrier that controls water levels in a water body for purposes other than hydroelectric power generation, for example the Bonaparte Dam, near 100 Mile House). Across Alberta and the Prairie Provinces no real patterns in fishway location emerge; fishways are located at water control structures and hydropower infrastructure across the region. In Ontario, almost all of the fishways (98 %) are located near major water bodies such as the Great Lakes or the St. Lawrence River. Ninety percent of the fishways in Ontario are located in southern Ontario, with the majority in the Golden Horseshoe area around Lake Ontario. Fishways in Quebec are located along the St. Lawrence River and in the James Bay region in northern Quebec. In the Atlantic provinces, fishways are found along the coast on salmon rivers impacted by hydropower infrastructure, water control structures and natural barriers.

Spatial patterns in fishway type

Pool and weir fishways (see Table 1 for a description of fishway type) are prevalent in provinces and territories with coastal or Great Lake shorelines (Fig. 2). This is likely due to both early observational evidence of their ability to pass salmonids (Bruce 1930; Clay 1995) and the numerous salmon streams and rivers in these areas. Newfoundland has the highest proportion of pool and weir fishways (i.e. 96 %) among provinces and territories that have five or more identified fishways. Pool and orifice fishways, similar in design to pool and weir fishways, can be found almost exclusively in British Columbia and are thought to enable the passage of fish with lower or no jumping ability (Clay 1995). Vertical slot fishways are well represented (proportionately by province) across the country and have been shown to be documented passing multiple species at different locations (see Manzer et al. 1985; Schwalme et al. 1985; Pon et al. 2006; Pratt et al. 2009; Thiem et al. 2012). Denil fishways are found primarily in Ontario and Alberta and have also been shown to be effective in passing multiple species (see Schwalme et al. 1985; Katopodis et al. 1991; Bunt et al. 1999, 2001). Nature-like fishways, including rock ramp and pool and riffle designs, are sparsely distributed across the country (proportionately by province) with the lowest values in the Atlantic Provinces. One of the largest, if not the largest rock ramp fishway in the world, is in northern Manitoba (Katopodis and Williams 2011). Eel ladders are located predominantly in Ontario and Quebec along their migration routes on the St. Lawrence River. One fishway, Cootes' Paradise in Hamilton, Ontario, is listed as "other" because of its unique construction, it also allows fish smaller than adult carp (*Cyprinus carpio*) constant upstream access to spawning grounds as well as access to downstream river and lake areas (Royal Botanical Gardens 1998).

Patterns in the type of barriers equipped with fishways

Fishways documented in the CanFishPass database are most commonly installed on very low head barriers (<3 m in head-height) and low head barriers (above 3 m but below 10 m in head-height) (Fig. 3). High head barriers (≥10 m) represented only 7 % of the identified fishways. The most common type of fishway on high head barriers in Canada are pool and weir fishways and the maximum head-height at which a fishway (pool and riffle) was installed is 28.2 m at the

Fig. 1 Distribution of fishways across Canada as determined by the CanFishPass database. Each dot represents an identified fishway. Detailed location data were available for 204 out of 212 fishways

Table 1 Description of fishway types with reference material for fishways found in the CanFishPass database

Fishway type	Description	Reference
Pool and weir	Sloping channel separated by submerged weirs, each at a slightly higher elevation than the one downstream of it. Water moves down the weirs into the resting pools and then over the next weir. Pools dissipate water velocity and can be used by ascending fish as a rest area	See Katopodis 1992; Clay 1995
Pool and orifice	Sloping channel separated by weirs fitted with an orifice in their base; weirs do not have to be submerged. Water can move over the weirs or through the orifice	See Katopodis 1992; Clay 1995
Vertical slot	Sloping channel with baffles fitted with top to bottom opening(s) on one or both sides. Water moves through the openings (slots) in the baffles	See Katopodis 1992; Clay 1995
Denil	Sloping rectangular channel fitted with baffles (also called vanes) installed at 45° angles pointing either upstream (classic Denil) or downstream (steeppass Denil). Water moves through an angular horseshoe shaped opening in the baffle	See Katopodis 1992; Clay 1995
Pool and riffle	Nature-like fishway made up of boulders and rocks arranged in a stair like formation with areas of fast flowing shallower water followed by areas of deeper slower flowing water. Water can pass over the rocks or through holes in between boulders	See Garboury et al. 1995; Katopodis et al. 2001
Rock ramp	Nature-like fishway consisting of boulders secured to dissipate water velocity usually in a "boulder garden" configuration. Water flows around and over boulders	See Katopodis et al. 2001
Eel ladder	Sloping channel containing bristles, plastic tubing, or wood bunched together sitting vertically in the channel. Water is fed down the channel and eels can move up the channel by using the plastic tubing as simulated stairs	See Clay 1995

