FISH PASSAGE REQUIREMENTS FOR RAINBOW SMELT (*OSMERUS MORDAX*) AND GASPEREAU (ALEWIFE *ALOSA PSEUDOHARENGUS* AND BLUEBACK HERRING *A. AESTIVALIS*) AT FISHWAYS AND CULVERTS: CURRENT KNOWLEDGE, RESEARCH GAPS, AND RECOMMENDATIONS

Sean Landsman and Michael van den Heuvel

Canadian Rivers Institute
University of Prince Edward Island
Department of Biology
550 University Ave.
Charlottetown, PE C1A 4P3

2017

Canadian Technical Report of Fisheries and Aquatic Sciences 3210

Fisheries and Oceans Canada — Pêches et Océans Canada

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base Aquatic Sciences and Fisheries Abstracts.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. II n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données Résumés des sciences aquatiques et halieutiques.

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développement, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report of
Fisheries and Aquatic Sciences 3210

2017

FISH PASSAGE REQUIREMENTS FOR RAINBOW SMELT (*OSMERUS MORDAX*) AND GASPEREAU (ALEWIFE *ALOSA PSEUDOHARENGUS* AND BLUEBACK HERRING *A. AESTIVALIS*) AT FISHWAYS AND CULVERTS: CURRENT KNOWLEDGE, RESEARCH GAPS, AND RECOMMENDATIONS

by

Sean Landsman and Michael van den Heuvel

Canadian Rivers Institute
University of Prince Edward Island
Department of Biology
550 University Avenue
Charlottetown, PE C1A 4P3
email: landsman.sean@gmail.com
mheuvel@upei.ca

Cat. No. Fs 97-6/3210E-PDF ISBN 978-0-660-08278-3 ISSN 1488-5379

Correct citation for this publication:

Landsman, S., and van den Heuvel, M. 2017. Fish passage requirements for Rainbow Smelt (*Osmerus mordax*) and Gaspereau (Alewife *Alosa pseudoharengus* and Blueback Herring *A. aestivalis*) at fishways and culverts: current knowledge, research gaps, and recommendations. Can. Tech. Rep. Fish. Aquat. Sci. 3210: vii + 29 p.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Historically, the design of fish passage structures such as fishways and culverts has focused on passing salmonids. Recently, however, increasing emphasis is being placed on passing non-salmonid species that are less proficient at ascending obstacles. In the Canadian Maritime Provinces, determining what factors facilitate passage of Rainbow Smelt (*Osmerus mordax*) and Gaspereau (collectively Alewife *Alosa pseudoharengus* and Blueback Herring *A. aestivalis*), species of particular economic and cultural importance. This report presents fish passage information for Rainbow Smelt and Gaspereau for four topics: 1) passage performance of different fishway and culvert designs; 2) swimming performance; 3) life history and behavioural considerations; and 4) physiological considerations. We also draw on supplemental information from select studies on species related to Rainbow Smelt and Gaspereau, and present preliminary data for Rainbow Smelt passage studies currently in progress in Prince Edward Island. Overall, there is a dearth of information for Rainbow Smelt passage at fishways and culverts. However, the scant available information suggests that this species requires heterogeneous flow conditions to successfully ascend structures. To this end, nature-like fishways may be an appropriate design for this species. Data for Gaspereau indicate considerable variability in passage performance at different fishways, although Alewife passage was high at Denil and nature-like fishways. No information related to Gaspereau passage through culverts was found. The behavioural information presented in this report aids in understanding the constraints to passage for both Rainbow Smelt and Gaspereau. Our findings show a dearth of fish passage research for Rainbow Smelt, particularly at culverts. Much of our present knowledge of Rainbow Smelt passage appears to be observational, but preliminary data from tracking studies presented in this report provides new information that may guide future fishway installations. Indeed, nature-like fishways may be the most viable option for passing Rainbow Smelt. Considerably more fish passage research is available for Gaspereau. Gaspereau passage at fishways is highly variable, with estimates ranging from 0% to 97% and high rates at both nature-like and technical fishways. As with smelt, little information on culvert passage is available for Gaspereau. We recommend continued research for both species with particular attention to studies that incorporate experimental manipulation of fishway and culvert design characteristics that may help elucidate the key requirements for successful passage.

