Advancing fishway science in Canada

by

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Abstract

Fishways have been constructed to maintain longitudinal connectivity for fish in fluvial systems impacted by barriers but there are relatively few studies of their biological effectiveness. Trend analysis of the CanFishPass fishway database showed that only 9% of Canadian fishways have been studied using methods that enable proper evaluation of biological effectiveness. A biological evaluation of the Vianney-Legendre fishway in Quebec for the passage of three redhorse species (*Moxostoma anisurum, M. carinatum, M. macrolepidotum*) showed attraction efficiencies of 51%, 12%, 50%, respectively, and passage efficiencies of 88%, 50% and 69% respectively. Evaluation of the physiological capacity and relative swimming ability of three redhorse species showed silver redhorse performing the worst in the laboratory and shorthead redhorse performing the best. Additional research is required to understand how organismal performance, environmental conditions, and other factors interact with fishway designs to dictate which fish are successful and to inform research of future fishways.

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Co-Authorship

Chapter 2: The status of fishways in Canada: trends identified using the national CanFishPass database. Charles Hatry, Thomas R. Binder, Jason D. Thiem, Caleb T. Hasler, Karen E. Smokorowski, Keith D. Clarke, Christos Katopodis and Steven J. Cooke.

While this study is my own, the research was undertaken as part of a collaborative effort and each co-author played a role in its completion. The project was conceived by Binder, Smokorowski, Clarke, Katopodis and Cooke. Data was collected by Hatry and Thiem, with help from 3 summer research assistants and 2 QMNRF technicians. All figure construction and analysis were conducted by Hatry. Data were interpreted by Hatry, Thiem, Smokorowski and Cooke. All writing was conducted by Hatry. All co-authors provided comments and feedback on the manuscript. This manuscript has been accepted by *Reviews Fish Biology and Fisheries* and is available online DOI:10.1007/s11160-012-9293-3.

Chapter 3: Behaviour of three redhorse species (*Moxostoma anisurum, M. carinatum, and M. macrolepidotum*) downstream of and in a vertical slot fishway on the Richelieu River, Quebec. Charles Hatry, Jason D. Thiem, Daniel Hatin, Pierre Dumont, Karen E. Smokorowski and Steven J. Cooke.

While this study is my own, the research was undertaken as part of a collaborative effort and each co-author played a role in its completion. The project was conceived by Hatry, Thiem, Hatin, Dumont, Smokorowski and Cooke. Fieldwork and data collection were conducted by Hatry, Thiem, Stamplecoskie and Molina. All data analyses were conducted by Hatry. Data were interpreted by Hatry, Thiem, Smokorowski and Cooke.

All writing was conducted by Hatry. All co-authors will have provided comments and feedback on the manuscript prior to submission. This manuscript is currently in the final stages of co-author review with submission to *Environmental Biology of Fishes* to follow shortly.

Chapter 4: Comparative physiology and relative swimming performance of three redhorse (*Moxostoma* spp.) species: associations with fishway passage success and implications for fishway research. Charles Hatry, Jason D. Thiem, Thomas R. Binder, Daniel Hatin, Pierre Dumont, Keith M. Stamplecoskie, Juan M. Molina, Karen E. Smokorowski and Steven J. Cooke.

While this study is my own, the research was undertaken as part of a collaborative effort and each co-author played a role in its completion. The project was conceived by Hatry, Thiem, Binder, Hatin, Dumont, Smokorowski and Cooke. Fieldwork and data collection were conducted by Hatry, Thiem, Stamplecoskie and Molina. All data analyses were conducted by Hatry. Data were interpreted by Hatry, Thiem, Hatin, Dumont, Smokorowski and Cooke. All writing was conducted by Hatry. All co-authors provided comments and feedback on the manuscript. This manuscript has been submitted to *Physiological and Biochemical Zoology: Special Issue on Conservation Physiology*.

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1 Chapter: General Introduction

The disruption of natural river connectivity through the construction of barriers used for hydropower, irrigation, flood control, navigation, or drinking water has severely damaged riverine ecosystems, reducing habitat quality, and fragmenting previously continuous stretches of river (Dynesius and Nilsson 1994; Poff et al. 1997; Acreman 2001). Migration delays, habitat loss (e.g., spawning and rearing habitat), flow alteration, temperature changes, changes in water quality and increased exposure to predators are all negative effects that barriers impose on migratory fish populations (Drinkwater and Frank 1994; Larinier 2001). The regulation of rivers through anthropogenic activities has led to the extinction of many populations of migratory fish on almost every continent including Europe, Asia, Australia, North America (Larinier 2001) and South America (Oldani et al. 2007). Fishways are frequently constructed to maintain longitudinal connectivity for fish in fluvial systems impacted by barriers by providing a means of passage for fish around them (Clay 1995).

Fishway success is generally determined through quantification of fishway attraction and passage efficiency (Roscoe and Hinch 2010) where each refers to the proportion of the population attracted to the fishway entrance and the proportion of those attracted that successfully ascend (Lucas and Baras 2001). Successful fish passage at fishways is thought to be related to the interaction between an individuals' motivation, ability, and behavioural choices and the hydraulic conditions encountered at a site (Kemp 2012). Fish behaviour in terms of passage success through a fishway can be determined by a fish's behaviour downstream of as well as inside a fishway. Using radio telemetry (e.g., Bunt et al. 1999; Hinch and Bratty 2000) the downstream behaviour of fishes can be recorded to determine a fishway's ability to attract fish (attraction efficiency) as well as identify potential obstacles to attraction success. Radio telemetry can also be used to monitor coarse scale fish passage in fishways (e.g. Bunt et al. 2000). Passive integrated transponder (PIT) arrays can be used to record fish behaviour within a fishway (e.g., Castro-Santos et al. 1996) as well as quantifying fishway attraction and passage efficiency. Swimming ability amongst fishes is commonly measured in a laboratory setting where a fish is forced to swim against a current with a known velocity; the time to fatigue is also recorded (e.g., Peake et al. 2007). Swimming ability amongst different fishes has also been used to generate models for use in the evaluation of different fish passage facilities (Haro et al. 2004). Physiological methods such as blood sample analysis have been identified as a useful way to measure the effort associated with fishway passage (Hasler et al. 2009; Pon et al. 2012).

The aim of this thesis is to advance fishway science in Canada. To that end, Chapter 2 involves a trend analysis of the CanFishPass database (see Hatry et al. 2011) to characterize the state of fishway science in Canada. Several recent studies have reported the need for the continued research into how well current fish passage facilities work (Roscoe and Hinch 2010; Bunt et al. 2012). Those syntheses have revealed that most fishway studies focus on salmonids and rely solely on behavioural approaches without considering physiological perspectives (e.g. Pon et al. 2012). Chapter 3 and 4 focus on a comparative study of three redhorse species (*Moxostoma anisurum M. carinatum*, and *M. macrolepidotum*). In Chapter 3, comparative swimming ability, and measures of blood physiology will be related to passage success in an attempt to provide more insight into what may limit the passage of redhorse species at the Vianney-Legendre fishway, near St.

Ours, Quebec. In Chapter 4, downstream and in fishway behaviour of the three species will be investigated using a combination of radio and PIT telemetry to determine how effective the fishway is at attracting and passing redhorse. Finally, performance of the three fishes at the fishway will be linked with physiological parameters such as each fishes relative metabolic capacity and recovery rate, swim speed, and time to exhaustion. This project is expected to provide information that is useful to resource managers, engineers, utilities and fisheries managers in that will provide information relevant to assist future fishway projects, provide a contemporary analysis of fishway performance and elucidate reasons for differential fishway success between species.

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

2.1 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 globe. Although CanFishPass may not include all fishways in Canada, our analysis identified 211, which are primarily located along 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 warm water 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.

2.2 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, 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; Katopodis 2005; 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 2005; Katopodis and Williams 2011; Bunt et al. 2012; Noonan et al.

2012). 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 un-named culverts installed across Canada (Langill and Zamora 2002). The database does cover all other fishway types across a range of barrier sizes.

2.3 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.

2.4 Findings

Spatial Patterns in Fishway Numbers

In total, the database (as of January 1st, 2012) contained 212 fishways, of which location data (GPS 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 (Figure 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 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 (Figure 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 and 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 eel migration routes on the St. Lawrence River. One fishway, at 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) (Figure 3). High head barriers (≥10 m) represented only 7% of the sites with 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 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 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; 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 (Figure 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 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 (Figure 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 (Figure 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 (Figure 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 (Figure 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 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 2), 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*) (Figure 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 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. 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. 2012) 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.

2.5 Conclusion

Our analysis confirmed what was already suspected based on studies relying on peer reviewed and grey literature (i.e., Hinch and Roscoe 2010; Bunt et al. 2012; Noonan et al. 2012); that there is little published information available that could be included in the CanFishPass 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 database 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.

2.6 Tables

Table 2-1. 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 45º 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.

Table 2-2. 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

2.7 Figures

Figure 2-1. 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.

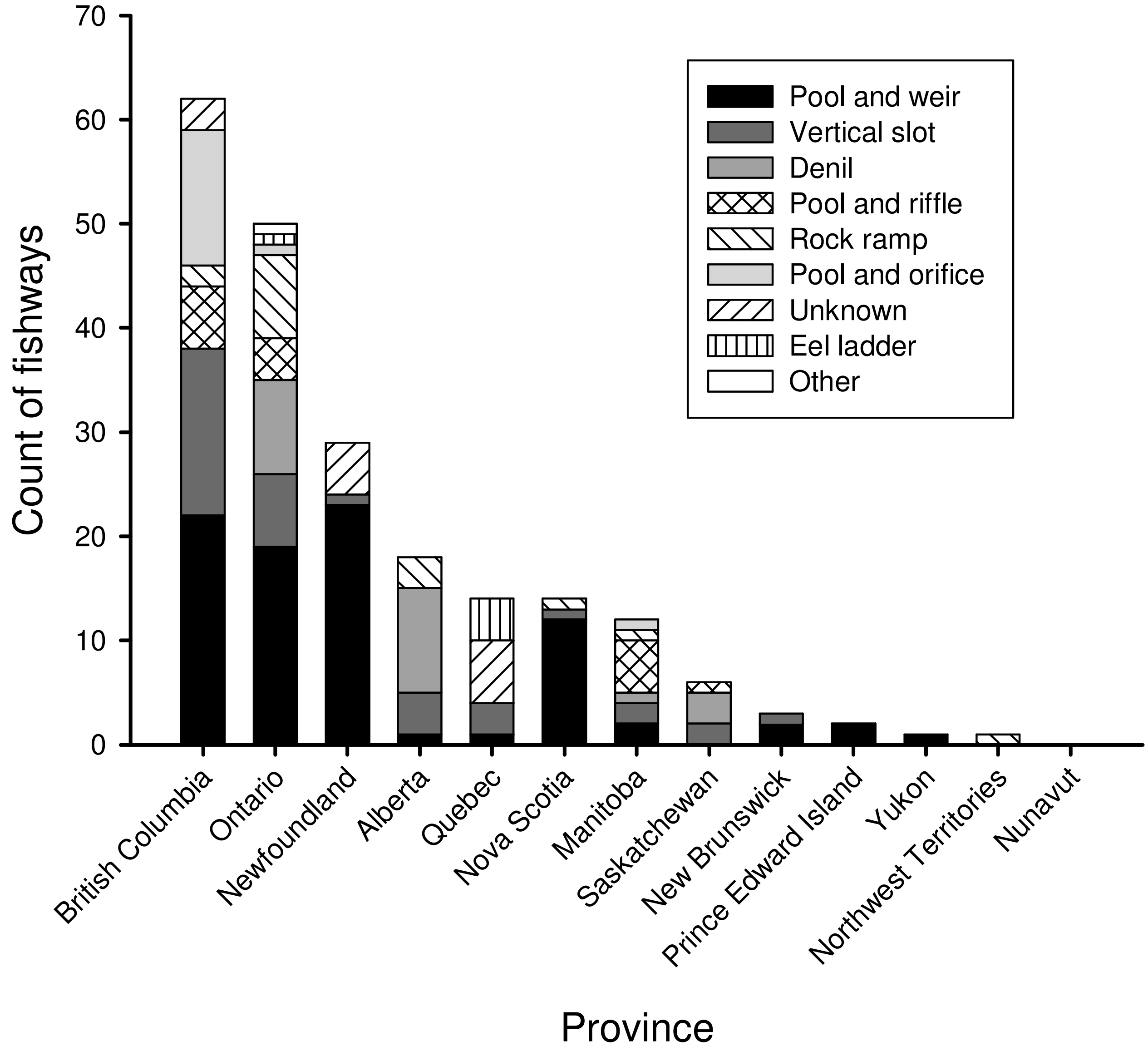

Figure 2-2. Count of fishways by province or territory. Conventional-type fishways are displayed in gray scale and nature like fishways are displayed with crosshatching. Eel ladders were displayed with vertical crosshatching to differentiate them from conventional type fishways. One fishway is listed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

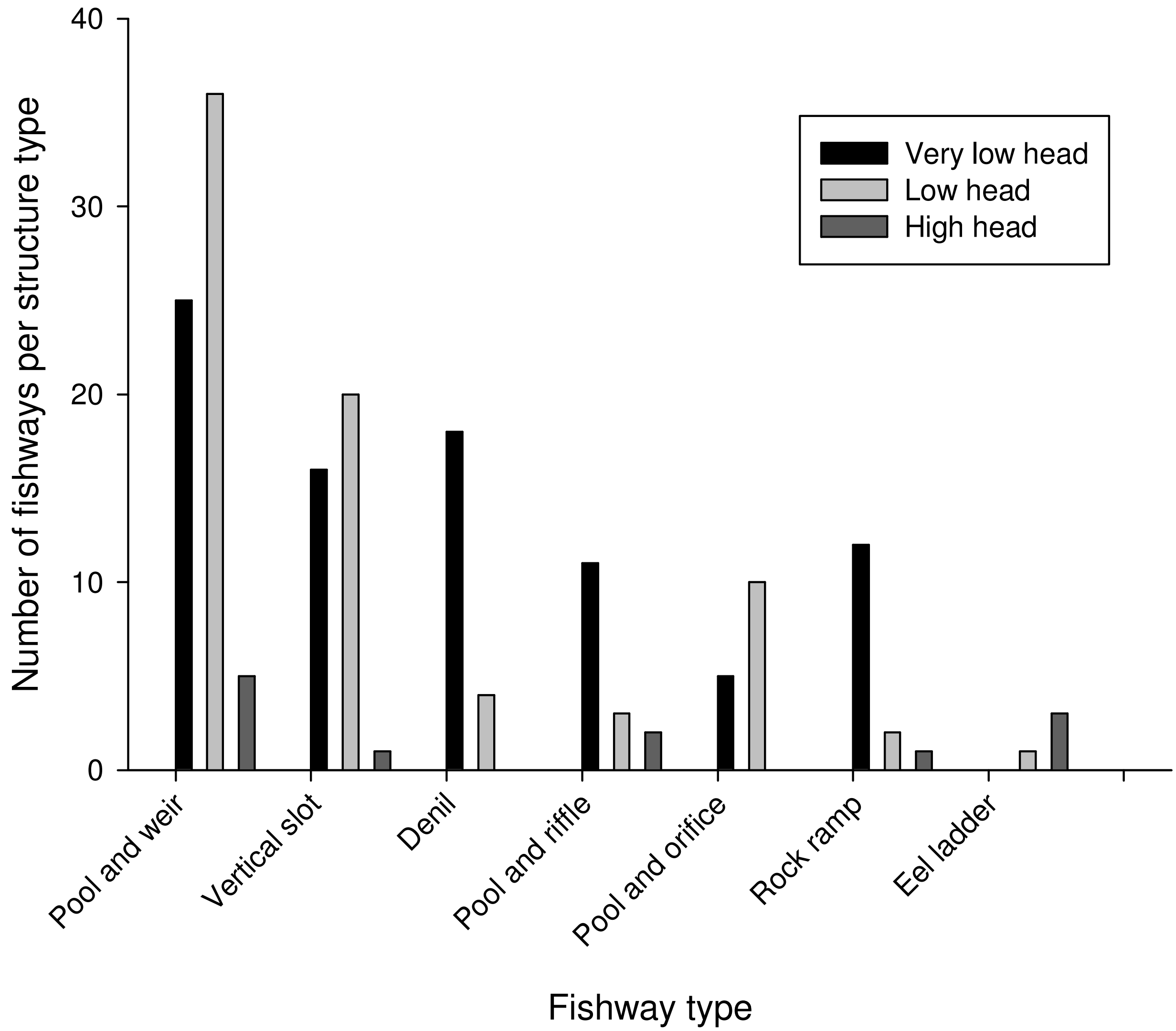

Figure 2-3. Number of fishways per dam category for the different types of fishways contained in the CanFishPass database. Dams were separated into three categories; the very low head category contained dams less than 3 meters in head-height, the low head category contained dams equal to and greater than 3 meters but less than 10 meters in head-height, and the high head category contained dams equal to and greater than 10 meters in head-height. Head-height data were available for 175 of 212 fishways.