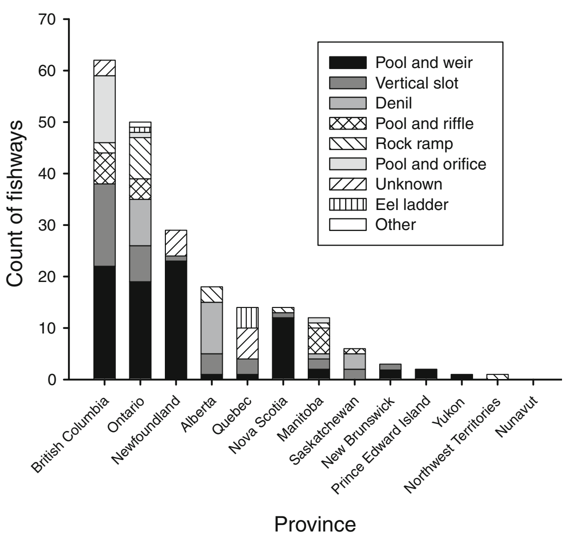

Fig. 2 Count of fishways by province or territory. Conventional-type fishways are displayed in *gray scale* and nature like fishways are displayed with *crosshatching*. Eel ladders were displayed with *vertical crosshatching* to differentiate them from conventional type fishways. One fishway is listed as in the "other" category, this fishway is unique in its design and does not fit into the other categories

Moses Saunders Dam near Cornwall. Difficulties that exist for the installation of fishways on high head barriers are primarily the slope at which the fishway would need to be installed, entrance location and its proximity to the outflow of the barrier, and the cost required to build such structures (Katopodis et al. 2001). Denil, pool and riffle, and rock ramp fishways are most commonly found on very low head barriers; this may be due to the modular nature of the Denil style fishway which does not require much space and the lower costs involved with the construction of nature-like fishways like the pool and riffle and rock ramp fishways (Katopodis 1992; Katopodis et al. 2001). Pool and weir, pool and orifice, and pool and riffle fishways feature predominantly on barriers built for hydropower and hydropower infrastructure, as well as on water control structures and natural barriers such as natural waterfalls and shallow stretches of rivers (Fig. 4). Vertical slot fishways have been installed mainly on water control structures and natural barriers with some installed on hydropower facilities. Conversely, Denil fishways have been built almost exclusively on water control structures.

In Canada, over 900 large dams (>10 m hydraulic-head height) and several thousand smaller dams exist (Canadian Dam Association 2003). Of these thousands of dams, between 450 and 600 of them are fitted to generate hydroelectric energy and least 200 of them are small hydro plants (Environment Canada contends there are 596, while other sources such as Waterpower

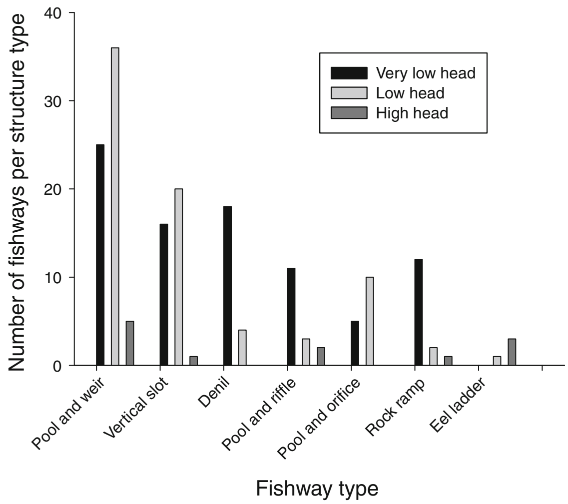

Fig. 3 Number of fishways per dam category for the different types of fishways contained in the CanFishPass database. Dams were separated into three categories; the very low head category contained dams <3 m in head-height, the low head category contained dams equal to and >3 m but <10 m in head-height, and the high head category contained dams equal to and <10 m in head-height. Head-height data were available for 175 of 212 fishways