RÉSUMÉ

Par le passé, les structures pour le passage du poisson, comme les passes migratoires et les ponceaux, étaient conçus en fonction du passage des salmonidés. Toutefois, récemment, on s'est davantage concentré sur le passage des autres espèces qui franchissent plus difficilement les obstacles. Dans les provinces maritimes canadiennes, on tente d'établir quels facteurs facilitent le passage de l'éperlan arc-en-ciel (*Osmerus mordax*) et du gaspareau (soit l'*Alosa pseudoharengus* et l'*Alosa aestivalis* aussi connu sous le nom d'alose d'été), deux espèces d'une importance particulière du point de vue économique et culturel. Le présent rapport contient les renseignements suivants sur le passage de l'éperlan arc-en-ciel et du gaspareau : 1) la performance des différentes conceptions de passes migratoires et de ponceaux; 2) les performances de nage; 3) le cycle de vie et le comportement; 4) les aspects physiologiques. Nous nous appuyons également sur des renseignements provenant d'études choisies portant sur les espèces liées à l'éperlan arc-en-ciel et au gaspareau, et nous présentons les données préliminaires d'études sur le passage de l'éperlan arc-en-ciel qui sont en cours à l'Île-du-Prince-Édouard. Dans l'ensemble, nous observons un manque d'information concernant le passage de l'éperlan arc-en-ciel dans les passes migratoires et les ponceaux. Les quelques renseignements disponibles laissent tout de même entendre que cette espèce ne peut franchir les structures que sous des conditions de débit hétérogène. Par conséquent, les passes migratoires imitant les conditions naturelles conviennent à l'éperlan arc-en-ciel. Les données pour le gaspareau indiquent que la performance varie grandement d'une passe migratoire à une autre; notons néanmoins qu'elle était élevée aux passes de type Denil et dans les passes migratoires imitant les passes naturelles. Nous n'avons trouvé aucune information concernant le passage du gaspareau dans les ponceaux. Les renseignements comportementaux figurant dans le présent rapport aident par ailleurs à comprendre les contraintes du passage de l'éperlan arc-en-ciel et du gaspareau. Nous constatons qu'il y a eu peu de recherches sur le passage de l'éperlan arc-en-ciel, en particulier aux ponceaux. Une grande partie de nos connaissances actuelles sont fondées sur des observations directes. Les données préliminaires provenant d'études de suivi présentées dans le présent rapport pourraient orienter l'installation de passes migratoires. En effet, les passes migratoires imitant les passages naturelles pourraient être la meilleure option pour le passage de l'éperlan arc-en-ciel. En revanche, les recherches sur le passage du gaspareau sont nombreuses. Le passage du gaspareau aux passes migratoires est très variable, les estimations allant de 0 % à 97 %; les taux les plus élevés sont observés aux passes migratoires imitant les passes naturelles et aux passes migratoires techniques. Comme pour l'éperlan, nous disposons de peu d'information sur le passage du gaspareau aux ponceaux. Nous recommandons de poursuivre la recherche sur les deux espèces, et de porter une attention particulière aux études qui intègrent les manipulations expérimentales des caractéristiques de la conception des passes migratoires et des ponceaux qui pourraient aider à régler les problèmes qui nuisent au passage.

INTRODUCTION

Construction of dams for the purpose of flood control, irrigation, recreation, drinking water supplies, and hydropower as well as installing road culverts at stream crossings has had profound effects on river systems around the world, particularly through the fragmentation of habitats (Dynesius and Nilsson 1994; Malmqvist and Rundle 2002; Jackson 2003; Nilsson et al. 2005). Barriers such as dams and culverts alter the natural flow regimes of rivers and disrupt the longitudinal connectivity of river systems (Poff et al. 1997). In turn, the ability of fishes to move upstream to access critical habitats, including those used for spawning, becomes compromised (Nilsson et al. 2005; Cooke et al. 2012).

Fishways are designed to facilitate movement around barriers, allowing fish to access upstream and downstream reproductive, refuge, and/or feeding habitats. Culverts may function in a similar capacity, although the primary purpose of culvert installations is to facilitate infrastructure development (e.g., road building). Designs for fishways and culverts vary considerably. Fishways may be constructed with concrete and steel or natural materials such as rocks (Larinier 2002a; Katopodis and Williams 2012). Some fishways may also be highly engineered (e.g., Thiem et al. 2012) or constructed with few resources and planning (e.g., Rackham's Pond nature-like rock-ramp fishway, Prince Edward Island; R. MacFarlane, Prince Edward Island Forests, Fish, and Wildlife, personal communication). Culverts vary in shape and material with some that have open or closed bottoms, others that contain baffles, and still more with outlets that may be perched above the waterline (Katopodis 1992; Savoie and Haché 2002).