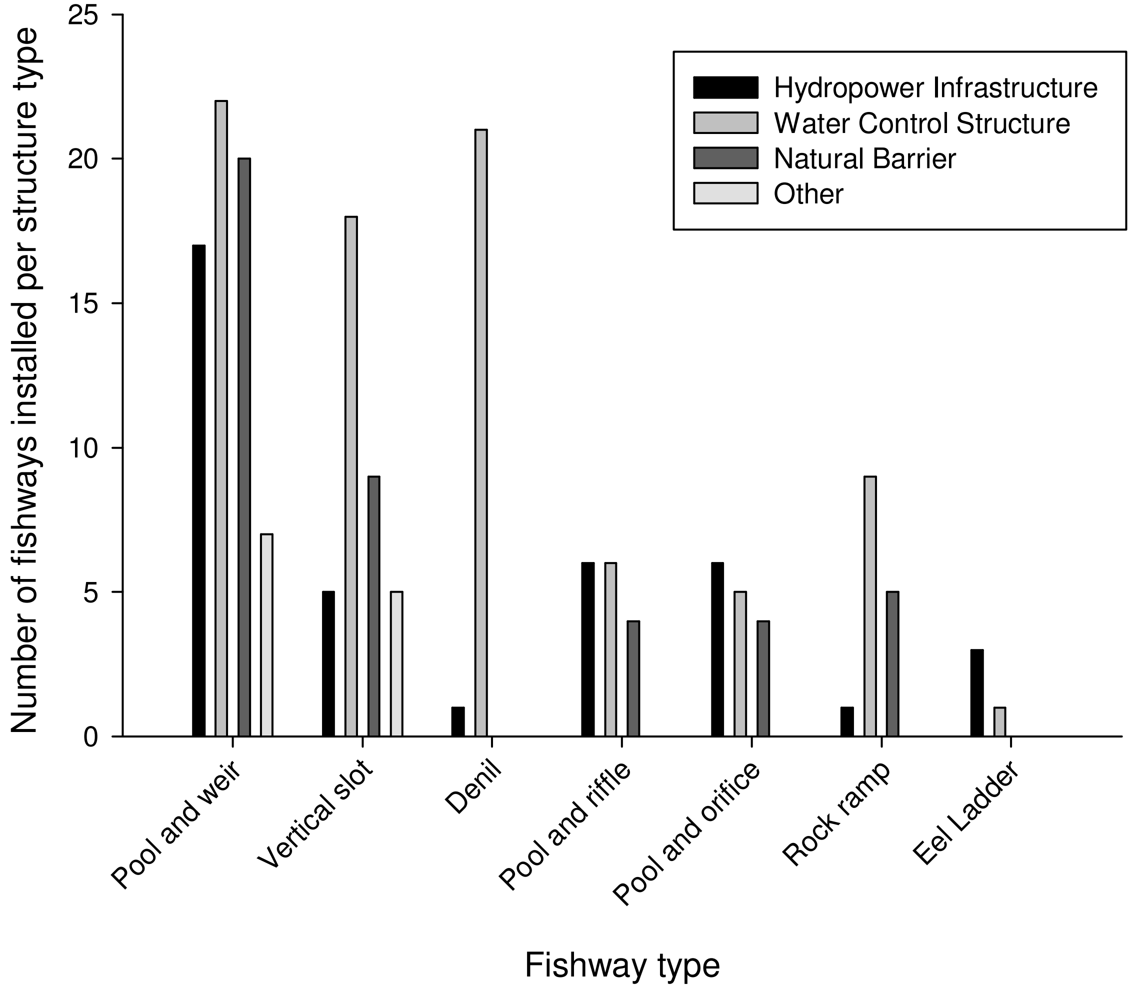

Figure 2-4. The number of fishways by barrier type is shown for different fishway designs. The hydropower infrastructure grouping represents fishways that were installed to mitigate the effects of both hydropower dams (n=28) and natural barriers (n=11) exposed by hydropower operations. The other grouping consisted of hatchery fences (n=7) and sea lamprey (*Pertomyzon marinus*) barriers (n=5).

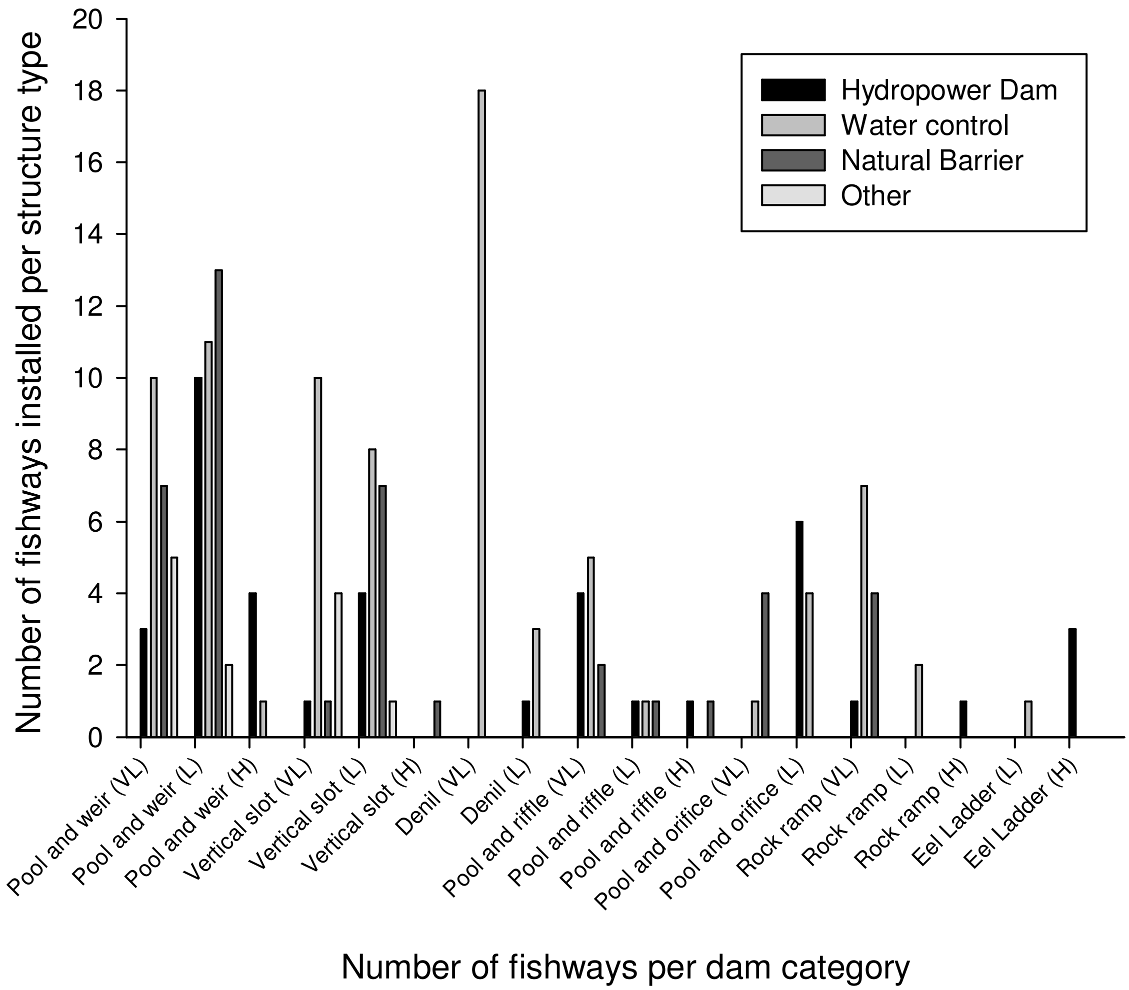

Figure 2-5. Number of fishways per structure for different fishway designs at a national level. The hydropower infrastructure grouping represents fishways that were installed to mitigate the effects of both hydropower dams (n=28) and natural barriers (n=11) exposed by hydropower operations. The 'other' 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 less than 3 meters in head-height, the L category (low head) category contained dams equal to and greater than 3 meters but less than 10 meters in head-height, and the H (high head) category contained dams equal to and greater than 10 meters in height. Head height data were available for 175 of 212 fishways.

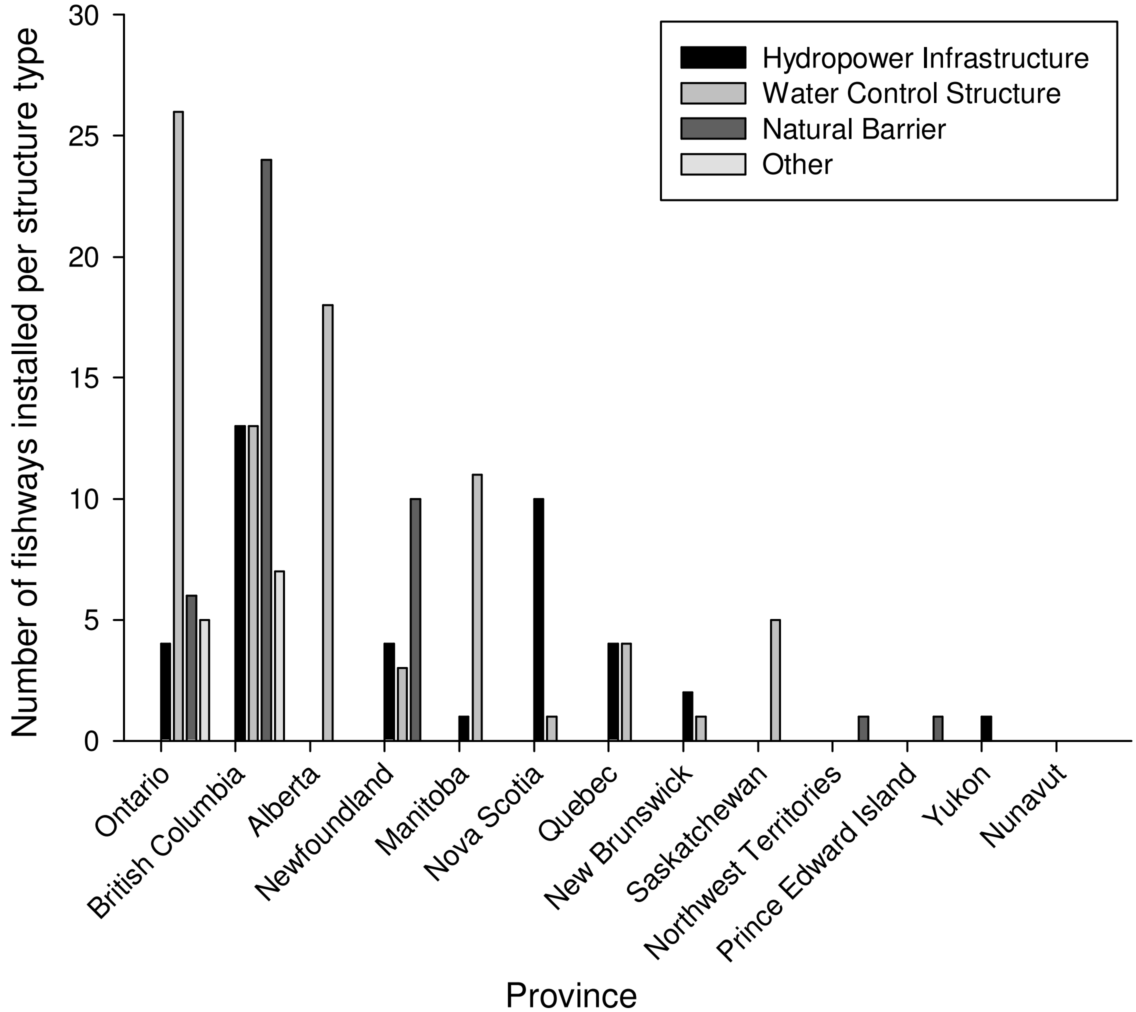

Figure 2-6. Number of fishways per structure type for each province. The hydropower infrastructure grouping represents fishways that were installed to mitigate the effects of both hydropower dams (n=28) and natural barriers (n=11) exposed by hydropower operations. The 'other' grouping consists of hatchery fences, all of which are in British Columbia (n=7), and lamprey barriers (n=5) which are all located in Ontario.

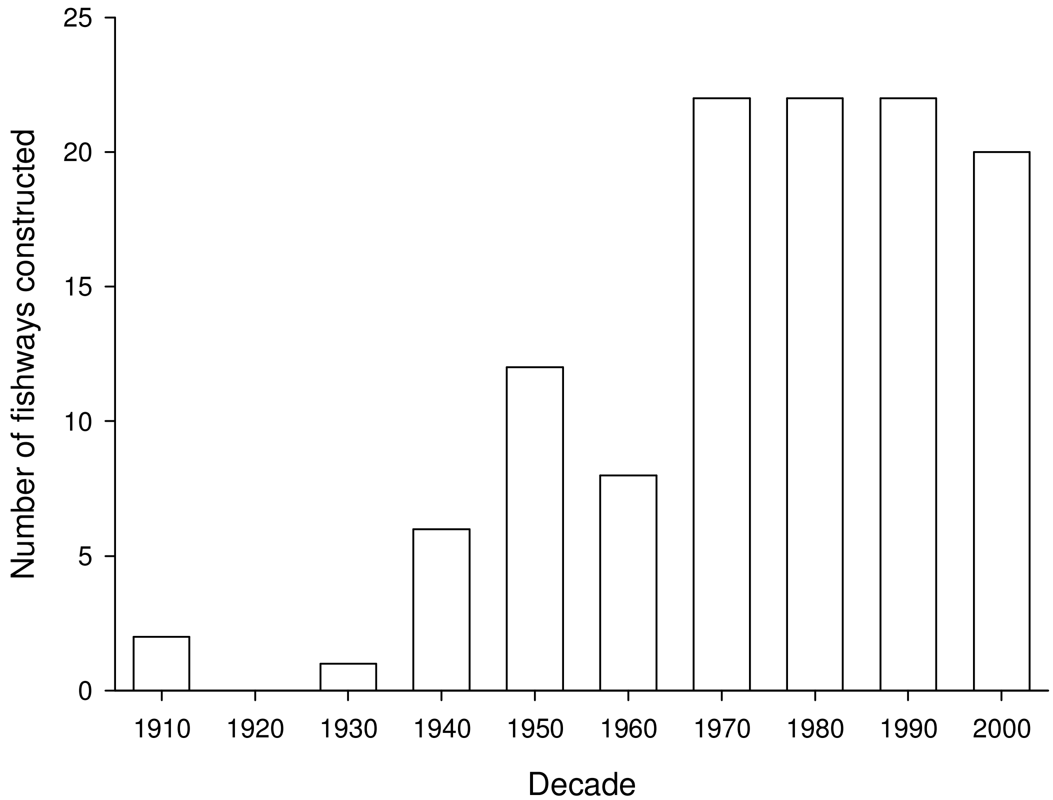

Figure 2-7. Number fishways constructed per decade in Canada over the last century. Date of construction was available for 117 of the 212 fishways identified in the database.

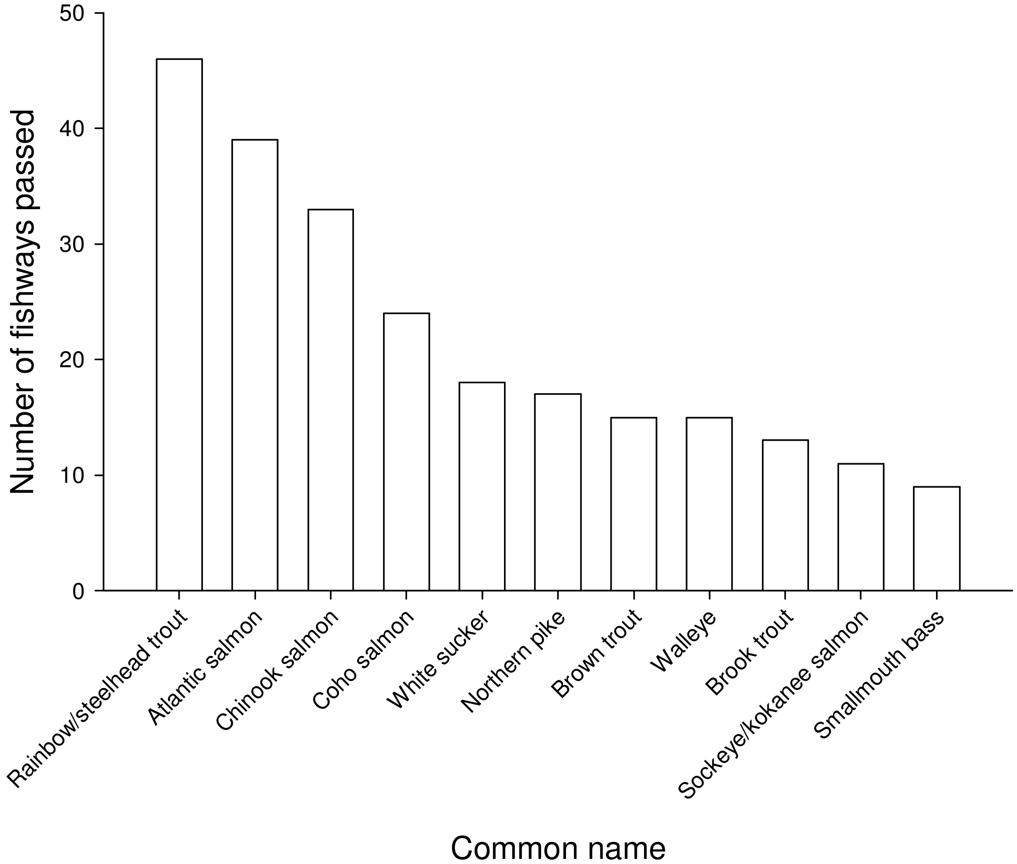

Figure 2-8. Counts of documented fish passage at fishways in Canada. Only the 11 most passed species are shown in the figure.