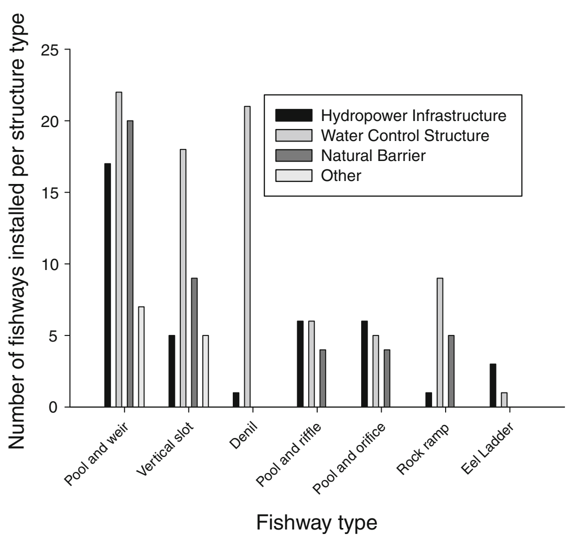

Fig. 4 The number of fishways by barrier type is shown for different fishway designs. The hydropower infrastructure grouping represents fishways that were installed to mitigate the effects of both hydropower dams (n = 28) and natural barriers (n = 11) exposed by hydropower operations. The other grouping consisted of hatchery fences (n = 7) and sea lamprey (*Pertomyzon marinus*) barriers (n = 5)

magazine puts the number closer to 450). Based on these numbers we expected to find a sizable proportion of the fishways we identified to be fitted on hydroelectric dams. We were able to determine the type of barrier associated with 175 fishways. Of those 175, we found only 28 fishways installed directly on hydroelectric dams with an additional 11 fishways installed to bypass 'natural' barriers exposed due to hydropower operations (Fig. 5). We classified natural barriers exposed due to hydropower operations as different than regular natural barriers as they would not be a barrier if there was no impact (lower water levels) from hydropower infrastructure. Pool and weir fishways have been used on the largest variety of dams, both in head-height and function, and are also widely used to try and bypass natural barriers (Fig. 5). Pool and riffle fishways have also been installed on a number of low head dams and barriers, but have also been used to bypass a high head hydropower dam and one high head natural barrier. Vertical slot fishways are used predominantly on water control structures than any other type of barrier, but are also used to bypass a number of natural barriers.

The distribution of the types of barriers fishways are installed on differs by province (Fig. 6). British Columbia and Nova Scotia have the largest number of fishways installed on or for hydropower impacts. Water control structures feature prominently across the country as barriers that are fitted with fishways. Natural barriers in many provinces have had fishways installed to enable fish passage, but these barriers with fishways are mainly found on the coast in order to try and increase the amount of available salmonid spawning habitat (Moores and Ash 1984; Clay 1995).

Temporal patterns in fishway installation

The number of fishways constructed per decade appears to have peaked in the 1970's with approximately 20 per decade up until the end of 2010 (Fig. 7). It should be noted that date of construction data could only be found for 117 of the 212 fishways identified in Canada.

Patterns in biological evaluation and passage documentation

Fishway evaluations in Canada have produced 21 peer reviewed articles describing 24 fishways in the country. The number of fishways with passage or attraction evaluation studies (whether peer reviewed or not) is low (Table 2); 31 of 212 (14.6 %) of