Different design elements of culverts and fishways may dictate their ability to pass fish. In general, water velocities through culverts and fishways should not exceed the swimming ability of the particular fish species attempting to move upstream (Katopodis 1992; Larinier 2002b); if it does, fish will likely not be able to successfully ascend the structure. Fishways may also create turbulent, confusing flows for fish, be constructed in a way that fails to match the behavioural requirements of a fish species, or be positioned in such a way that fish cannot find the entrance (Katopodis 1992; Clay 1995; Bunt 2001; Katopodis et al. 2001; Larinier 2002b). Difficult barriers to pass may cause a delay in upstream migration. For example, a large-scale examination of Chinook salmon *Oncorhynchus tshawytscha* passage through several fishways on the Columbia River, Washington showed that the longer a fish is delayed on its upstream migration, the less likely it is to reach its spawning grounds (Caudill et al. 2007).

The ideal fishway is one that all fish can enter and successfully ascend or descend without delay and without incurring any energetic costs, physical injury, or other fitness-associated problems (Castro-Santos et al. 2009). However, full transparency may rarely, if ever, be achieved. Despite problems associated with many culverts and fishways, effectiveness monitoring is rarely performed (Roscoe and Hinch 2010). Instead, it is commonly assumed that "If you build it, they will pass."

Historically, fish passage structures, and fishways in particular, were typically designed to pass salmonids (Katopodis et al. 2001; Mallen-Cooper and Brand 2007). Recently, however, managers and biologists are beginning to place increasing emphasis on passing entire fish communities. Instead of targeting salmonids that often have superior swimming abilities to other species within a system, an increasing number of fish passage structures are being designed to pass the weakest swimmers (Larinier 2002b). In Atlantic Canada, Rainbow Smelt *Osmerus mordax* have some of the poorest swimming abilities of diadromous fishes in the region (see Peake 2008). Moring (2005) suggested that Rainbow Smelt could not ascend fishways and that relatively minor in-stream blockages would prohibit upstream movement. Their poor swimming performance,their importance to Atlantic Canadian culture, and their need to access upstream spawning habitats makes conserving Rainbow Smelt populations in the region a priority. As such, there is an interest in determining what design characteristics of fishways may facilitate passage of Rainbow Smelt around barriers. Similarly, there is interest in determining what types of culvert designs do not act as barriers to upstream movement for Rainbow Smelt.

Two other species of interest in Atlantic Canada include the Alewife *Alosa pseudoharengus* and Blueback Herring *Alosa aestivalis* (collectively referred to as “Gaspereau” and hereafter referred to as such unless stated otherwise). Gaspereau populations have suffered as a result of losses to spawning habitat following dam construction (Hall et al. 2010) and culvert installation (Limburg and Waldman 2009). Additionally, Gaspereau are economically important, providing bait for the lobster fishing industry (DFO 1997). Furthermore, the swimming performance of Gaspereau is relatively weak compared to species like Atlantic Salmon *Salmo salar* and Brook Trout *Salvelinus fontinalis* (Katopodis and Gervais 2016). As diadromous species, Gaspereau need access to spawning as well as juvenile rearing habitats (Loesch 1987; Klauda et al. 1991). Like Rainbow Smelt, Gaspereau are being targeted as a conservation priority within the region, particularly in the context of passage through culverts and fishways.

The objectives of this review are: 1) collate and synthesize available information relative to Rainbow Smelt and Gaspereau passage; 2) identify research gaps; and 3) provide recommendations to fisheries managers and researchers. This review has the potential to guide future research and inform conservation of Rainbow Smelt and Gaspereau in Atlantic Canada.

METHODS

Multiple databases (i.e., Web of Science, Google Scholar, Google) were sourced in order to find information related to passage requirements at fishways and culverts for Rainbow Smelt and Gaspereau. Our process for conducting this review took place in the following order: selecting keywords; searching online databases; filtering titles, abstracts, and full manuscripts for relevant papers; and extracting information. Searches were expanded when necessary to include species related to Rainbow Smelt and Gaspereau. Information was collated and organized into discrete sections: passage, swimming performance, life history, behavior, and physiological considerations. Papers discussing Rainbow Smelt and Gaspereau behaviour as well as physiology were filtered for their relevancy to fishway and culvert passage; a complete discussion of these topics is beyond the scope of this review, but several studies had immediate relevancy to this report. Fisheries biologists within both Provincial and Federal management agencies were also queried for grey literature that might otherwise be difficult to obtain. We also present research gaps and recommendations based on the information revealed in our search of the literature.