3 Chapter: Behaviour of three redhorse species (*Moxostoma anisurum, M. carinatum,* and *M. macrolepidotum*) downstream of and in a vertical slot fishway on the Richelieu River, Quebec

3.1 Abstract

Fishways have been constructed to maintain longitudinal connectivity for fish in fluvial systems impacted by barriers but there are relatively few studies of their biological effectiveness, particularly for multiple species. We evaluated the biological effectiveness of the Vianney-Legendre vertical slot fishway on the Richelieu River, Quebec, Canada. Research focused on three congeneric redhorse species, silver: *M. anisurum,* river*: M. carinatum*, and shorthead redhorse *M. macrolepidotum*, during the peak of their respective spawning migrations. Radio telemetry (RT) and passive integrated transponder (PIT) telemetry were combined to examine the downstream and in-fishway behaviour of the externally-mounted radio tags which resulted in behavioural impairments despite tag burdens being <2% of body mass such that little useable data were obtained due to high levels of fallback. Attraction efficiencies generated with PIT were 51%, 17% and 50% for silver, river, and shorthead redhorse respectively. PIT-determined passage efficiencies were 88%, 50%, 69% for silver, river and shorthead redhorse respectively. Silver redhorse had significantly shorter entrance delay and passage duration times than shorthead redhorse. Attraction efficiency was increased in silver redhorse if they were released on the opposite bank to the fishway, and passage efficiency increased for larger shorthead redhorse. For all species, failures in the fishway were likely to occur before the second turning basin in the fishway (84% of failures).

Silver redhorse had significantly lower passage failure rates than river and shorthead redhorse. Activity patterns in the three species were quite different; crepuscular activity patterns were observed in shorthead and river redhorse, with silver redhorse activity peaking at midnight and decreasing throughout the 24 hr period.

3.2 Introduction

Natural and man-made barriers can reduce the quality of fish habitat, and prevent the upstream movement of migratory fish (Dynesius and Nilsson 1994; Poff et al. 1997; Malmqvist and Rundle 2002). Fishways are frequently constructed to maintain longitudinal connectivity for fish in fluvial systems impacted by barriers by providing a means of passage for fish around them (Clay 1995). While biological evaluations of fishways are increasingly common (Roscoe and Hinch 2010), recent syntheses have demonstrated that the majority of studied fishways do not work as efficiently as intended (Bunt et al. 2012; Noonan et al. In Press). In general, biological assessments, especially those that quantify passage efficiency by individuals, have been conducted for relatively few of all fishways that exist (e.g. 19 according to Bunt et al. 2012). For context, over 200 fishways exist in Canada alone emphasizing the paucity of such efficiency studies (Hatry et al. 2012). The majority of studies assessing biological effectiveness have used one or more forms of electronic tagging (passive integrated transponder, PIT, tagging or radio tagging) to study fish behaviour in the field as they attempt to locate and migrate through a fishway (Castro-Santos et al. 1996; Bunt et al. 2000; Thiem et al. In Press). A recent meta-analysis (i.e., Bunt et al. 2012) suggested that fishway studies be conducted using electronic tagging so that individual fish could be monitored entering as well as exiting the fishway in natural conditions. Tagging techniques would enable a robust assessment of attraction efficiency (defined as the proportion of fish tagged and released during the study that were located close enough (within a few meters of) to a fishway to have been attracted by the fishway's attraction flow) and passage efficiency (defined by dividing the number of fish of a particular species that exited a fishway by the number that was detected at the fishway entrance).

Many of the studies that used telemetry to monitor fish behaviour and passage at fishways have been performed on salmonids and other popular game fish (Roscoe and Hinch 2010) and there is comparatively little known about the behaviour of non-game fish passage at fishways (e.g., 58% of the peer reviewed studies from Roscoe and Hinch 2010 focused on salmonids alone). Additionally, most electronic tagging studies tend to focus on a single species and have not explored comparative passage and behaviour within a single spawning season, particularly among congenerics. Catostomids, a common family of non-game fish, often dominate numbers and biomass at fishways in North America when locally abundant (e.g., Schwalme et al. 1985; Bunt et al. 2001; Pratt et al. 2009) and are susceptible to river fragmentation because they are obligate spring migrants (Cooke et al. 2005; Reid et al. 2008) making them a suitable model for comparative passage research.

On the Richelieu River, Quebec, Canada, several species of redhorse (*Moxostoma* spp.) fishes are of interest to fisheries managers and conservation scientists. While most of the six redhorse species found in the river are present in high numbers, copper redhorse (*M. hubbsi*) are federally endangered (COSEWIC 2004) and are not found anywhere else in Canada. River redhorse (*M. carinatum*) are considered federally as a species of "special concern" (http://www.cosewic.gc.ca), yet are present in the Richelieu in large numbers. Shorthead and silver redhorse (*M. macolepidotum* and *M. anisurum*, respectively) are also abundant in the Richelieu River. These fishes are known to be negatively affected by river fragmentation because they are obligate migrants (Reid et al. 2008) and rarely occur together outside of their spawning season due to their preference for different silt levels (COSEWIC 2006). Hence the study site, the Vianney-Legendre vertical slot fishway, provides a unique opportunity to attempt a study of the comparative upstream passage and downstream behaviour of members of the Moxostoma genus. In general there are very few studies of redhorse movement using electronic tagging techniques (but see Bunt et al. 2001; Clark 2004; Gariépy 2008) and only preliminary work with PIT telemetry (i.e., Thiem et al. In Press) at the Vianney-Legendre fishway specific to fish passage. Therefore, our objectives were to evaluate the comparative downstream behaviour, including the attraction efficiency and passage efficiency, of silver, river and shorthead redhorse at the Vianney-Legendre fishway during the peak of their respective spawning migrations. Additionally, we sought to determine potential reasons for attraction or passage failure, such as bank side approach to the fishway, and areas of difficult passage within the fishway itself using a combination of radio and PIT telemetry.

3.3 Methods

Study site and fish collection

The study was conducted at the Vianney-Legendre fishway located on the Richelieu River near St. Ours, Quebec, Canada (45º52´N 73º09´W). A detailed description of the fishway can be found in Thiem et al. (2011). Briefly, the fishway is a long concrete fishway with 15 vertical slots (0.6 m width), with a total rise of 2.65 m and an average slop of 4 percent. The total length of the fishway is 85 m. The fishway is divided into 12 rectangular basins (3.5 × 3.0 m), two turning/resting basins with curved walls (2.75 m radius), and a large entry and exit basin (see Figure 1). Each basin has a height drop of 0.15 m. The three redhorse species used in this study (silver, river and shorthead) were captured directly from a fish trap located at the top of the fishway which was lifted daily. The fish trap is a 2.2 × 2.0 m cage designed so that fish cannot exit the fishway with the general purpose of enumerating fish that have moved up the fishway. It was not possible to capture fish downstream using nets or electrofishing given the presence of endangered copper redhorse and concerns regarding their incidental capture. We assumed that capture in the fish trap of large numbers of redhorse by species indicated optimal timing of migration and thus tagged each species as they were encountered. In 2012, the water temperatures experienced by fish during peak migration windows were reasonably stable such that tagging for a given species occurred within a relatively narrow temperature range. Rather than conduct experiments at a fixed temperature for all species it was deemed more ecologically relevant to conduct experiments at ambient temperatures that coincided with peak migration time for each species.

Experimental design

A passive integrated transponder (PIT) array was installed in the fishway consisting of 15 antennas, beginning at antenna 15 downstream and ending at antenna 1 upstream (Figure 1.) (see Thiem et al. 2011 for more information on the PIT antenna array) connected to multiplexers and dataloggers (Oregon RFID, Oregon, USA) capable of generating electronic time stamp records for tag detections. Fish are required to move upstream through each antenna to successfully navigate the fishway. A PIT telemetry method validation study conducted concurrently with the present one found that detection efficiency (the chance of a tag being detected in the array as it passed through an antenna) in the PIT array was 91 ± 1.8% for the size of tags used for redhorse (i.e., 23 mm tags; Burnett et al. In Press). PIT antennas had a maximum detection range of ~50 cm and were located on the upstream side of each vertical slot baffle. In addition, a radio antenna array consisting of 14 antennas (three and five element yagi antennas, AF Antronics, Urbana, Illinois) connected to four data-logging digital radio receivers (three SRX 600s and one SRX 400, Lotek Wireless, Newmarket, ON) was installed to monitor downstream approach behaviour. Multiple antennas fed into each receiver via an ASP-8 antenna switcher (Lotek Wireless) and the antennas were set to scan sequentially for each radio frequency on each antenna for a period of 8 seconds each. The entire cycle period was less than 120 seconds in all instances. Radio antenna locations and their approximated detection cells (detection cells are estimated based on detection range testing during array setup) are shown in Figure 2.

Fish were tagged immediately after capture from the trap at the top of the fishway. Three redhorse species (n = 39 *M. anisurum*, n = 38 *M. carinatum*, n = 39 *M. macrolepidotum*) were tagged externally with coded radio tags (149 MHz, 30 × 8 mm, 8 g weight in air, 4 g in water, burst rate 2 sec, 90 day battery life, Sigma Eight Inc., Newmarket, Ontario, Canada) at the base of the dorsal fin (Figure 3) and with unique PIT tags (23 x 3.85 mm HDX: Texas Instruments, Dallas, USA) injected into their peritoneal cavity. An additional group of fish was only fitted with PIT tags (n = 120 *M. anisurum*, n = 70 *M. carinatum*, n = 120 *M. macrolepidotum*). External radio tagging was accomplished using 6 gauge hypodermic needles, and 20 gauge stainless steel wire was used to secure tags. Tagging methods were similar to those previously used on several species (Cooke and Bunt 2001a; Collins et al. 2002). Plastic backing plates were also used on each side of the fish to minimize any pressure on the fish's back caused by the tag attachment process, and by the additional weight of the tag. The total tag burden including backing plate and wire weighed ~12 g in air, and never exceeded 2% of weight based on length-weight relationships (Table 1). The coefficient of determination (R^2) values generated for the three species' log-log relationships are comparable to those reported in Meyer (1962) for silver and shorthead redhorse. Total length (TL) of each fish was measured along with a determination of sex accomplished through visual identification (abdominal pressure and gamete extrusion as well as the presence of tubercles on caudal fins and snout). The same experienced surgeon conducted all radio tagging. Fish were tagged in V-shaped troughs with flow through ambient river water supplied throughout each tagging event. Holding tanks for recently tagged fish had a constant supply of fresh river water. In all cases, tagging occurred with the head and gill complex of fish submerged in fresh water to minimize tagging stress and fish required only light restraint administered by the individual holding the fish during radio tag attachment. Anesthetics were not used given the assumption that there would be a protracted behavioural recovery period and based on earlier experience where we determined that some redhorse species did not respond well to anesthesia (Cooke, Unpublished data).

PIT and radio tagging of the three redhorse species was carried out between the 9th and 25th of May 2012. Silver and shorthead redhorse were all tagged May 9-11 and

May 17. River redhorse were all tagged between May 24-25. Fish were tagged during the peak migratory period for each species. Peak migratory periods were determined by using a combination of historical spawning data for the river, monitoring water temperatures and through determining large numbers of fish caught in the fish trap at the top of the fishway. Areas downstream and within the fishway were continuously monitored using fixed antenna (radio and PIT) arrays between May 9, and July 10, 2012.

Passage success and duration

In contrast to the previous experiments (i.e., Thiem et al. In Press) fish used for the determination of passage success were not held in recovery basins for 1-2 hours prior to experimentation but were tagged immediately after capture from the fish trap at the top of the fishway. Following tagging fish were held in a recovery bag for a short time (~15min) and then were released ~200 m downstream of the fishway in equal numbers of species and sex, on both banks of the river. We defined passage success as a fish successfully moving past the most upstream antenna (antenna 1) which was determined using the PIT antenna array described in Thiem et al. (In Press). Passage duration was determined by calculating the time taken from a fish's first detection on the most downstream antenna (antenna 15) to the first detection on antenna 1.

Data analysis

Attraction efficiency was defined as the number of fish detected in the fishway divided by the total number of fish released for that species, sex, or release bank. Passage efficiency was calculated as the total number of fish detected on antenna 1 divided by the total number of fish detected in the fishway. Differences in length, entrance delay (defined as the time from release to the time to first detection in the fishway), and passage duration among species (river redhorse were not included in the entrance delay and passage duration comparisons due to a lack of data) were analyzed using independent samples t-tests assuming unequal variances (Ruxton 2006). Differences in entrance delay and passage duration within species between sex and bank release were tested using two-way ANOVAs, with Bonferonni post hoc tests used to identify significantly different groups. Silver redhorse entrance delay and shorthead redhorse passage duration data were transformed using the natural logarithm function in order to meet the assumption of normality. Similarly, silver redhorse data for passage duration was normalized using a reciprocal transformation. The probability of detection and successful passage of each species was tested using multiple logistic regression analysis incorporating length, sex and release bank as predictor variables. Differences in passage failure rates at locations (antennas) in the fishway were tested by first converting antenna locations to distance metrics, with antenna 15 (the most downstream antenna) being equal to a distance of 0 and antenna 1 (the most upstream antenna) being equal to 56.2 m. Distance metrics were then used in LogRank survival analyses to determine if differences in passage failure rates at incremental distance locations occurred between species. LogRank survival analysis was used to compare all three species as well as to investigate whether passage failure locations differed within a species based on sex, with Holm-Sidak post hoc tests used to identify significantly different groups. For the survival analyses antenna locations were converted into distances which are based on the shortest possible distance a fish could move between antennas. Assumptions for analyses were checked according to Field (2009). All results are reported as significant at $p < 0.05$. All statistical analyses were performed using SigmaStat (SigmaPlot 11, Systat Software Inc.) and PASW Statistics 18 (SPSS, IBM 2009, USA).

3.4 Results

The phenology of migration was such that silver redhorse (12.3 ± 0.1 ºC, 11.4-15.1 ºC) and shorthead redhorse (12.3 ± 0.1ºC, 11.4-15.1 ºC) were tagged first and river redhorse (18.5 ± 0.1 ºC, 17.4-19.4 ºC) shortly thereafter. Fish encountered in the trap at time of tagging were all considered to be mature and ripe based on the ease with which gametes could be expelled as well as external characteristics (e.g., tubercles). Female fish were significantly longer (TL) than male fish for all three species (silver redhorse, $t = 5.64$, $df = 118$, $p < 0.001$; river redhorse, $t = 2.88$, $df = 59$, $p = 0.003$; shorthead redhorse, $t=8.61$, $df=118$, $p < 0.001$; Table 2; Table 3).

Radio telemetry study

In general radio tagged fish spent very little time in the antenna array and presumably moved downstream en masse after being released following tagging. There was insufficient radio telemetry data collected to enable statistical analyses so we simply present summary information in Table 2. Female silver redhorse were detected in the array more often (70% of female silver redhorse were detected) and spent longer in the array than any other group of radio tagged fish (Table 2). Approximately 30% of male silver redhorse and female shorthead redhorse were detected in the array while comparatively fewer male shorthead redhorse (~15%) and river redhorse of either sex (~10%) were detected in the array. Despite spending the most time in the array, only a single female silver redhorse was considered to be attracted to the fishway and that same individual successfully ascended the fishway.

PIT telemetry study

Silver redhorse had shorter entrance delay times and shorter passage duration times than shorthead redhorse ($t = -2.43$; $df = 95$; $p = 0.017$ and $t = -3.79$; $df = 42$, $p < 0.001$, respectively). Within species, female silver redhorse had significantly lower entrance delay times than male silver redhorse and there was no effect of release bank, and no interaction effect of release bank and sex on silver redhorse entrance delay times (Table 4). There was no effect of sex or release bank and no interaction effect of sex and release bank on passage duration among silver redhorse (Table 4). Within shorthead redhorse, there was no effect of sex or release bank and no interaction effect of sex and release bank on entrance delay times (Table 4). There was a significant interaction effect of sex and bank release on passage duration among shorthead redhorse ($df = 1, 34$; $p = 0.004$; Table 4) which post-hoc tests revealed that male shorthead redhorse released on the east bank had significantly longer passage duration times than females released on the east bank ($p = 0.007$).

There was a higher probability of detecting silver redhorse if they were released on the east bank rather than the west bank, and a higher probability of passing silver redhorse if they were female and released on the east bank (Table 5). The probability of detecting and passing river redhorse was unrelated to length, sex, or release bank (Table

5). The probability of detecting shorthead redhorse was unrelated to length, sex, or release bank but the probability of passage was increased as length increased (Table 5).

Generally (all 3 species), passage failure was most likely to occur at or before the 32 m mark (ant 8) in the fishway (84%), with few failures occurring after this point (16%) (Figure 4). Failures at the 32 m mark (antenna 8) accounted for the largest proportion of failure (19%) locations in the fishway. The failure rate was significantly different between species ($\chi 2 = 9.7$; df = 2; $p = 0.008$). Silver redhorse had a significantly lower rate of failure than both river redhorse ($p = 0.004$) and shorthead redhorse ($p = 0.008$). There was no significant difference in the rate of failure between river and shorthead redhorse ($p = 0.40$) (Figure 4). Within species, there was no significant difference in failure rates between males or females ($p > 0.20$ for all species).