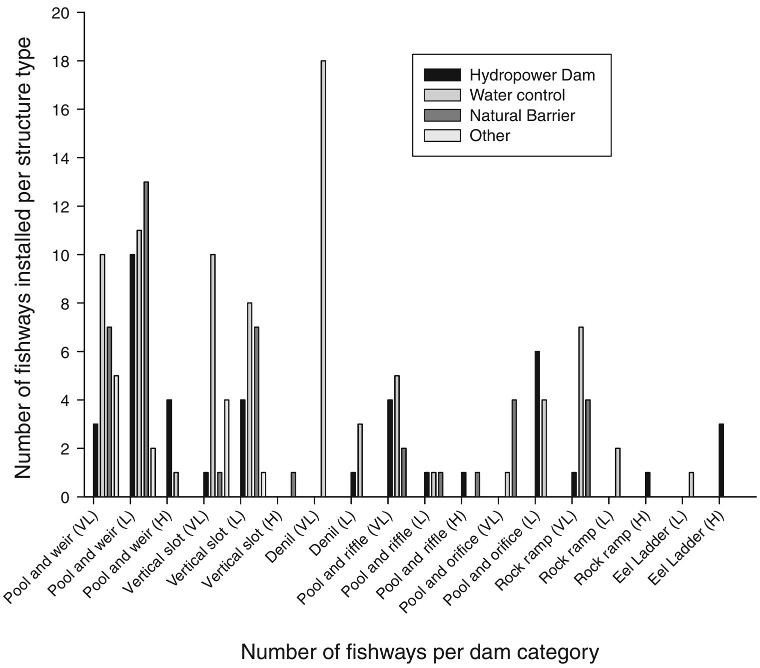

Fig. 5 Number of fishways per structure for different fishway designs at a national level. The hydropower infrastructure grouping represents fishways that were installed to mitigate the effects of both hydropower dams (n = 28) and natural barriers (n = 11) exposed by hydropower operations. The 'other' grouping consists of hatchery fences (n = 7) and lamprey barriers (n = 5). Dams were separated into three categories; the *VL* (*very low head*) category contained dams <3 m in head-height, the *L* category (*low head*) category contained dams equal to and >3 m but <10 m in head-height, and the *H* (*high head*) category contained dams equal to and >10 m in height. Head height data were available for 175 of 212 fishways

fishways have had some form of an efficiency evaluation. In order for the evaluating study to be sorted in the 'yes' category some form of passage efficiency or attraction efficiency study must have been carried out on the fishway. Observational counting data reports were not enough to be considered a true evaluation study, as per Bunt et al. (2012). Another necessary caveat for performance evaluations of fishways, as described by Bunt et al. (2012), is that fishways must be evaluated using some form of electronic tagging (radio telemetry or passive integrated transponder (PIT) telemetry) in order to obtain reliable information on both passage and attraction efficiency. Of the 31 fishways in Canada that have had evaluation studies only 17 of these have had some form of telemetry study performed to evaluate fish passage (Table 1), resulting in 8 % of Canadian fishways having had adequate evaluations and the remaining 92 % categorized as data deficient. Furthermore, where evaluations have been conducted, the majority of these have focused on one or two focal species rather than the entire fish community.

Rainbow trout (*Oncorhynchus mykiss*) are documented passing the most fishways in Canada, followed by Atlantic salmon (*Salmo salar*) (Fig. 8). Salmonids make up the top four species passed at fishways in Canada. Seventy-four species in total have been documented passing upstream at fishways in Canada; for context there are ~242 species of freshwater fish in Canada (Fishbase.org 2012). The Vianney Legendre fishway on the Richelieu River in Quebec passes the largest documented number of fish species (i.e. 36 different species have been documented in traps at the top of the fishway) (Desrochers 2009). The Mannheim weir east bank fishway on the Grand River near Waterloo, Ontario, passes the second largest documented number of fish species (i.e. 26 different species have been documented in traps at the top of the fishway).

Recommendations

Based on our experiences populating CanFishPass we have several recommendations for the future of

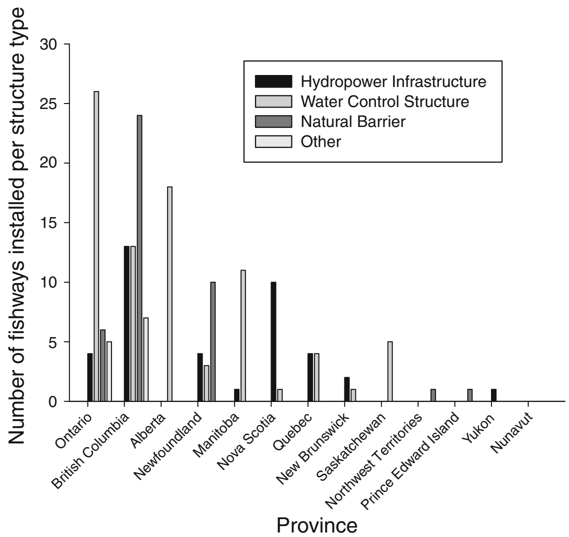

Fig. 6 Number of fishways per structure type for each province. The hydropower infrastructure grouping represents fishways that were installed to mitigate the effects of both hydropower dams (n = 28) and natural barriers (n = 11) exposed by hydropower operations. The 'other' grouping consists of hatchery fences, all of which are in British Columbia (n = 7), and lamprey barriers (n = 5) which are all located in Ontario