RESULTS AND DISCUSSION

LITERATURE REVIEW

Rainbow Smelt

There is a dearth of information on Rainbow Smelt passage requirements at culverts and dams. For example, using “Rainbow Smelt” as a keyword returned 488 search results in the Web of Science database. Further filtering by “fishway” returned no results; “culvert” returned one paper, but the content of that paper did not provide any information on specific features of culverts that could facilitate passage. A single study (Hamel et al. 2008) was found by filtering with “dam”. Filtering by “Great Lakes” showed that 34% of the Rainbow Smelt literature (34%, 167 of 488) relates to Great Lakes smelt populations. Similarly, at least 100 of the 444 (22.5%)

search results using the Google Scholar database were associated with Great Lakes populations of Rainbow Smelt. Much of the Rainbow Smelt literature relates to the species' ecology, the genetic structure of populations, abundance and population dynamics within the Laurentian Great Lakes, recruitment of early life stages, and Rainbow Smelt invasion biology. Searches for research addressing the swimming performance and behavioural characteristics of Rainbow Smelt also yielded few results.

After exploring other sources of literature, only two studies addressed Rainbow Smelt passage through fishways. Landsman and van den Heuvel – who are currently conducting Rainbow Smelt passage studies using passive integrated transponder (PIT) tags and antenna arrays in multiple rivers within Prince Edward Island – added preliminary data to this report to supplement knowledge presented in this review.

Gaspereau

Our search through the literature used a combination of "Gaspereau" (a term commonly used only in the Atlantic Canada provinces to describe both Alewife and Blueback Herring), "river herring" (commonly used in the United States), Alewife, and Blueback Herring. Of the 662 studies identified by searching "Alewife," 35.6% were related to the Great Lakes. Only 1.5% and 1.9% (2 of 106) of Alewife and Blueback Herring studies, respectively, referenced fishways. Similarly, zero of 11 and only two of 50 articles found using the search terms "gasperau" and "river herring," respectively, contained a reference to fishways. After consulting both the primary and grey literature, we found a total of nine studies that assessed Gaspereau passage at fishways, albeit using different methodologies; our efforts returned no results for Gaspereau passage at culverts. Four studies in the primary literature assessed the swimming performance of Gaspereau.

FISH PASSAGE

Rainbow Smelt Passage

Our search of the literature yielded only three results directly related to Rainbow Smelt passage at fishways. Only one study, in two separate publications (J.-B. Torterotot, N.E. Bergeron, and M. Clément. 2009. Evaluation of passage efficiency of Rainbow Smelt in a nature-like fishway. Unpublished report; extended abstract of Clément et al. 2012), presents results from a rigorous assessment using Passively Induced Transponder (PIT) tags and antenna arrays of movements through a fishway. The study was conducted on the Pisquid River, Prince Edward Island at a full-width rock-ramp nature-like fishway (53.5 m in length, 2.3% slope) with five rock weirs (drop heights range from 0.11 to 0.26 m; Figure 1). The researchers found that of the smelt approaching the fishway, 50% actually entered the structure and only 6% of those fish actually passed through the entire fishway (J.-B. Torterotot, N.E. Bergeron, and M. Clément. 2009. Evaluation of passage efficiency of Rainbow Smelt in a nature-like fishway. Unpublished report; Clément et al. 2012). They also noted considerable delay from detection at the entrance to their eventual exit from the fishway (Clément et al. 2012). Visual observations suggested that smelts might have difficulty traversing the second weir, which had the greatest drop height. Passage peaked at discharges of 1.3 $m^3 s^{-1}$ and nearly ceased at discharges above 2.5 $m^3 s^{-1}$ (Clément et al. 2012).

A report prepared for the Department of Fisheries and Oceans (ASE UPEI 1997) examined several aspects of impoundments in Prince Edward Island, including passage at 13 fishways, mostly of the pool-and-weir and vertical-slot variety and two nature-like bypass channels (note: report references a fishway labeled "drop inlet," but gives no description of the type of structure). Of the 13 fishways studied, 10 were determined to be complete blockages to upstream movement while three were partially passable, i.e., Rainbow Smelt were observed partway up the fishway. No smelt were observed passing through the fishways (Figure 1). One of the two nature-like bypass channels showed partial passage; the other was identified as a complete blockage. Of the nine pool-and-weir fishways, only two showed partial passage (ASE UPEI 1997). Potential causes of poor passage at these structures could be related to improper design, improperly maintained structures, poor functionality, or a combination of these factors. A third report assessed passage at pool-and-weir and vertical slot fishways in Prince Edward Island (Smith 1980). No smelt were observed ascending any of the structures examined (Smith 1980).