Water temperature ranged from 11 ºC to 21 ºC, progressively increasing over the course of the study period with a drop in water temperature occurring at the beginning of June (Figure 5). River discharge maintained an elevated level between May 12 and May 25, peaking on May 25 and decreasing afterwards. River discharge experienced two smaller peaks on May 29 and on June 2. All passage events for silver redhorse and a high proportion of passage events for shorthead redhorse occurred during the elevated but fairly uniform discharge period between the May 12 and 25. Most of the passage events for river redhorse occurred before May 30 with one lone event on the June 11. The spike in discharge on May 29 coincided with the passage of one river redhorse.

Silver and river redhorse had similar levels of activity during the day as they did at night, while shorthead redhorse were more active during the day (73% of records) than at night (Figure 6). Silver redhorse were most active during the early morning (0100-

0500 hrs) (Figure 6a). River redhorse were most active in the hours before sunset (1700-2000 hrs) (Figure 6b). Shorthead redhorse activity was high in the hours after sunrise (0600-1200 hrs) and before sunset (2000 hr) but dropped during the afternoon (1400-1700 hrs) (Figure 6c).

3.5 Discussion

In this study we set out to compare the behaviour of three redhorse species during their spawning migration using a combination of radio and PIT telemetry. Research focused on behaviour downstream of a vertical slot fishway as well as behaviour of fish within the fishway. Few studies have used a multispecies approach to study the effectiveness of fishways (Roscoe and Hinch 2010) and no studies that we are aware of have employed both radio and PIT telemetry to study upstream passage behaviour (both downstream of and inside a fishway) by multiple species in a single season (Bunt et al. 2012). A study performed by Thiem et al. (In Press) examined multispecies passage success at the Vianney-Legendre fishway using PIT telemetry which included silver, river, and shorthead redhorse. However, sample sizes were low in that study, and they were unable to study attraction efficiency because all fish were released within the fishway. The results from Thiem et al. (In Press) suggested that passage efficiency of the three redhorse species was low (between 30-45% for the three species). Because of the migratory requirements of redhorse species and since river redhorse are listed "of special concern" in Canada (http://www.cosewic.gc.ca) interest remained with fisheries managers to study the downstream and in fishway behaviour of redhorse in more detail.

Tagging of all three species occurred at the peak of their respective spawning migrations which was determined by abundance of fish captured in the fish trap at the top of the fishway. The timing of the spawning migrations of the three species experienced in 2012 is consistent with work by Reid (2006) conducted on the Grand and Trent Rivers in Ontario and the Muskegan River in Michigan. Reid (2006) found that silver and shorthead redhorse typically began their spawning runs in early to mid-May when water temperatures were between 10-14 ºC and that river redhorse began their spawning migration in late May with water temperatures ranging from 16-20ºC. Sizes for sexually mature silver, river, and shorthead redhorse from the current study were also comparable with the sizes reported by Reid (2006) and similar to the current study, Reid (2006) found that females from silver, river, and shorthead redhorse were all larger than males. Passage events for silver and shorthead redhorse all took place during a period of elevated discharge and rising water temperatures in the middle of May. River redhorse passed in lower numbers up until May 30 with only one more fish passing the fishway after this date. This information is consistent with knowledge of other catostomid migrations which typically take place during times of elevated river discharge and rising water temperatures (see Lucas and Baras 2001).

Based on the paucity of data garnered from fish that were double-tagged with radio and PIT tags relative to the large amount of data returned from those individuals carrying only the PIT tag, we believe that there was a significant tagging effect experienced by redhorse after radio tag attachment. Other reasons for low radio tag detection could include tag failures or poor performance of the telemetry array. However, that conclusion is not supported by data gathered from the PIT telemetry array which only detected one double-tagged fish inside the fishway – the same individual recorded on the radio receiver. Extensive testing of the radio telemetry array and occasional manual tracking confirmed that the array was indeed functioning properly. Fish that only received PIT tags were otherwise handled in the exact same manner as those that were double tagged (i.e., radio and PIT tags). Greater redhorse in the Grand River, ON were tagged externally using a similar approach to what we used here (see Bunt and Cooke 2001). In that study fish were tagged on spawning grounds downstream of a barrier and tracked to study post-spawn habitat use and movements. Bunt and Cooke (2001) noted that greater redhorse moved downstream after tagging which was assumed to be their natural post-spawning behaviour. The fish tagged in our study were mature and did not appear spent so it is unlikely that the reason for fallback was because fish spawned and then fell-back as a natural process. To our knowledge there are no studies that evaluate the effects of different telemetry tagging techniques on redhorse. We conclude that the presence of the tag (which was placed in an area commonly used for external tagging and was designed to be small and weigh <2% of the body weight of the fish (Bridger and Booth 2000) or the tagging procedure itself was sufficient to alter their behaviour relative to fish that were only tagged with PIT tags. Anecdotally (Cooke, personal communications), we are aware of several failed telemetry studies on redhorse although a commonality in those studies was the use of anesthesia and none of them were published. As such, although we consider the radio tagging component a failure, it is important to report such experiences to inform future telemetry studies.

River redhorse were not included in the analyses related to entrance delay and passage duration because sample sizes were too low. The low sample sizes for these variables and for river redhorse attraction and passage efficiency may be explained by the installation of a gill net (5 inch mesh size) across the entrance to the fishway on the May 28 for a separate attempt to capture brood stock for the endangered copper redhorse. The gill net was in place from approximately 0900-1730 for two weeks following its installation, and two river redhorse were captured in this net. While few river redhorse were captured in the net it may have acted as a deterrent to fish attempting to move up the fishway. Due to the timing of their respective spawning migrations we assumed that the gill net had no effect on the silver and shorthead redhorse passage results. Silver redhorse had significantly lower entrance delay and passage duration times than shorthead redhorse. Similar trends regarding passage duration for silver and shorthead redhorse were identified in Thiem et al. (In Press) however sample sizes did not allow for robust statistical analysis. Within species, female silver redhorse had lower entrance delay times than males while male shorthead redhorse had shorter passage duration times than females. These differences may be explained by the different bioenergetic costs of migration experienced by fish of different sizes; smaller fish must expend more energy to move at the same speed as larger fish but to save energy can move at slower speeds (Lucas and Baras 2001). This may explain why female silver redhorse entrance delay times and female shorthead redhorse passage duration times were shorter than their male counterparts as for both species females were significantly larger than males. There may also be differences in sex-specific reproductive hormone titers which could influence motivation, however, we are unaware of any endocrine studies on redhorse.

Passage efficiencies for silver, river, and shorthead redhorse were higher than passage efficiencies for the same three species at the same fishway reported by Thiem et al. (In Press) (%'s of 30, 31, 46, respectively) two years earlier. Thiem et al. (In Press) could not measure attraction efficiency but a study on modified vertical slot fishways on white suckers (a confamilial) in the Big Carp River, Ontario, reported attraction efficiencies of between 73-84% over a three season study period (Pratt et al. 2009). While attraction efficiency was lower at the Vianney-Legendre fishway for silver and shorthead redhorse (~50%) it is important to note that tagged fish from this study had already succeeded in locating the fishway entrance at least once and may have been less motivated to do so again. We had anticipated that there would be higher attraction efficiency for fish released on the same bank (west) as the fishway because of the shorter distances involved with travelling to the fishway entrance. Additionally, fish released on the west bank needed only to swim upstream along the bank to find the fishway which we assumed would be easier for individuals, rather than swimming across the river and locating the fishway entrance. However, for silver redhorse there was a higher probability of being detected in the fishway if fish were released on the opposite bank (east) to the fishway. A possible explanation for this is the nature of the modulated attraction flow patterns coming out of the fishway; flow is designed to pass out towards the middle of the river rather than down the west bank. Detailed hydraulic studies conducted simultaneously with detailed tracking studies would be needed to further elucidate the pattern we observed. The probability of successful passage was higher in larger shorthead redhorse than smaller ones, however, this trend was not observed for silver redhorse. It is possible that since shorthead redhorse are in general of considerably smaller size than silver and river redhorse that the relationship between size and swimming capacity plays a greater role in their ability to pass the fishway (Lucas and Baras 2001).

The majority of passage failures amongst all three redhorse species occurred at or before antenna 7 located just downstream from the second turning basin in the fishway. This type of passage behaviour is somewhat different to that shown by the same three species but similar to passage failure patterns shown by other catostomids (white and longnose suckers, *Catostomus commersoni* and *C. catostomus* respectively*)* in the same fishway (Thiem et al. 2011; Thiem et al. in press). Silver redhorse had lower failure rates than both river and shorthead redhorse suggesting that they have either greater physiological or swimming capacity (e.g., ability to recover from exercise, greater aerobic capacity) or have sensory or behavioural attributes compared to the other species potentially allowing them to optimize route selection through the fishway. It is worth noting that all of the tagged fish had previously ascended the fishway so the tagged individuals all had the ability to do so prior to tagging. A study by Hinch and Bratty (2000) at a fishway on sockeye salmon (*Oncorhynchus nerka*) showed that fish which successfully passed through the fishway had lower average, minimum and maximum swim speeds than fish which failed to pass the fishway suggesting that choosing the right path through an area of varying flow is an important factor in passage success.

Activity patterns in the fishway were quite different among the three redhorse species. The activity patterns for shorthead redhorse and river redhorse match the activity patterns presented by Thiem et al. (In Press) in 2010 and are generally crepuscular. Differences in the activity patterns of silver redhorse from the Thiem et al. (In Press) study and the current one may be due to the low sample size from the Thiem et al. (In Press) study. Here we observed that silver redhorse activity was greatest around midnight and then roughly decreased throughout the rest of the 24 hr period. Previous studies have reported daytime, afternoon and evening activity peaks for other catostomids (Schwalme et al. 1985; Bunt et al. 1999) and based on our work there appears to be extensive variation in diel passage activity even among congeneric species.

3.6 Conclusion

This study provided new information regarding the passage of silver, river, and shorthead at the Vianney-Legendre fishway. Contrary to the only previous behavioural study on these three species (i.e., Thiem et al. In Press), our work revealed attraction efficiencies for silver, river and shorthead redhorse as well as passage efficiencies for silver and shorthead redhorse that were much higher than previously reported at the Vianney-Legendre fishway (Thiem et al. (In Press). Fish passage metrics such as entrance delay, passage duration, attraction efficiency, passage efficiency, and failure locations are usually reported incompletely from fishway evaluations (Roscoe and Hinch 2010; Bunt et al. 2012) but are useful for fisheries managers as spawning failures stemming from inadequate fish passage at dams can have severe consequences on migratory fish populations (Wilcox and Murphy 1985) and ecosystems in general (Holmlund 1999). Although the radio telemetry component of the study failed, it does point to the need for tag validation studies when conducting tracking studies of redhorse given their apparent sensitivity to a technique that is generally regarded as minimally invasive (Bridger and Booth 2000).

3.7 Tables

Table 3-1. Tag burden as a proportion of body weight for three redhorse species. R^2 values for the length-weight relationship for each species generated from unpublished data are also shown.

	Silver redhorse		**River redhorse**		**Shorthead redhorse**	
	Female	Male	Female	Male	Female	Male
Mean (% of body weight) ± SE	0. 56 ± 0.02	0.77 ± 0.06	0.47 ± 0.03	0.54 ± 0.04	1.41 ± 0.06	1.88 ± 0.06
R^2 ($\log_{10}$length:$\log_{10}$weight)	0.86	0.93	0.83	0.80	0.94	0.85

Table 3-2. Summary information for three species of redhorse that were radio and PIT tagged and were released downstream of the Vianney-Legendre fishway.

Species (*n*)	Sex (*n*)	Mean length and Range (mm)	Percent detected in the array (*n*)	Average number of days fish were detected in the array	Percent reaching fishway entrance (*n*)	Percent successful passage (*n*)
Silver redhorse (39)	M (20)	519 ± 8.2 415-559	30 (6)	2.7	0	0
	F (19)	559 ± 5.4 496-590	73.7 (14)	4.7	2.6 (1)	2.6 (1)
River redhorse (38)	M (19)	588 ± 4.7 537-641	10.5 (2)	3	0	0
	F (19)	601 ± 8.1 528-654	10.5 (2)	1.5	0	0
Shorthead redhorse (39)	M (20)	395 ± 3.8 367-429	15 (3)	1	0	0
	F (19)	434 ± 5.5 404-486	31.6 (6)	1.8	0	0

Table 3-3. Summary information for three species of redhorse PIT tagged and released downstream of the Vianney-Legendre fishway.

Species (*n*)	Sex (*n*)	Total length (mm)	Release bank* (*n*)	Attraction efficiency % (*n*)		Passage efficiency % (*n*)		Entrance delay (h)**		Passage duration (h)**	
				By release bank	Species as a whole	By release bank	Species as a whole	By release bank	Species as a whole	By release bank	Species as a whole
Silver redhorse (120)	M (58)	519 ± 5.6 410-610	East (27)	41 (11)	50 (60)	100 (11)	88 (53)	194 ± 24 (9)	153 ± 10 63-308 (45)	0.9 ± 0.2 (9)	7 ± 4 0.4-140 (38)
			West (31)	32 (10)		70 (7)		164 ± 20 (9)		0.9 ± 0.2 (6)	
	F (62)	559 ± 4.3 482-624	East (33)	82 (27)		85 (23)		135 ± 14 (20)		11 ± 9 (16)	
			West (29)	41 (12)		100 (12)		137 ± 29 (7)		8 ± 7 (7)	
River redhorse (70)	M (36)	595 ± 5.4 521-660	East (21)	10 (2)	17 (12)	50 (1)	50 (6)	-	71 ± 33 38-103 (2)	-	2 ± 0.6 1-3 (3)
			West (15)	5 (1)		100 (1)		-		1 (1)	
	F (34)	622 ± 7.9 533-709	East (14)	14 (2)		50 (1)		-		-	
			West (20)	35 (7)		43 (3)		71 ± 33 (2)		3 ± 0.8 (2)	
Shorthead redhorse (39)	M (59)	392 ± 3.0 343-436	East (29)	38 (11)	51 (61)	55 (6)	69 (42)	191 ± 31 (10)	190 ± 11 69-409 (52)	119 ± 22 (5)	51 ± 11 0.3-217 (35)
			West (30)	47(14)		64 (9)		201 ± 19 (13)		47 ± 22 (8)	
	F (61)	432 ± 3.6 368-500	East (31)	61 (19)		68 (13)		176 ± 19 (16)		20 ± 12 (10)	
			West (30)	57 (17)		82 (14)		193 ± 23 (13)		52 ± 22 (12)	

*Fishway is located on the west bank

** Numbers in parentheses are the number of individuals for which entrance delay and passage duration could be determined.

Table 3-4. Results of two-way ANOVA performed for two passage variables, entrance delay and passage duration, with sex, bank release, and sex × bank as effects.

Species	Passage variable	Sex			Release bank			Sex × Release bank		
		F	df	p	F	df	p	F	df	p
silver redhorse	Entrance delay	4.70	1, 41	0.036	0.30	1, 41	0.30	0.38	1, 41	0.54
	Passage duration	1.10	1, 34	0.30	0.60	1, 34	0.44	0.52	1, 34	0.47
shorthead redhorse	Entrance delay	0.25	1, 48	0.62	0.37	1, 48	0.55	0.016	1, 48	0.90
	Passage duration	5.72	1, 31	0.023	0.18	1, 31	0.68	9.82	1, 31	0.004

Table 3-5. Results of logistic regression analysis examining the probability of detection and passage at the Vianney-Legendre fishway for three redhorse species.

Variable	Detection			Passage		
	Silver redhorse	River redhorse	Shorthead redhorse	Silver redhorse	River redhorse	Shorthead redhorse
Constant: β ± SE	-1.48 ± 3.27	-8.22 ± 6.71	-3.99 ± 3.56	0.61 ± 3.26	-7.44 ± 7.87	-7.16 ± 3.83
p	0.65	0.22	0.26	0.85	0.35	0.062
Length (mm): β ± SE	0.0081 ± 0.0055	0.012 ± 0.010	0.011 ± 0.0075	0.0039 ± 0.0054	0.0082 ± 0.012	0.016 ± 0.0080
p	0.14	0.25	0.16	0.48	0.49	0.050
Odds ratio, interval	1.01, 1.00-1.02	1.01, 0.99-1.03	1.01, 1.00-1.03	1.00, 0.99-1.01	1.01, 0.99-1.03	1.01, 1.00-1.03
Sex (F or M): β ± SE	-0.81 ± 0.44	-1.08 ± 0.91	-0.26 ± 0.47	-0.91 ± 0.44	-0.48 ± 0.99	-0.25 ± 0.50
p	0.065	0.24	0.58	0.040	0.63	0.62
Odds ratio, interval	0.45, 0.19-10.05	0.34, 0.057-2.02	0.77, 0.31-1.94	0.40, 0.17-0.96	0.62, 0.088-4.31	0.78, 0.29-2.08
Release bank: β ± SE	-1.15 ± 0.40	0.33 ± 0.81	0.052 ± 0.37	-1.05 ± 0.40	0.47 ± 0.99	0.30 ± 0.40
p	0.004	0.69	0.89	0.008	0.63	0.46
Odds ratio, interval	0.32, 0.14-0.70	1.39, 0.28-6.8	1.05, 0.51-2.19	0.35, 0.16-0.76	1.59, 0.25-10.23	1.35, 0.62-2.94
Likelihood ratio p	<0.001	0.125	0.143	0.001	0.599	0.024

3.8 Figures

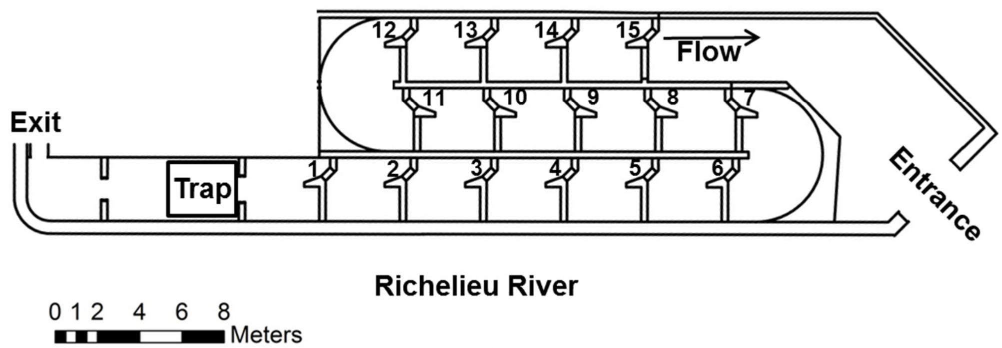

Figure 3-1. A schematic of the fishway showing the fishway entrance and exit, the location of the fish trap, the flow direction, and each basin labeled with its corresponding PIT antenna number.