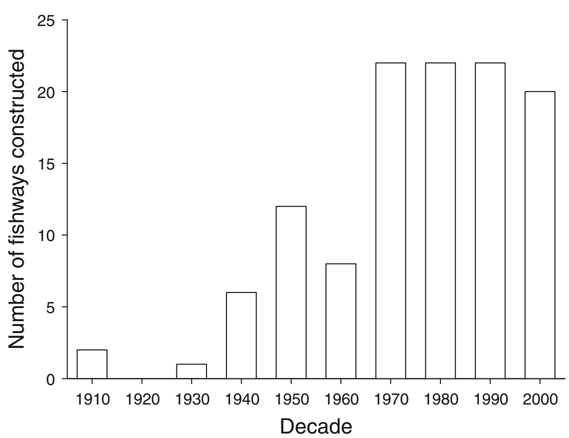

Fig. 7 Number fishways constructed per decade in Canada over the last century. Date of construction was available for 117 of the 212 fishways identified in the database

Table 2 The number of fishway evaluation studies performed on fishways in Canada as determined from the CanFishPass database. Categories listed include fishway evaluation conducted using radio telemetry, PIT telemetry or no telemetry (e.g. counting data)

Technology	Attraction	Passage	Both	Total
Radio telemetry	–	3	12	15
PIT telemetry	–	2	2	4
No telemetry	–	12	–	12

fishway related research and the storage of this information. After the extensive research required to populate the database one concern related to trying to locate pertinent information on biological and engineering aspects of fishways is the inconsistent manner in which fishway related language is used both in the peer reviewed literature and in grey literature. As the Canadian Fisheries Act describes fish passage facilities as both upstream and downstream (Fisheries Act, F-14 s.20 2010) structures we suggest that authors be explicit (e.g. facility is designed as an upstream passageway or downstream passageway) when describing the facilities that they construct or describe through research. In order to focus the related literature we suggest that authors use the following descriptions of passive upstream fishways; Denil, pool and weir, pool and orifice, and vertical slot fishways, as employed by Clay (1995) and Katopodis and Williams (2011), and eel ladders as by Knights and White (1998). Furthermore, we suggest that authors delineate between conventional fishways and nature-like fishways (rock ramp and pool and riffle fishways) as defined by Katopodis et al. (2001).

In addition to standardizing fishway-related language we recommend that researchers work towards standardizing the methods in which fishways are evaluated. Roscoe and Hinch (2010) identified in their review of primary literature fishway articles that the manner in which fishway evaluations were performed had not changed significantly over the past 50 years, and that all of the articles (n = 96) except for one published after 1980 included questions regarding fishway efficiency. This is of interest because a meta-analysis performed by Bunt et al. (2012) aimed at evaluating the upstream attraction and passage efficiency of both peer reviewed and grey literature related to fishway studies found only 19 out of 116 articles satisfied the three criteria necessary for inclusion in their meta-analysis. The three criteria laid out by the authors include individually monitored fish (they recommend monitoring be done using electronic tagging) detected near the entrance to each fishway and detected passing the exit of the fishway, fish actively migrating in a single spawning season, and the evaluation of fish in natural conditions.