To our knowledge, the only other information that exists on Rainbow Smelt passage through fishways or culverts is unpublished data from S. Landsman and M. van den Heuvel at the University of Prince Edward Island. These researchers are currently undertaking studies of smelt passage at multiple fishways. The following is a summary of preliminary data from research completed in 2014 and 2015.

One site located at Tuddy MacKinnon's Pond on the Glenfinnan River, Prince Edward Island, includes a downstream culvert (24.2 m in length, 1.4% slope; Figures 2a and 3) as well as a pool-and-weir fishway (9.8 m length, 16.0% slope; Figures 2b and 3) and nature-like bypass channel (60.6 m length, 2.4% slope) at the same dam (Figures 2c and 3). In 2014, 340 Rainbow Smelt were PIT tagged and their movements monitored via in-stream antenna arrays. Fish were tagged just downstream of the culvert. Landsman and van den Heuvel found 66.8% of the tagged fish did not ascend the culvert, despite a reduction in flow rates through the culvert as tides raised water levels. At low tide, this culvert has a drop height of approximately 0.3 m, which may create a considerable barrier to movement, at least until the tide rises. Of the fish that made it past the culvert, 80.5% of those were detected at some point during the study just in front of the dam, presumably as a result of being attracted to water spilling over the structure. Of the fish that passed the culvert, 30.1% (n = 34) of those entered the bypass channel and 26.5% (n = 9) of the smelt entering the bypass channel successfully ascended the structure. Time from initial detection in the bypass channel until exiting the structure was, on average, over 48 hrs. No smelt were observed successfully ascending the pool-and-weir fishway, despite 46.0% of those successfully passing the culvert entering the pool-and-weir fishway itself. Similar to the Hillsborough River pool-and-weir fishway, failure to ascend this structure was likely related to large between-pool drop heights. The only drop height meeting the recommended 0.15 m separated the first from the second cell; all other baffles ranged from 0.16 m to 0.29 m, with the largest at the last baffle separating the fishway from the pond. The majority of all detections took place at night from 2200 to 0600 hours.

Landsman and van den Heuvel undertook monitoring at Rackham's Pond on the Wheatley River, Prince Edward Island in 2015. The site contains a full width, rock-ramp nature-like fishway with a slope of 1.5% and length of 108.3 m. They tagged 179 Rainbow Smelt over four tagging days and found that 98 individuals successfully entered the fishway. Of these, 41.8% successfully passed. Passage duration varied widely from 31 minutes to over 24 hours. Larger fish also tended to pass faster than smaller sized individuals (size range 137-267 mm, mean 170 mm). Fish that successfully passed were significantly larger than smelt that did not.

A small 4-cell pool-and-weir fishway on the Hillsborough River, Prince Edward Island, with a slope of 13.1% and weir drop heights ranging from 0.15 to 0.20 m was also studied in 2015 (Figure 4). Over five tagging events, 450 smelt were implanted with PIT tags. Two antennas were placed within the fishway (one at the bottom and one at the top) and a third positioned below the dam. Only 15.3% (n = 69) of the tagged fish made it to the area below the dam. Although it is unclear what effects the tagging process has on post-release smelt, the lack of upstream detection may partially be explained by the presence of suitable spawning habitat between the tagging site and dam as well as by a logjam approximately 100 m downstream of the dam. However, of the 69 fish that made it to the dam, 44 (63.7%) of them entered the pool-and-weir fishway. Of those that entered 31.8% (n = 14) successfully passed, taking an average of just over three hours to complete the movement. Although some between-pool drop heights fall within the recommended 0.15 m (e.g., Conrad and Jansen 1983; Haché 1990), the largest drop at the last baffle (0.20 m) may be problematic and could be prohibiting complete passage at this structure.

The evidence presented by Clément et al. (2012) as well as Landsman and van den Heuvel's unpublished data suggests Moring's (2005) assertion that smelt cannot ascend fishways is incorrect. Smelt, instead, appear capable of ascending low-slope fishways such as nature-like designs, though minimal passage was observed at a small pool-and-weir fishway in Prince Edward Island. The single culvert studied by Landsman and van den Heuvel also suggests that, despite the aid of rising tides, relatively uniform water velocities like those frequently observed in culverts may be detrimental to facilitating upstream movement of Rainbow Smelt. It should be noted that the lack of detection at the culvert could be a result of the tagging process, which may influence Rainbow Smelt behaviour or cause some degree of mortality.