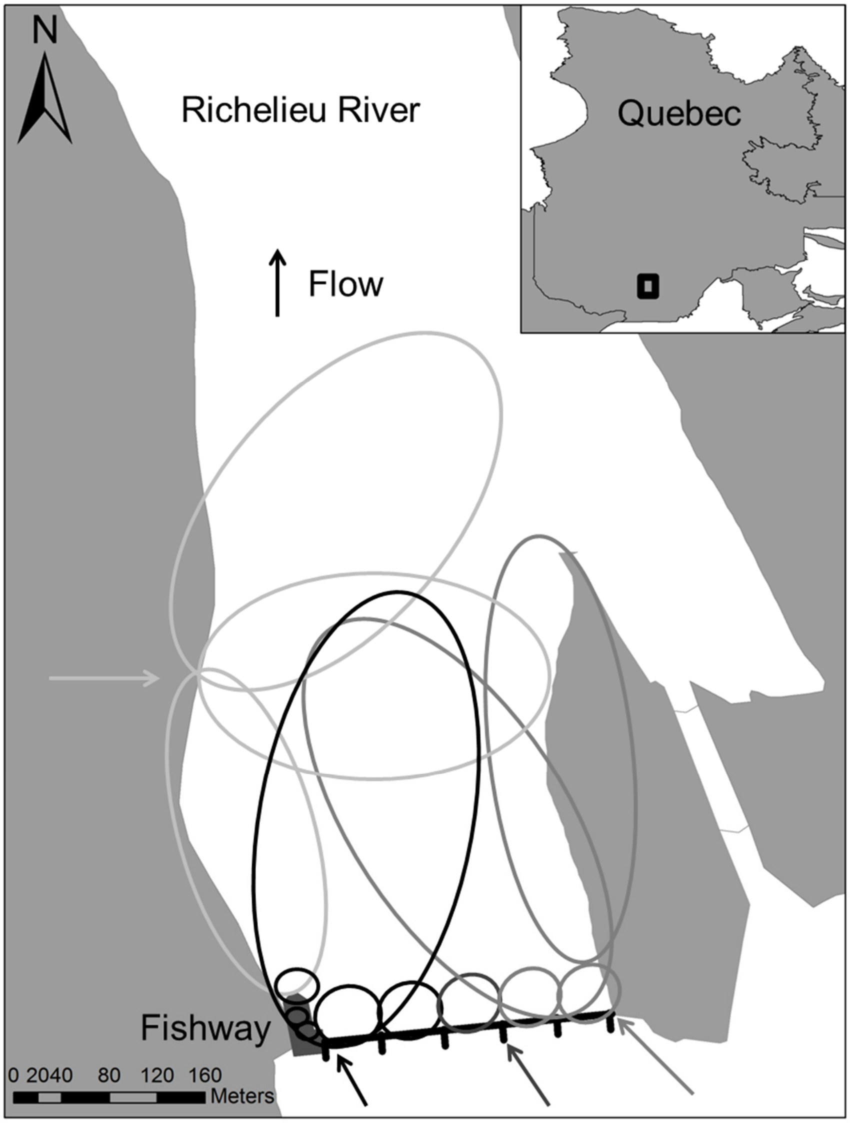

Figure 3-2. Schematic overhead view of the Richelieu River downstream of the St. Ours dam, arrows point to the location of each radio receiver and radio antenna detection cells are shown and shaded differently for their respective receivers. The fishway is just to the right of the fishway label. Two reception cells are shown within the fishway with a third just outside the fishway entrance.

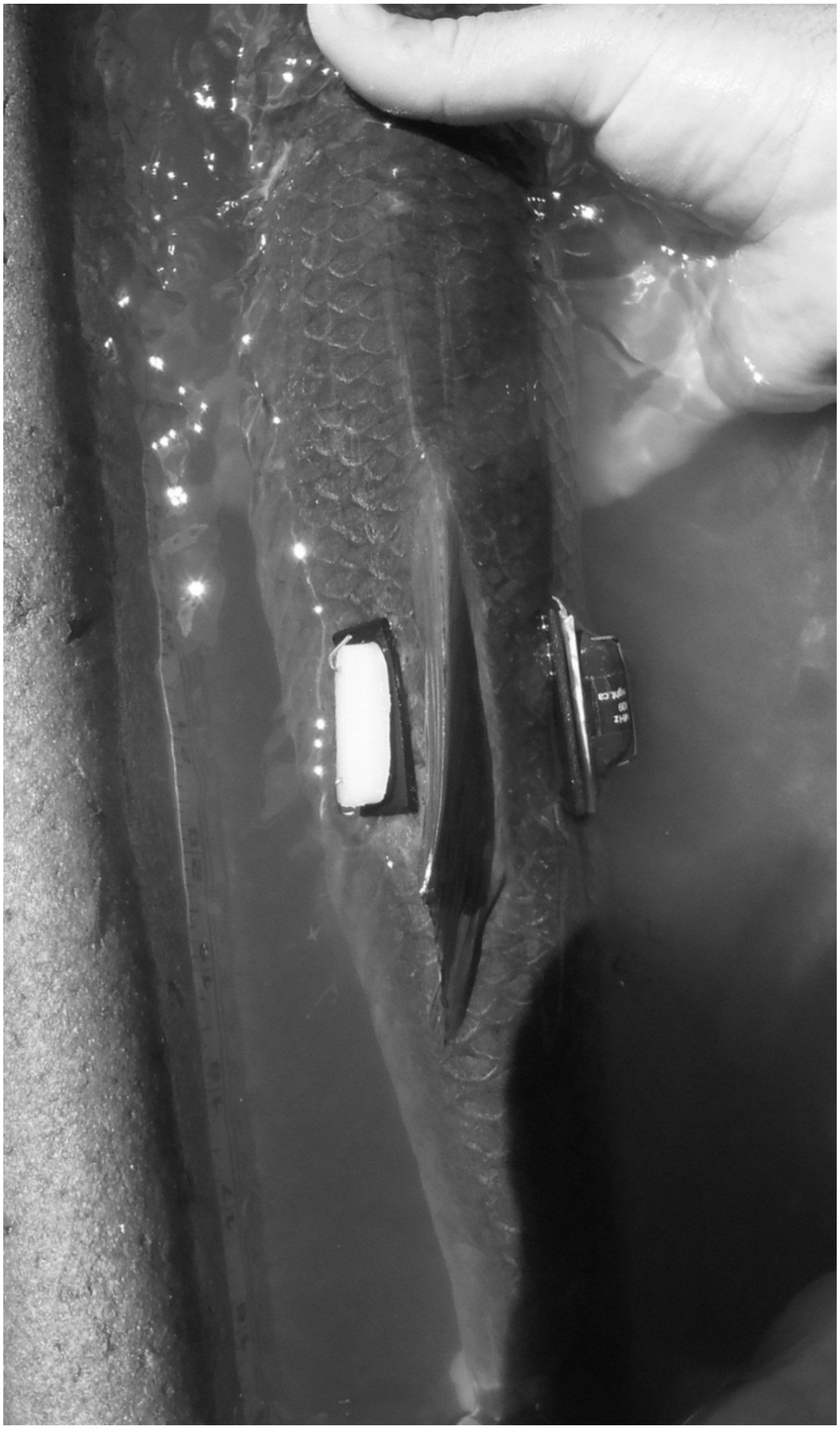

Figure 3-3. An attached radio tag and plastic backing plate held in place by stainless steel wire below the dorsal fin of a shorthead redhorse (*M. macrolepidotum*).

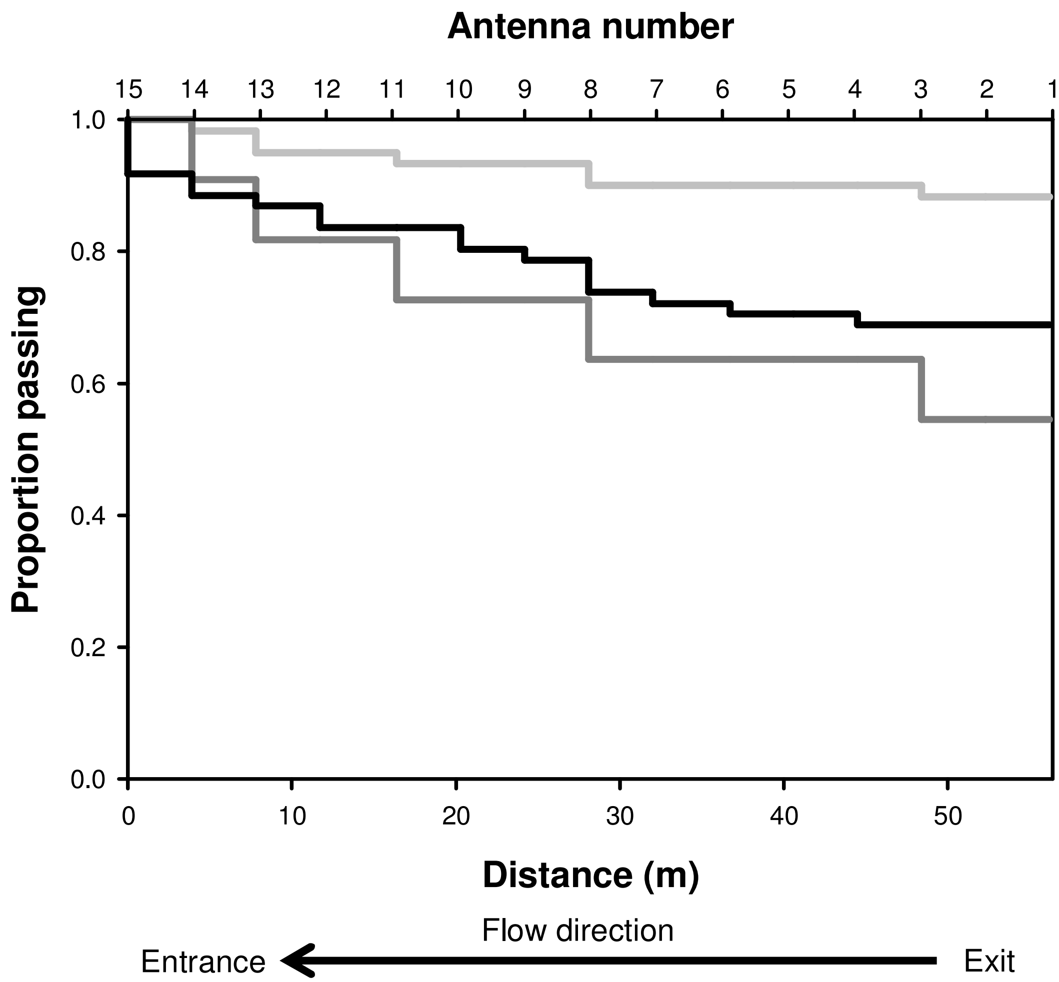

Figure 3-4. Proportional maximum upstream distance achieved by three redhorse species attempting to ascend the Vianney-Legendre fishway determined using LogRank survival analysis. Flow in this figure is moving from right to left. The coloured lines represent passage by different species (— silver redhorse; — river redhorse; — shorthead redhorse).

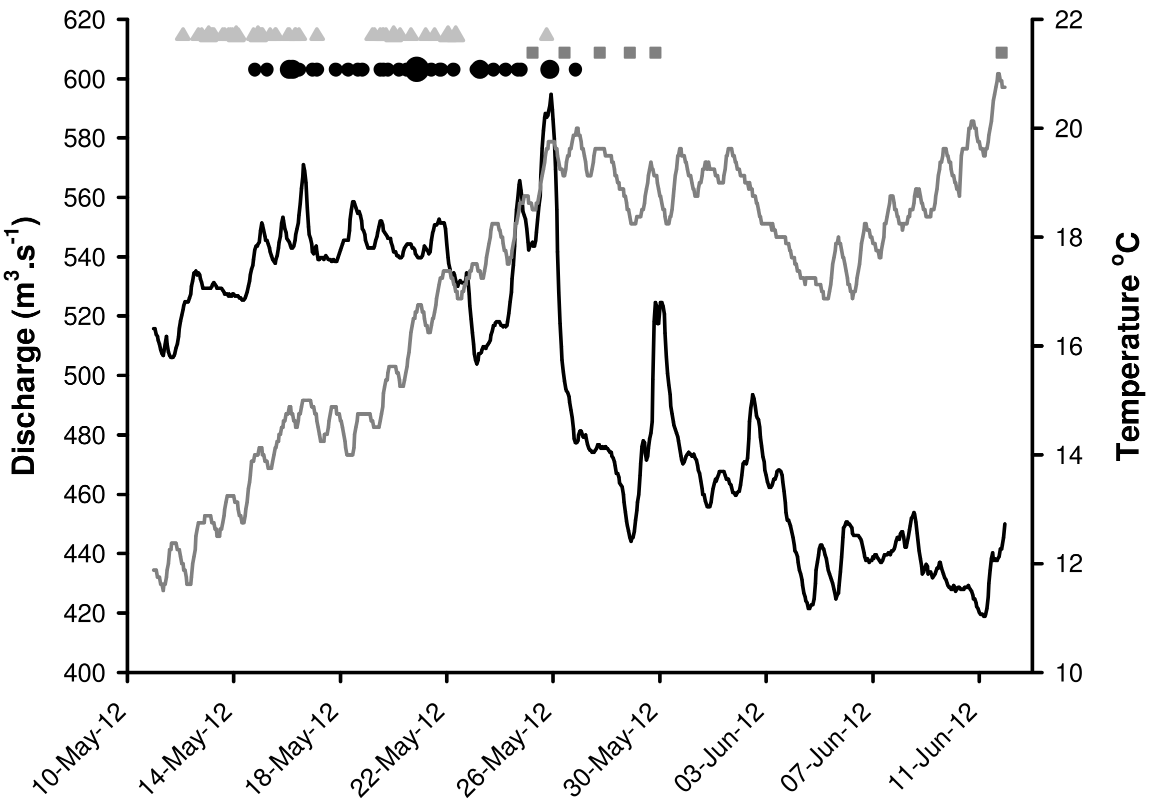

Figure 3-5. River discharge ($m^3.s^{-1}$) and water temperature (ºC) for the Richelieu River during passage events by three redhorse species at the Vianney-Legendre fishway in the spring of 2012. Larger symbols indicate passage by more than 1 individual. Symbols represent; ━Temperature (ºC), ━ Discharge $m^3.s^{-1}$, ▲ silver redhorse, ■ river redhorse, ● shorthead redhorse.