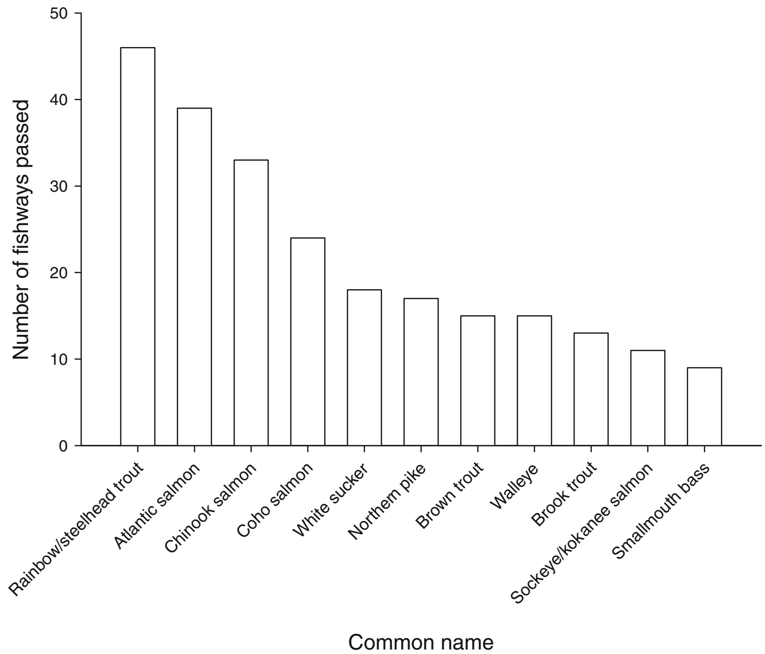

Fig. 8 Counts of documented fish passage at fishways in Canada. Only the 11 most passed species are shown in the figure

Considering that telemetry technology was first being used on fish towards the end of the 1970s (Lucas and Baras 2000) it is remarkable that so few fishways evaluated for efficiency after the 1980s were able to meet the Bunt et al. (2012) criteria. Indeed, electronic tagging techniques are becoming more cost effective, but equally relevant is the fact that there are enormous costs to not having credible data to inform fishway design. Given increasing resources devoted to fish passage research (Roscoe and Hinch 2010; Noonan et al. In Press) a need exists to evaluate the success of fishways using standard metrics (e.g. those proposed by Bunt et al. 2012) so that future fishway projects can build on previous successes. That said, we do recognize the value of other information sources (including simply documenting species observed at the top of the fishway) and encourage collection and dissemination of any biological information which could aid in our understanding of fishway design.

Finally, we encourage engineers, researchers and managers to update CanFishPass with past, current, and future fishway projects and fishway evaluations, so that knowledge of these fishways is centralized and easily accessed to inform future fishway projects. This will enable those engaged in new fishway development projects to learn from past successes and failures. Additionally, this information could be used to improve existing structures that are known to have difficulty passing target species. For example, one could search for details such as ideal elevation, velocity and slope for a particular species without spending a large amount of time searching for this information. At present much of this information exists in file cabinets or non-peer-reviewed technical reports. The CanFishPass concept certainly applies to other jurisdictions around the globe.

Conclusion

Our analysis confirmed what was already suspected based on studies relying on peer reviewed and grey literature (i.e. Roscoe and Hinch 2010; Bunt et al. 2012; Noonan et al. In Press); that there is little published information available that could be included in the database, and of these studies not all had the required rigour to assess attraction and passage efficiency using contemporary tagging methods. Using the CanFishPass database we evaluated trends in fishway construction and biological evaluation. However, the analysis is only as good as the data in the data-base. There are other data entry fields in the database for which sufficient data were not available for evaluation. Although the database will expand in the future, we are confident that it currently contains the majority of non-culvert fishways and thus that our trend analysis is representative of fish passage in Canada. As noted in the recommendations above, more complete reporting of details on fishway design, operation, and biological evaluation would be a valuable contribution to the CanFishPass database. We argue that biological evaluations must improve to ensure resources are being spent in a manner that can inform decisions regarding when to use fishways, what type of fishway to use, and perhaps most importantly to ensure that river connectivity is maintained where necessary. This trend analysis, although largely descriptive, represents the first national-scale fishway exercise that we are aware of anywhere in the globe. The lack of national or regional-scale databases and associated trend analyses reflects some of the historical and contemporary problems with fishway practice, namely the site-specific nature of fishway design and evaluation and the difficulty in obtaining existing material on previous fishway successes and failures. We recognize that fishway design is inherently site-specific (depending on the type and size of barrier, local geology/topography and fish communities), but note that the data-base is a starting point for those tasked with evaluating fish passage options for a given site. It is our hope that this analysis will stimulate other fishway databases to be populated around the globe and that in due course those collective data sources could serve as a rich resource for utilities, regulators, and other interested parties when designing future fishways.

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