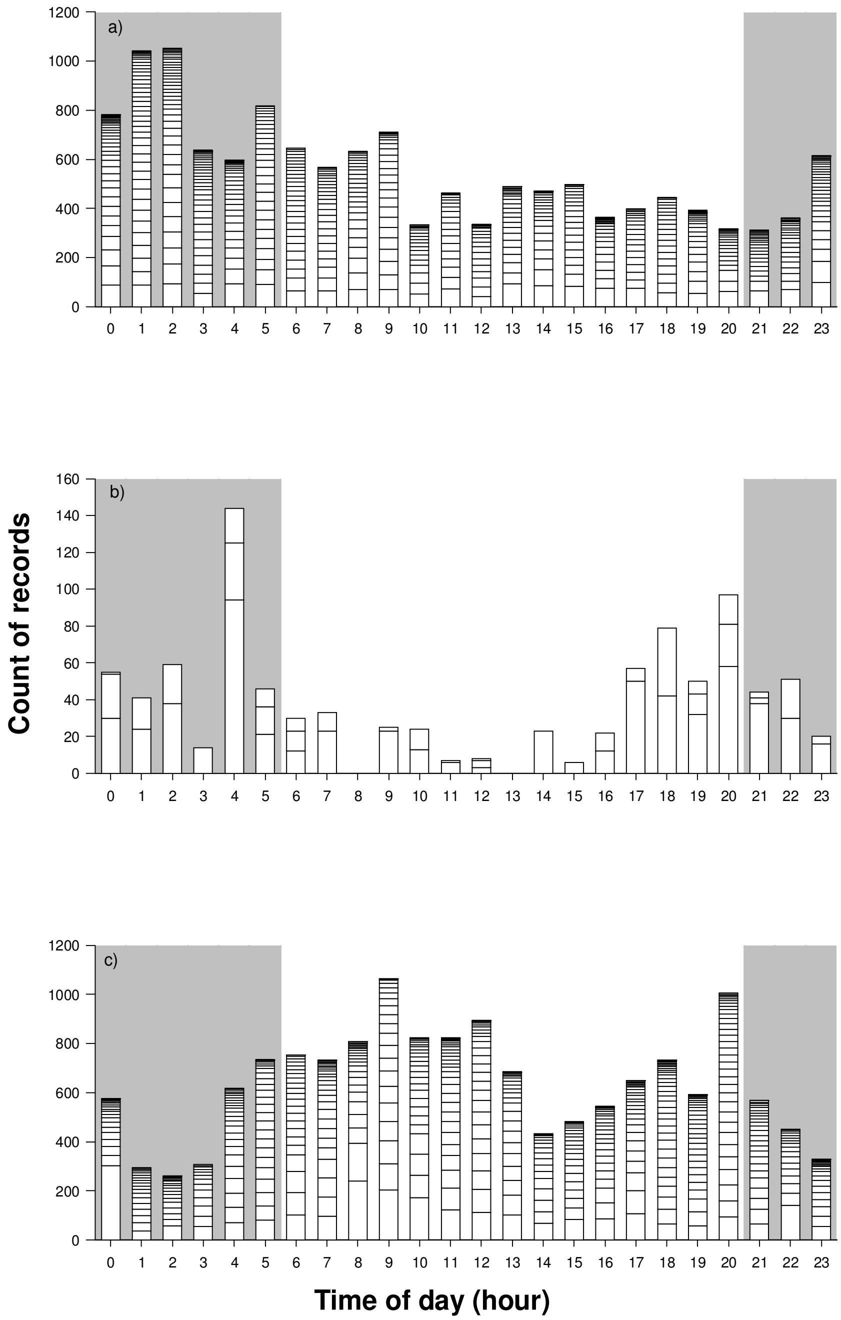

Figure 3-6. Diel fishway use by a) silver redhorse, b) river redhorse, and c) shorthead redhorse. Stacked bars show the relative contributions of individuals (all fish through all the antennas) and data is pooled over the entire study period. Grey shading indicated approximate night periods and no shading indicates approximate day periods based on local sunrise/sunset conditions for middle of the study period (~0530 and 2030).

4 Chapter: Comparative physiology and relative swimming performance of three redhorse (*Moxostoma* spp.) species: associations with fishway passage success and implications for fishway research

4.1 Abstract

Our understanding of biological design criteria to facilitate fishway passage design is limited, partially due to the lack of understanding of biological motivators, cues and constraints, as well as a lack of biological performance evaluations of structures once they are built. The Vianney-Legendre vertical slot fishway on the Richelieu River, Quebec, passes large numbers of migrating redhorse (*Moxostoma* spp.) upriver to spawning grounds each year. We evaluated the physiological capacity and relative swimming ability of three redhorse species (*M. anisurum, M. carinatum*, *M. macrolepidotum*; silver, river and shorthead redhorse respectively) to determine how these biotic factors relate to variation in fishway passage success and duration. Shorthead redhorse had higher maximum metabolic rates and were faster swimmers than silver and river redhorse. River redhorse recovered their lactate and glucose concentrations more quickly than silver and shorthead redhorse, and river redhorse were second in terms of metabolic recovery and swim speed. Additionally, fish sampled from the top of the fishway had nearly identical lactate, glucose and pH values compared to control fish. Using passive integrated transponders in 2010 and 2012 we observed that passage success and duration was highly variable among redhorse species and was not consistent among years suggesting that other factors such as water temperature, timing of the study and river flows modulate passage success. Clearly additional research is needed to understand how organismal performance, environmental conditions, and other factors

(including abundance of conspecifics and other co-migrants) interact with fishway design features to dictate which fish will be successful and to inform research of future fishways. Our research suggests that there may be an opportunity for a rapid assessment approach where manual chasing and sampling of fish from the top of the fishway are used to determine which species (or sizes of fish) are exceeding their physiological capacity during passage.

4.2 Introduction

The use of physiological knowledge to inform conservation problems (i.e., conservation physiology; Wikelski and Cooke 2006) has great potential, particularly given that physiological tools can quantify individual responses of organisms to anthropogenic changes that might contribute to population declines (Cooke and O'Connor, 2010). For fish, physiological tools have been applied to understand and solve conservation problems or other fisheries management issues for some time (summarized in Young et al. 2006). However, the application of physiology to fishway science has been limited (Roscoe and Hinch 2010). Recently, some physiological tools have been successful in identifying how fish populations are affected by dams (e.g., Hasler et al. 2009) and fishway passage (Pon et al. 2012). Although fishways are a fairly common conservation strategy to address river fragmentation, they are rarely subject to adequate biological study to determine if they are successful (Bunt et al. 2012). Early studies would deem a facility successful if fish were observed (e.g., captured in traps, documented via video, human observation) reaching the top of a fishway, but that approach does not document those individuals that fail to do so (Roscoe and Hinch 2010). More recently, studies of fishway success (mostly using biotelemetry) have begun to focus on quantifying fishway attraction (the proportion of a fish population attracted to the fishway entrance) and passage efficiency (proportion of fish attracted to the fishway that successfully ascend) (Roscoe and Hinch 2010; Noonan et al. 2012). Recent meta-analyses have revealed that attraction and passage success are highly variable among fishway types and species, and in many cases are quite low (Bunt et al. 2012; Noonan et al. 2012). Clearly, our understanding of biological criteria to facilitate fishway passage design is limited which is due in large part to the lack of knowledge on biological motivators, cues and constraints, as well as a lack of biological data on fishway performance once they are built (Bernhardt et al. 2005; Castro-Santos et al. 2009; Kemp 2012).

There are many possible factors that influence attraction and passage efficiency at fishways. Successful passage is thought to be driven by the relationship between an individuals' motivation, ability and behavioural choices, and the environmental and hydraulic conditions encountered at a site (Kemp 2012). In other words, one must understand the behaviour, endocrinology, sensory physiology, swimming, and metabolic capacity of fish and how they interact with complex environmental cues and features (including hydraulic properties such as variable flows, velocity and turbulence, as well as light, temperature, etc.) to understand the potential mechanisms driving passage success or failure (Castro-Santos et al. 2009; Williams et al. 2012). This type of information is needed if we are to then find out how the aforementioned biotic factors relate to fishway design and success, something that is sorely needed but has been very difficult to do (Kemp 2012; Williams et al. 2012).

Fish behaviour in terms of attraction and passage success can be determined by studying a fish's movement both downstream and inside a fishway (e.g., Castro-Santos et al. 1996; Bunt et al. 1999; Hinch and Bratty 2000). Information such as transit times and resting periods can often be studied using bio-telemetry (e.g. Thiem et al. 2011). Swimming ability of fishes is commonly measured in a laboratory setting where a fish is forced to swim against a current with a known velocity, often generating estimates of critical swimming speed or estimates of time to fatigue (e.g., Peake et al., 2008). Knowledge of the swimming ability of different fishes has been used to identify potential velocity barriers (Peake et al. 1997a,b; Cheong et al. 2006) and generate models for use in the evaluation of different fishway passage facilities (Haro et al. 2004), thus informing biological design criteria (Rodriguez et al. 2006; Katopodis and Gervais 2012). Physiological methods such as muscle and blood biochemistry, and respiratory energetics (e.g., metabolic rate, aerobic capacity), have been identified as useful ways to measure the physiological consequences of fishway passage (e.g., Connor et al. 1964; Dominy 1971; Schwalme et al. 1985; Roscoe et al. 2010; Cocherell et al. 2011; Pon et al. 2012). Additionally, physiological methods have also been used to evaluate factors determining passage success (Peake and Farrell 2004; Pon et al. 2009; Hasler et al. 2009). However, there have been relatively few studies that have evaluated physiological aspects of fishway passage despite the fact that physiology is one of the primary drivers of ability. In their review, Roscoe and Hinch (2010) determined that only 7% of fishway studies incorporated some measure of fish physiology. The tool box for studying the mechanistic basis for fishway passage success certainly exists (reviewed in Roscoe and Hinch 2010; Hasler et al. 2009; outlined above) and various tools and techniques have been used independently, but few studies have attempted to study behavioural and physiological attributes simultaneously to understand the mechanistic basis of differential passage success.

Most studies on fishway passage have focused mainly on salmonids but there is a need to examine other fish species, such as catostomids, which frequently dominate the bulk of biomass at fishways (e.g., Schwalme et al. 1985; Bunt et al. 2001; Pratt et al. 2009) and exhibit an obligate migratory phase (or similar) resulting in susceptibility to fragmentation (Cooke et al. 2005a; Reid et al. 2008). The Richelieu River offers us a unique opportunity due to its high abundance and diversity of this family in particular members of the *Moxostoma* genus. The objective of this study was to evaluate the physiological capacity and swimming ability (in a field laboratory on the riverbank) of three congeneric species of redhorse (*Moxostoma carinatum*, *Moxostoma macrolepidotum* and *Moxostoma anisurum*) and determine how those biotic factors relate to variation in passage success and duration through a vertical slot fishway. Specifically, we evaluated swimming ability (time to exhaustion and distance swam per unit time), aerobic scope and recovery, and post-exercise blood chemistry with the expectation that the species with better performance would have higher passage efficiency. For the purpose of this paper we consider the physiological findings in the context of patterns observed in passage success and timing in the discussion rather than focusing on an extensive analysis of behavioural data. The integrative conservation physiology approach used here has the potential to elucidate the reasons for interspecific variation in passage success and the factors that may hinder successful passage. Ideally such knowledge will inform biological design criteria such that fishways can pass entire fish communities.

4.3 Methods

Study site and fish collection

The study was conducted at the Vianney-Legendre fishway located on the Richelieu River near St. Ours, Quebec, Canada (45º52´N 73º09´W). A detailed description of the fishway can be found in Thiem et al. (2011). Briefly, the fishway is a 85 m long concrete fishway with 16 vertical slots (0.6 m width, 2.3 m to 4.0 m in height per slot as you move downstream), with a total rise of 2.65 m and an average slope of 4 percent. The fishway is divided into 12 rectangular basins (3.5 m x 3.0 m), two turning/resting basins with curved walls (2.75 m radius), and a large entry and exit basin. Each basin has a drop of 0.15 m moving downstream. Experiments were carried out over two seasons due to widespread flooding of the Richelieu River in 2011. Respirometry trials were conducted between May 30th and June 13th, 2011. The swimming performance and blood physiology experiments were conducted between April 22nd and May 25th, 2012. The three redhorse species used in this study (*M. macrolepidotum, M. anisurum and M. carinatum,* shorthead redhorse, silver redhorse, and river redhorse respectively) were captured directly from a fish trap located at the top of the fishway. The fish trap is a 2.2 m x 2.0 m cage designed with the general purpose of enumerating fish that have moved up the fishway. The fish trap was emptied once per day for the duration of the study. Fish were held on-site for 24 hours prior to all experimentation in 2250L flow-through hatchery tanks (with water pumped directly from the river replaced at a rate of ca. 50 $L.min^{-1}$) and allowed to recuperate from their capture. Fish were not fed to allow for gut clearance. It was not possible to capture fish downstream using nets or electrofishing given the presence of critically endangered copper redhorse (*M. hubbsi*) and concerns regarding their incidental capture. We assumed that capture in the fish trap of large numbers of redhorse by species indicated optimal timing of migration and thus conducted experiments for each species as they were encountered. In 2012, the water temperatures experienced by fish during peak migration windows were reasonably stable such that experiments for a given species occurred within the relatively narrow temperature range (silver redhorse 9.6 ± 0.4 ^{o}C, shorthead redhorse 9.9 ± 0.4 ^{o}C, river redhorse 16.4 ± 0.3 ^{o}C). Rather than conduct experiments at a fixed temperature for all species it was deemed more ecologically relevant to conduct experiments at ambient temperatures that coincided with peak migration time for each species.

Respirometry study

It was not possible to measure standard metabolic rate. Instead we adopted a model where we chased fish to exhaustion and then monitored their metabolic recovery at intervals over 4 hours. We considered the 4 hour period to represent baseline values (return to routine metabolic rate) given that previous studies have demonstrated metabolic rate recovers in that time period (Brett 1964; Redpath et al. 2010) although we acknowledge that the values we recorded after 4 hours were higher than true standard metabolic rate. Recovery rates were determined using closed system respirometry as described in Steffensen (1989), where oxygen consumption is measured by calculating the amount of O_2 depletion in the respirometry chamber when the flush pump (the pump which brings fresh river water into the chamber) is turned off. Oxygen concentrations in the chambers were measured using dissolved oxygen probes (Qubit Systems, S120 dissolved O_2 probe, accuracy ± 0.2mg/L) and logged using c901 LoggerPro software, version 3.6.1., (Vernier Software and Technology) connected to a laptop through the c410 LabPro interface (Vernier Software and Technology). The experiment was designed so that the recovery of each fish could be quantified from their oxygen consumption at 4 time intervals: immediately post exhaustion, 30 minutes post exhaustion, 2 hours post exhaustion, and 4 hours post exhaustion.

Aerobic capacity and recovery from exhaustive exercise were compared among 9 silver redhorse (TL (total length) 408 ± 20 mm; mean ± SD), 9 shorthead redhorse (TL 337 ± 15 mm), and 9 river redhorse (TL 571 ± 59 mm). Fish were initially chased to exhaustion in an annular swim flume (diameter 130 cm, water depth of 40 cm, at ambient water temperature) before being transferred into cylindrical polycarbonate respirometry chambers (75 cm length with a 10 cm radius, 23.55L volume). Exhaustion for a fish was determined when the fish was unable to right itself after 2 seconds following chasing by hand (tail poking and pinching). Each respirometry chamber was connected to two standard aquarium pumps (Maxi-Jet 900, Marineland Aquarium Supplies) with one pump recirculating water through the chamber and the other pump periodically pumping fresh oxygenated river water into the chamber.

Since DO_2 concentrations below 75% of air saturation levels have been shown to have negative effects on the swimming ability of some fishes (Dahlberg 1968) measurement cycles were calibrated for different size classes of fish. Fish greater than 1.5 kg were subject to measurement periods of 5 cycles which consisted of a 2 minute measurement phase and 3 minute flush phase to replace water in the chamber. Fish with mass between 0.5 kg and 1.5kg were subject to 3 cycles which consisted of a 5 minute measurement phase and 3 minute flush phase. Fish under 0.5 kg in weight were subject to 2 cycles which consisted of a 10 minute measurement phase and a 3 minute flush phase. Oxygen consumption values across each measurement phase were averaged for each respective recovery period.

The change in oxygen concentration was calculated using the following equation:

$$MO_2 = \alpha V_{resp} M_b^{-1},$$

where MO_2 represents the oxygen consumption in milligrams of oxygen per kilogram of fish per hour (MO_2 = mg O_2 $kg^{-1}h^{-1}$), α is the change in oxygen concentration for each fish ($\Delta O_{2saturation}/\Delta t$), V_{resp} is the volume of the respirometer minus the volume of the fish (L) and M_b which was the mass (kg) of the fish (Steffensen, 1989). Calculated O_2 consumption rates were adjusted for background O_2 consumption by running a background respirometer and subtracting the values calculated for the background chamber from those calculated for the chambers containing fish. Oxygen probes were calibrated following the guidelines provided in the Qubit Systems manual before each trial was conducted.

Relative swimming ability

Fish were sourced and held for 24 hrs (such that fish were in a post-absorptive state) as described above. Relative swimming ability between the three redhorse species (n=60 per species; TL *M. anisurum* 520 ± 7 mm, TL *M. carinatum* 608 ± 5 mm, TL *M. macrolepidotum* 404 ± 4 mm) was tested by swimming individual fish to exhaustion in an annular swim flume 130 cm in diameter with water that was 40 cm deep (e.g. Portz, 2007). Water was refreshed between fish and was obtained from the river such that temperatures were the same as the water in the tanks where they were held prior to experimentation. The annular swim flume was divided into four quadrants and the number of quadrants each fish passed through was recorded for the first 20 seconds of swimming for each fish to allow for relative swimming speed measurements to be made. The total distance swam by each fish until exhaustion was also recorded. Since fish almost always swam around the outside edge of the flume the distance swum by each fish per quadrant was the total circumference of the flume divided by four, or 1.02 m. Fish were determined to be exhausted when they were no longer able to regain equilibrium (right themselves) after 2 seconds. Equilibrium was used as the measure of exhaustion because some of the redhorse species (silver and river redhorse) did not respond to tail grabbing. This relative measure of swimming performance used here for comparative purposes has been used in the past by others (see Portz 2007). Although the actual values are not a direct measure of swimming ability, the relative differences between groups (or species) is relevant. Swim speeds were normalized by converting data to body lengths swam, per distance unit (cm) per second.

Blood physiology profiles

To generate physiological recovery profiles for each species, fish were placed in hypolon fish carrying bags (recovery bags) (Dynamic Aqua Supply Ltd., Vancouver, British Columbia; 101 cm length, 23 cm diameter with 0.5 cm mesh on both ends; product #FT940) post exhaustion. Recovery profiles were generated by blood sampling fish for glucose, lactate, and pH levels at six different time intervals (n=10 fish per species per time interval – no fish were sampled more than once). The first recovery group contained fish that were blood sampled immediately (within 1 min of landing) after they were dip netted out of the fish trap at the top of the fishway. The second recovery group contained fish used as the baseline group. Fish in the second recovery group were not swum to exhaustion and after the initial minimum holding time of 24 hours had passed, these fish were placed in recovery bags for 24 hours (to avoid any influence of handling stress) and then blood sampled. Recovery groups three, four, five and six contained fish blood sampled after being in recovery bags for 30 minutes, 60 minutes, 120 minutes, and 240 minutes respectively after swimming to exhaustion. Upon removal from recovery bags or upon capture (first group), fish were immediately placed in a water-filled v-shaped trough in a supine position and non-lethally blood sampled via caudal puncture using a 3 ml vaccutainer (lithium heparain anticoagulant) and 18 g needle (Cooke et al. 2005). Blood samples (~1 ml was collected from each fish) were placed in a water-ice slurry and analyzed within 10 minutes of collection for glucose, lactate and pH levels. Glucose levels were measured using Accu-chek® Compact Plus glucose meters (Roche Diagnostics, Indianapolis, USA) and lactate levels were measured using the Lactate Pro LT-1710 Analyzer (Arkay Inc., Kyoto, Japan). These physiological measurement tools have previously been validated as blood diagnostic tools for fish providing results that are comparable to laboratory tools (e.g., Venn Beecham et al. 2006; Cooke et al. 2008). Blood pH was measured using the mini-lab IQ128 pH meter which has an accuracy of ± 0.02 pH.

Passage success and duration

In contrast to the previous experiments (i.e., Thiem et al. In Press) fish used for the determination of passage success were not held in recovery basins for 24 hours prior to experimentation but were tagged immediately after capture from the fish trap at the top of the fishway. The three redhorse species were tagged (n=120 *M. macrolepidotum*, n=120 *M. anisurum*, n=60 *M. carinatum*) with uniquely coded passive integrated transponder (PIT) tags (23 x 3.85 mm HDX: Texas Instruments, Dallas, USA) inserted into their peritoneal cavity (more details on the tagging procedure see Thiem et al. 2012). Total length (TL) of each fish was measured along with a determination of sex accomplished through visual identification (abdominal pressure and gamete extrusion as well as the presence of tubercules on caudal fins and snout). Following tagging fish were released approximately 200m downstream of the fishway in equal numbers on both banks of the river. Passage success described as a fish successfully moving past the most upstream antenna, was then determined using the PIT antenna array described in Thiem et al. (2011). Passage duration was determined by calculating the time taken from a fish's first detection on the most downstream antenna to the first detection on the most upstream antenna. Fish were tagged during the height of their migratory period respective for their species; *M. macrolepidotum* and *M. anisurum* were tagged between May 5th and May 14th, 2012, while *M. carinatum* were tagged between May 24th and May 25th, 2012. The fishway was monitored for passage between May 14th and July 10th, 2012.

Data Analysis

Changes in oxygen consumption for the four recovery groups were analyzed using a two-way repeated measures ANOVA; pairwise comparisons were performed using Bonferonni post-hoc tests. Changes in blood lactate, glucose, and pH levels were analyzed using separate two-way ANOVAs, significant interactions were investigated using Holm-Sidak and Bonferonni post-hoc tests. Differences in relative swimming speed and time to exhaustion between the three species were analyzed using separate one-way ANOVAs, significance was investigated using Tukey's HSD (honestly significant difference) test. Assumptions for all analysis (including sphericity for the repeated measures ANOVA) were checked according to Field (2009). All effects are reported as significant at $p < 0.05$. All analysis were performed using SigmaStat (SigmaPlot 11, Systat Software Inc.) and PASW Statistics 18 (SPSS, IBM 2009, USA).

4.4 Results

Respirometry study

Oxygen consumption during recovery differed among species. There was a significant main effect of species on oxygen consumption ($F_s = 5.95$; df = 2, 16; $p = 0.015$; Figure 1). Shorthead redhorse had significantly higher oxygen consumption values than silver redhorse ($p = 0.001$), but was not significantly higher than river redhorse ($p = 0.350$). Additionally river redhorse consumption was not significantly higher than silver redhorse consumption ($p = 0.106$). There was also a significant main effect of recovery interval on oxygen consumption ($F_s = 45.31$; df = 3, 24; $p < 0.001$; Figure 1A) where oxygen consumption peaked immediately following exercise and then decreased to some extent by 2 hours post exercise. Pairwise comparisons for recovery intervals revealed that significant differences existed between all recovery intervals ($p < 0.001$) except for the comparison between the thirty minute and 2 hour recovery groups ($p = 0.078$) and the comparison between the 2 hour and 4 hour recovery groups ($p = 0.064$). There was no significant interaction effect between species and the recovery interval. Shorthead redhorse also recovered the largest proportion of their maximum O_2 consumption the fastest, with silver redhorse and river redhorse recovering at approximately the same rate (Figure 1B).

Blood analyses

There was a significant interaction effect between species and recovery interval for blood lactate concentrations ($F_s = 5.899$; df = 10, 162; $p<0.001$; Table 1). Silver redhorse had significantly lower lactate levels than river redhorse at the half hour ($p = 0.006$) time interval but had significantly higher lactate levels than river redhorse at the 2 hour ($p = 0.002$) and 4 hour ($p < 0.001$) time intervals. Shorthead redhorse had significantly higher lactate levels than river redhorse at the 2 hour ($p = 0.015$) and 4 hour ($p < 0.001$) time intervals. No other comparisons were significant (Figure 2).

There was a significant interaction effect between species and recovery interval for blood glucose concentrations ($F_s = 2.753$; df = 10, 162; $p = 0.004$; Table 1). Silver redhorse had significantly higher glucose levels than river redhorse at the one hour ($p < 0.001$), 2 hour ($p = 0.001$) and 4 hour ($p = 0.012$) intervals. Additionally, silver redhorse had significantly higher glucose levels than shorthead redhorse at the 2 hour ($p = 0.009$) and 4 hour ($p = 0.013$) time intervals. No other comparisons were significant (Figure 2).

No effect of species on blood pH was found and there was no significant interaction effect between species and recovery group, however, a significant effect of recovery group on blood pH levels was identified ($F_s = 5.32$; df = 10, 153; $p < 0.001$; Table 1). The baseline and fish trap groups had significantly higher pH levels from all other time interval groups ($p < 0\ .03$) except at the 4 hour time interval (the baseline group did not differ significantly from the one hour time interval group, $p = 0.056$). In general, pH values dropped after exercise and then rebounded to near pre-exercise levels after 4 hours of recovery (Figure 2).

Swimming speed analysis

We identified a significant effect of species on swimming speed (F_s = 47.47; df = 2, 117; $p<0.001$; Figure 3). All three species differed significantly ($p<0.001$) in their relative swim speeds (i.e., shorthead redhorse swam the fastest, river redhorse had intermediate swim speeds and silver redhorse were the slowest).

Similarly, we identified a significant effect of species on time to exhaustion (F_s = 10.95; df = 2,117; $p<0.001$; Figure 3). River redhorse became exhausted sooner than both shorthead redhorse ($p<0.001$) and silver redhorse ($p<0.05$). There was no significant difference in the time to exhaustion between silver redhorse and shorthead redhorse ($p>0.05$).

Passage success and duration

In 2012, silver redhorse had the highest passage efficiency between the three species with an 88% success rate (Table 2). Shorthead redhorse followed with 69% success with river redhorse having the lowest passage success rate at 50%. Silver redhorse also had the shortest passage duration times with a median passage duration time of 0.94 hours (56.4 minutes). River redhorse had the second shortest passage duration time with a median value of 1.95 hours (117 minutes; only one record was available). Shorthead redhorse had the longest passage duration times with a median value of 5.14 hours (308.4 minutes).

4.5 Discussion

In this study we sought to determine the relationship between physiology and fishway performance (i.e., passage success, passage speed) among three congeneric redhorse species. To date, physiology has rarely been incorporated into fishway science (Roscoe and Hinch 2010) despite the fact that physiological capacity underlies passage potential (Kemp 2012) and therefore has the potential to explain the high level of variability in passage success observed in field assessments of the biological effects of fishways (Hasler et al. 2009). Beyond exploring the physiology of redhorse relative to passage at the Vianney-Legendre fishway, a secondary goal was to highlight the potential role of physiology for enhancing biological evaluations of fishways (Roscoe and Hinch 2010) and informing the development of design criteria necessary build new fishways or refine existing ones. Here we discuss the comparative physiology of three redhorse species as well as their associations with patterns of fishway passage documented at the Vianney-Legendre fishway in 2010 (as documented by Thiem et al. 2012) and 2012. Although none of the species studied here are considered endangered, in Canada, the river redhorse is considered of special concern and thus of high priority to resource managers. This work is consistent with the theme of conservation physiology which includes the concept of using physiological knowledge to inform the development of various mitigation strategies that would benefit animal populations (Wikelski and Cooke 2006; Cooke and O'Connor 2010).

Relative metabolic recovery rates differed significantly between shorthead and silver redhorse, however, river redhorse did not have significantly different recovery rates than either of the other two species. Shorthead redhorse were also able to recover a larger proportion from their maximum oxygen consumption rate more quickly than the other two species. Oxygen consumption rates for actively swimming white suckers (see Saunders, 1982; Thurston and Gehrke 1993) were higher than the rates we obtained for three redhorse species immediately post exercise. It is important to note, however, that the values for the white suckers were taken at higher temperatures. Relevant here is the fact that we did not measure oxygen consumption at the same temperature for the three species studied. Instead we conducted respirometry trials at temperatures that coincided with peak migration time for each species. Clearly some of the inter-specific variation in respiration noted here might be expected to be driven by the manifold influence of water temperature on fish metabolism (Fry 1971). That said, the highest temperature group were the river redhorse yet their metabolic rate was intermediate between the other two species. Recent work on Pacific salmon suggests population-specific relationships between metabolic performance and temperature reflecting historic river conditions (e.g., Eliason et al. 2011) and we would predict the same for redhorse at the species level. Oxygen consumption rates that we obtained from three species of redhorse (after 4 hours of recovery) are comparable to those published for white suckers at rest, (see Beamish 1974; Clarke and Johnston 1999) but are lower than the values reported by Altman and Dittmer (1971) and from Thurston and Gehrke (1993). Independent of the influence of temperature, it is not surprising that the three species we studied showed different oxygen consumption rates as several studies have shown that even congeneric species can exhibit different rates of oxygen consumption while at rest (Basu 1959; Brett 1972; Beamish 1974). However, it is interesting that while silver redhorse and shorthead redhorse showed the greatest recovery from maximum oxygen consumption within the first 30 minutes after exhaustion exercise, river redhorse had their largest proportion of recovery from maximum consumption in the third and fourth hours post exercise. This suggests that river redhorse may require more resting time than the other two species.

Examining the blood physiology of the three redhorse species pre and post-exhaustive exercise showed recovery patterns typical of teleost fish following exhaustive exercise; an increase in blood lactate and blood glucose and a decrease in blood pH with values usually peaking within 1 to 2 hours post exercise and decreasing afterwards (Wood, 1991; Kieffer 2000). 4 hours after exercise recovery to near baseline lactate levels occurred only in the river redhorse, but pH values for all three species were close to baseline levels. Blood glucose levels for all three species showed recovery patterns consistent with an eventual return to baseline levels but had yet to return to near baseline values after 4 hours of recovery. Black (1960) showed that blood lactate levels can remain above baseline levels in strenuously exercised (fish chased in a circular hatchery trough) rainbow trout (*Oncorhynchus mykiss*) for up to 8 hours post exercise, and glucose levels remained elevated for up to 24 hours. Similarly, a study by Schwalme and Mackay (1985) on northern pike (*Esox lucius*) showed blood lactate levels above baseline levels for up to 8 hours post exercise, blood glucose levels above baseline values for up to 12 hours and blood pH values returning to baseline levels 8 hours after exercise. Silver and shorthead redhorse showed results similar to those found in the above mentioned studies, however, river redhorse appear to have recovered to baseline lactate and pH levels more quickly than rainbow trout and northern pike. Of particular interest for this study are the results from the blood samples taken from fish out of the fish trap. The lactate, glucose, and pH levels measured from fish sampled directly from the fishway are lower (or higher for pH) than laboratory controls. Moreover, the physiological profiles from fish sampled from the fishway trap at the top of the fishway are nowhere near the more altered values obtained following exhaustive manual chasing. Essentially, fish did not seem to be exerting themselves to the same level in the fishway as they were in the laboratory. While fish in the fish trap may have been resting in the trap area instead of having recently moved into the trap, past experience (unpublished data) at this site suggests that fish are routinely moving in and out of the fish trap, sometimes moving down almost to the fishway entrance before re-ascending. In fact, we may have expected to see more extreme variation in those samples but that was not the case. Additionally, the maximum time fish could have been in the trap was 24 hours as the trap was emptied each day. Even while in the trap fish would have been exposed to various stressors (including captivity, crowding, attempts to escape) so it is remarkable (based on the swimming speed results discussed below) that the values from those fish are less disturbed (i.e., lactate and glucose lower and pH higher) than those control fish held in sensory deprivation chambers and sampled after 24 hours.

Shorthead redhorse swam the fastest (~3.3 $bl.s^{-1}$) and took the longest time to reach exhaustion. River redhorse swam the second fastest (~2.5 $bl.s^{-}1$) but exhausted the fastest while silver redhorse swam the slowest (~2.1 $bl.s^{-1}$) and were second in terms of time to exhaustion (Figure 3). Jones (1974) reported average critical swim speeds (U_{crit}) of 2.16 $bl.s^{-1}$ for longnose suckers (*Catostomus catostomus*) and 2.25 $bl.s^{-1}$ for white suckers (*Castostomus commersoni*).Our study tends to support the findings of Portz (1997) that swim speeds obtained using the same methods we used here are generally similar to the U_{crit} values of fish obtained using other forced swimming methods for other Castostomids. In terms of exhaustion, not much data is available for catostomids (Peake 2008); however, a study performed on largemouth bass (*Micropoterus salmoides*) by Gingerich et al. (2010) showed bass reaching exhaustion after ~40s which is considerably shorter than the times we recorded for three redhorse species.

Passage success in 2012 was higher than in 2010 for silver redhorse and shorthead redhorse but lower for river redhorse (Table 2). Interestingly, the rank of redhorse passage success varied among years which may indicate that larger sample sizes were needed or may reflect the fact that environmental conditions (e.g., rate of river warming) varied among years and may influence inter-specific patterns in passage success among years. It is likely that in 2010 passage success numbers were low for silver and shorthead redhorse because of the timing of the study, the study took place at the end of May and beginning of June 2010 and likely peak redhorse migration occurred before that. The low passage success numbers for river redhorse in 2012 is perplexing at first glance but may be explained by the installation of a gill net (5 inch mesh size) across the entrance to the fishway on the 28th of May, 2012, for a separate attempt to capture broodstock for the critically endangered copper redhorse (*Moxostoma hubbsi*). The gill net was in place from approximately 9 am to 5:30 pm for two weeks following its installation, and several river redhorse were captured in this net. Due to the body shape and timing of their respective spawning migrations we assumed that the gill net had no effect on the silver and shorthead redhorse passage results. Results from Thiem et al. (2012) show river redhorse ascending the fishway mostly during the hours of 11 am-7 pm, and therefore the presence of the gill net may have deterred many fish attempting to re-ascend the fishway. For comparison, passage success in 2010 at the same fishway was 48.7% for longnose suckers and 75.8% for white suckers (Thiem et al. 2012) further demonstrating the rather divergent values in fishway success observed among confamilial species.

We did not develop or test for any quantitative relationships among species-specific physiological characteristics and metrics of passage behaviour and success because doing so would create a scenario in which we would lack the statistical power to discern relationships (each species would be a data point). In order to test quantitative relationships two different approaches could be used. The first approach would require us to perform a similar study to the one we have done but instead look at many more species. Such a study would be possible at the Vianney-Legendre fishway because ~40 species have been reported to pass this fishway. A second approach could look at individual capacity of members of a given species, and link that to that individual's behaviour and success. A study by Roscoe et al. (2010) studied the fate of upriver migrating salmon and their respective physiological condition while moving through a fishway by obtaining a non-lethal blood sample and then releasing fish with telemetry transmitters. In both the Roscoe et al. (2010) paper and our study all fish sampled were successful (i.e., captured and tagged from the fish trap at the top end of the fishway) fish and perhaps the fish with poor capacity would not make it to the top of the fishway. Unfortunately we could not perform either of the quantitative tests described above so we ranked fish to qualitatively observe inter-specific trends. Table 3 ranks each species based on their experimental performance and also illustrates their respective passage success and duration. Based on the results from the physiological experiments we performed we anticipated that shorthead redhorse as the most successful (highest passage success and shortest passage duration) of the three redhorse species. This was not the case; silver redhorse had the poorest performance in the laboratory but had the highest passage success and shortest passage duration. Clearly, something more than metabolic, physiological and swimming performance could be influencing passage success and duration. This premise is supported by the physiological data obtained from the fish trap which showed that fish were likely not exhausted when they got to the top. Fish that were unsuccessful may have become exhausted during their ascent of the fishway and never made it to the trap to be sampled. It is equally possible that unsuccessful fish were confused and could not reach the top due to sensory or behavioural issues despite having the physiological capacity to do so. Had unsuccessful fish been tested, through dip netting in the fishway, it is possible that our results would better reflect fish with poor performance.

Implications for fishway science and practice

Although we failed to document clear relationships (anecdotal or quantitative) between species-specific physiology and passage success/behaviour, this study still has important implications for biological evaluations of fishways. Clearly additional research is needed to understand how organismal performance, environmental conditions, and other factors (including abundance of conspecifics and other co-migrants) interact with fishway design features to dictate which fish will be successful and to inform research of future fishways (Kemp 2012). Noteworthy was the fact that fish sampled from the top of the fishway had physiological profiles that were more similar to control values rather than fish that were manually exhausted. This information suggests that while physiological capacity is not a limiting factor in relation to passage success, physiology could be used as a tool for determining whether the impediments to passage success are behavioural or related to physiological capacity. As such, a rapid assessment technique could involve measuring blood and muscle physiology (e.g., metabolites, cortisol, ion status, hematology and tissue energy stores) of fish sampled from the top of the fishway and fish sampled 30 min following exposure to manual chasing to elicit physiological exhaustion. Such an approach could identify species (or size classes) that are physiologically taxed from fishway passage and thus that may benefit from further study. This approach could be coupled with sampling of fish throughout the fishway, which would require development of sampling techniques that are effective and capture fish rapidly with minimal stress (see Pon et al. 2012 for an example), to identify potential areas of difficulty within the fishway. In instances where passage success is low, yet there is no evidence that fish are physiologically or metabolically taxed from fishway passage, there may be good reason to suspect that the underlying problems are related to motivation or behavioural confusion (e.g., behavioural cues unclear) rather than a problem with ability. Developing these types of physiological tools is important as physiology has the potential to explain passage performance and enhance the practice of fishway science.

4.6 Tables

Table 4-1. Results of two-way ANOVAs performed for three blood variables, lactate, glucose, and pH, with species, recovery time interval and the species x recovery time interval as effects. Each two-way ANOVA compared three redhorse species (silver redhorse, river redhorse and shorthead redhorse) with six recovery time intervals (fishtrap, baseline, half hour, one hour, 2 hour and 4 hour) for each particular blood variable taken from individual fish. Italicized values represent those that are significant p < 0.05.

Blood variable	**Species**			**Recovery time interval**			**Species × Recovery time interval**		
	F	df	p	F	df	p	F	df	p
Lactate	5.26	2	0.006	105.18	5	<0.001	5.899	10	<0.001
Glucose	5.31	2	0.006	16.11	5	<0.001	2.75	10	0.004
pH	2.32	2	0.102	7.401	5	<0.001	0.967	10	0.475

Table 4-2. Passage efficiency and duration results for three species of redhorse for the Vianney-Legendre fishway, shown for two separate years of study. Data in the first three rows of the table was taken from Thiem et al. (2012). Data in the last three rows shows passage information for the 2012 season.

Species	TL (mm)	Number attempted	Number passed*	Passage efficiency (%)	Passage duration (h)**
2010 - silver redhorse ***Moxostoma anisurum***	432.4 ± 12.4 220-598	10	3	30	2.6 ± 1.3 ***1.6 1.0–5.2 (3)
2010 - river redhorse ***Moxostoma carinatum***	559.7 ± 8.7 312-679	26	8	31	5.6 ± 1.1 ***5.3 1.0-11.4 (8)
2010 - shorthead redhorse ***Moxostoma macrolepidotum***	360.3 ± 6.3 255-540	22	10	46	81.2 ± 38.1 ***57.6 2.4-237.5 (6)
2012 - silver redhorse ***Moxostoma anisurum***	549.0 ± 4.8 440-622	60	53	88	7 ± 4 ***0.94 0.4-140 (38)
2012 - river redhorse ***Moxostoma carinatum***	631.8 ± 10.6 551-681	12	6	50	2 ± 0.6 ***2.0 (1) 1-3
2012 - shorthead redhorse ***Moxostoma macrolepidotum***	417.7 ± 3.9 355-490	61	42	69	51 ± 11 ***5.14 0.3-217 (35)

*The number of individuals reaching the most upstream antenna.
**The numbers in brackets represent the number of individuals for which passage duration could be calculated.
***Median value

Table 4-3. Summary table ranking silver, river, and shorthead redhorse according to their respective experimental performance.

	silver redhorse	river redhorse	shorthead redhorse
Respiratory recovery	3	2	1
Lactate recovery	2	1	3
Glucose recovery	1	1	1
pH recovery	2	1	3
Swim speed	3	2	1
Time to exhaustion	2*	3*	1*
Passage success 2010	3	2	1
Passage success 2012	1	3	2
Duration 2010	1**	2**	3**
Duration 2012	1**	2**	3**

*As a longer time to exhaustion is seen as beneficial rather than detrimental to passage success a score of 1 was given to shorthead redhorse and 2 to silver redhorse and 3 to river redhorse.
**Median value used.

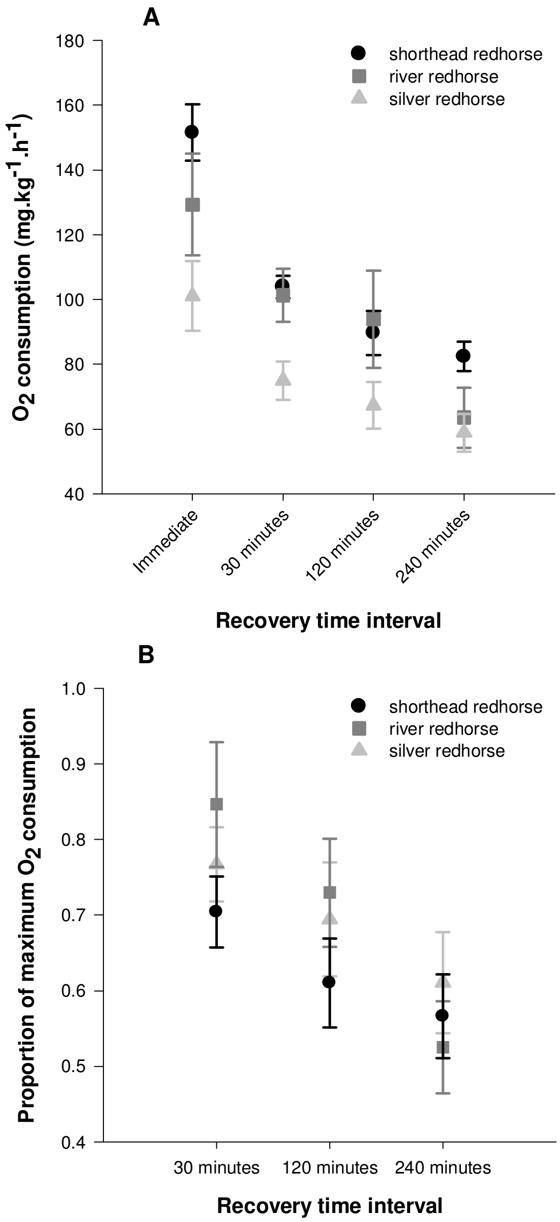

Figure 4-1. Panel A shows the oxygen consumption (in milligrams per kilogram hour) for four time periods post exhaustive exercise for three redhorse species. Panel B shows the proportion of maximum consumption (the 'immediate' group from panel A) for the three redhorse species for the three time periods post exhaustive exercise; 30 minutes, 120 minutes and 240 minutes.

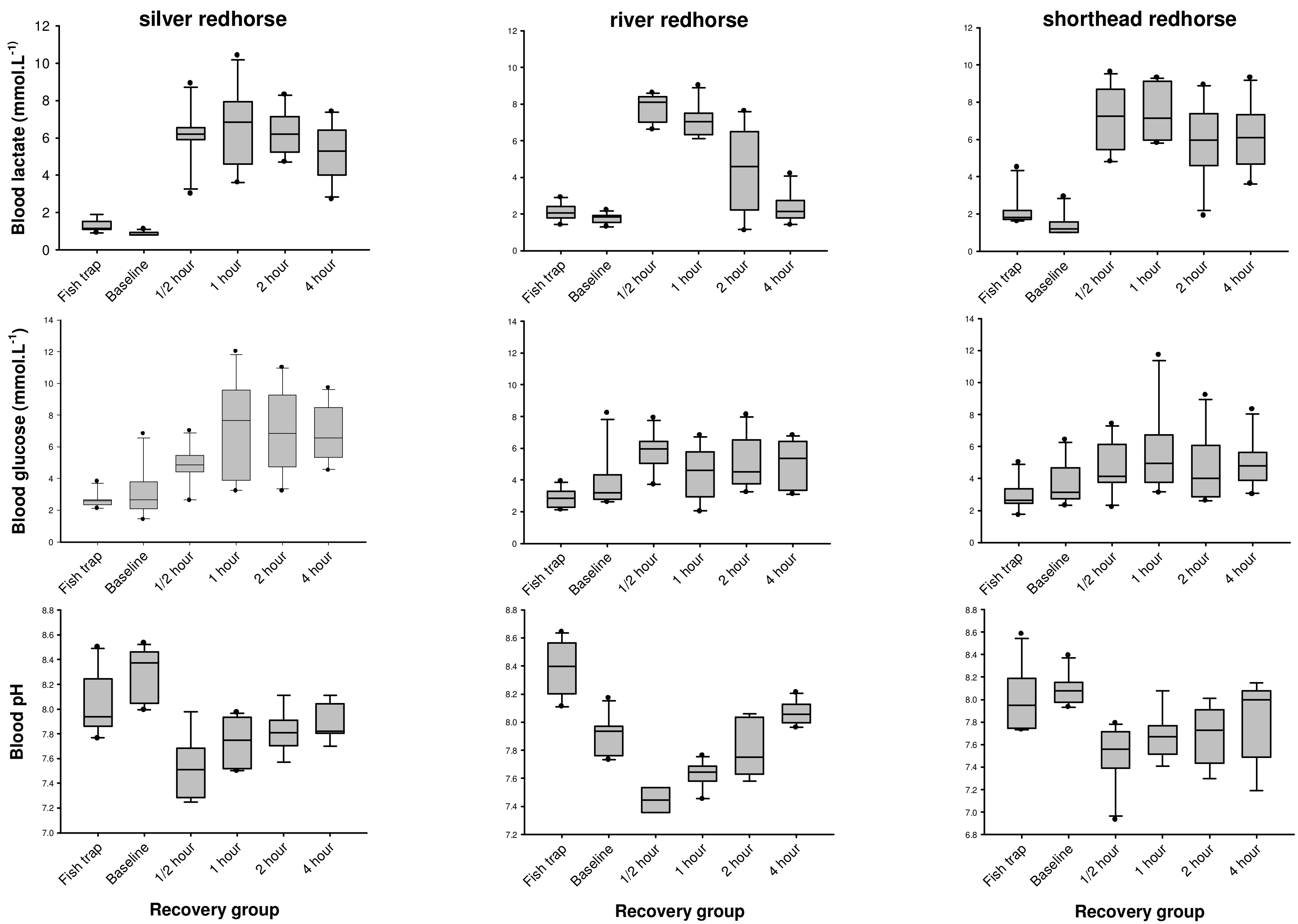
silver redhorse
river redhorse
shorthead redhorse
Blood lactate (mmol.L-1)
Blood glucose (mmol.L-1)
Blood pH
Fish trap
Baseline
1/2 hour
1 hour
2 hour
4 hour
Recovery group
Recovery group
Recovery group

Figure 4-2. Box and whisker plots showing recovery profiles for blood lactate ($mmol.L^{-1}$), blood glucose ($mmol.L^{-1}$), and blood pH for three redhorse species (*Moxostoma anisurum, carinatum* and *macrolepidotum*, respectively) over 6 different recovery profiles. Fish trap results show fish sampled immediately after being dipped netted out of the fish trap. Baseline results show results after fish have been held in recovery bags for 24 hours. Time periods of ½ hour, 1 hour, 2 hour and 4 hour, show the time fish were allowed to recover in recovery bags before being blood sampled. The ends of the boxes define the 25th and 75th percentiles, the line through the middle represents the median and the error bars represent the 10th and 90th percentiles.

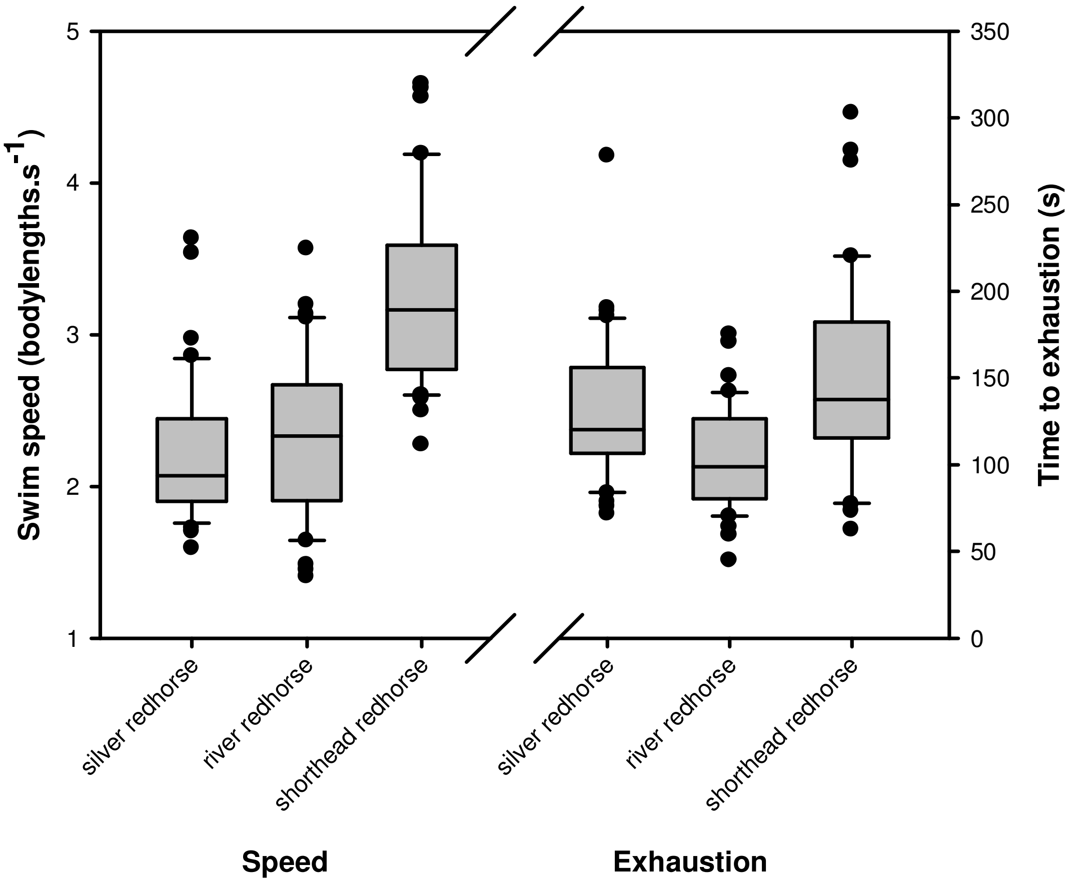

Figure 4-3. Relative swimming speed (bodylengths.s^{-1}) and the time taken to reach exhaustion (seconds) for three redhorse species. The ends of the boxes define the 25th and 75th percentiles, the line through the middle represents the median and the error bars represent the 10th and 90th percentiles.

5 Chapter: General Conclusion

With the overall goal of advancing fishway science in Canada this thesis began by performing a trend analysis on all of the fishways identified in Canada, contained in the CanFishPass database. This trend analysis confirmed what other review articles (Roscoe and Hinch 2010; Bunt et al. 2012; Noonan et al. 2012) had suggested that there is little information readily available pertaining to effective biological evaluations of fishways. Biological evaluations carried out in the future need to be performed in a manner that allow for the quantification of comparable metrics such as attraction and passage efficiency, two measures considered benchmark values on which to grade fishway success. The trend analysis of CanFishPass will hopefully stimulate the creation of other such database around the world so that collectively these data resources can serve as rich resources for utilities, regulators, and other interested parties when designing future fishways.

In keeping with the findings of the CanFishPass trend analysis findings, recommendations, and recommendations made by Bunt et al. (2012) the second chapter of this thesis evaluated the upstream fish passage of three redhorse species (silver, river and shorthead) at a vertical slot fishway. The biological evaluation of the fishway was able to provide both attraction and passage efficiencies for the three redhorse species and measures of entrance delay times, passage durations and diel fishway activity for silver and shorthead redhorse. Silver redhorse had similar attraction efficiency as shorthead redhorse but had the highest passage efficiency. In an attempt to discover reasons for differences in performance between the three species their physiological capacity and relative swimming ability was compared. Silver redhorse were outperformed by one or both of the other two species in all of the experiments we conducted indicating that there may be good reason to suspect that the lower passage efficiencies reported for shorthead and river redhorse are related to motivation or behavioural confusion (e.g., behavioural cues unclear) rather than a problem with ability. Additionally, this research suggests that there may be an opportunity for a rapid assessment approach where manual chasing and sampling of fish from the top of the fishway are used to determine which species (or sizes of fish) are exceeding their physiological capacity during passage.

Through the continued population and the subsequent trend analysis of the CanFishPass database and the biological evaluation of redhorse passage at the Vianney-Legendre fishway this thesis has been able to contribute to the advancement of fishway science in Canada.

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