Research on other small-bodied Osmeriformes like New Zealand's endemic Galaxias *Galaxias* spp., may be useful for understanding how Rainbow Smelt interact with culverts. MacDonald and Davies (2007) assessed passage of two galaxiid species – the Common Galaxias *Galaxias maculatus* and the Spotted Galaxias *Galaxias truttaceus* – through a modified and unmodified culvert. Passage improved greatly when baffles – and specifically the most complex baffle arrangement (see Figure 2B of MacDonald and Davies 2007) – were added inside the structure to provide flow refuges. The authors suggested that baffles arranged close together reduced the distance galaxiids needed to move to access zones of low-velocity and also reduced the amount of area beside the baffles that was exposed to high-velocity flows. Given the similarity in size and body shape of galaxiids to Rainbow Smelt, the results of MacDonald and Davies (2007) may have implications for culvert designs in the Maritimes. However, current guidelines (e.g., Fisheries and Oceans 2015) for baffle designs within culverts located in the Maritimes differ considerably from the size and shape used in MacDonald and Davies (2007). Guidelines suggest using slotted weir baffles whereas the design used in MacDonald and Davies (2007) were spoiler baffles. Studies of Rainbow Smelt movements through culverts should assess the impact different design modifications may have on passage performance.

Gaspereau Passage

Reported Gaspereau passage at fishways is highly variable. Based on current research, the highest passage efficiencies for Alewife were observed at a Denil fishway (97% passage; A. Spares, Acadia University, personal communication) and two small Alaskan steeppass fishways (i.e., similar in design to Denil fishways, but with more complex baffle arrangements and baffles that angle away from fishway walls). Franklin et al. (2012) demonstrated 96.6% passage at a steeppass fishway of 3 m length and 9.6% slope steeppass fishway, with another steeppass fishway of 3 m length and 29.6% slope passing 94.5% of Alewife (Table 2). In both cases, Alewife first had to ascend through a 48 m nature-like bypass channel with a 7.1% slope. Of the 212 Alewife that entered this structure, 40.6% passed. A nearby river system contained a full-width, rock-ramp nature-like fishway (32 m long, 4.2% slope) and a pool-and-weir fishway (14 m long, 14.3% slope) at a dam (Franklin et al. 2012). Of those entering the rock-ramp fishway, 94.2% (97 of 103 fish) passed, but upstream at the pool-and-weir fishway entrance efficiency was poor; of the 97 fish passing the rock-ramp fishway, only 28 fish entered the pool-and-weir fishway with only 6 (21%) of those actually passing (Table 2; Franklin et al. 2012). A second study also found poor passage at a pool-and-weir fishway (Andrews 2014); of the 197 Alewife entering the structure, only a single fish successfully passed (0.51%; Table 2). In contrast, two Denil fishways with slopes of 11.9% and 17.5% passed nearly 75% of the Alewife entering these structures (Andrews 2014). The pool-and-weir fishway used by Andrews was repaired in 2014 and then replaced in 2015, with passage rates improving to 50% and 63% in 2014 and 2015, respectively (A. Spares, Acadia University, personal communication). A third study further indicated poor passage at a pool-and-weir fishway (Dominy 1971a). Worth noting are the findings by Martin (1984) that indicated thousands of Alewife being trapped close to the top of a pool-and-weir fishway; however, it is unclear what percentage actually passed the structure because the Alewife were prevented from moving beyond the trap. Finally, a vertical slot fishway (unknown dimensions) passed just 1.7% of Gaspereau over a three year period (Perillo and Butler 2009). Gaspereau passage at an Alaska steeppass fishway 30.5 m in length with a slope of 25% increased after researchers adjusted nearby shoreline rip-rap and added a temporary weir, both of which seemed to increase attraction to the fishway (Eyler et al. 2002). Other studies compared passage of Alewife to Blueback Herring at Alaska steeppass fishways and observed better passage of Blueback Herring compared to Alewife (Fary and Golden 1998; Jones 1999).

In Prince Edward Island, of 17 fishways that were studied for passage of Gaspereau, six completely blocked passage, nine allowed some Gaspereau to ascend partway up the structure, and two allowed fish to fully ascend the structure (ASE UPEI 1997). The two fishways that allowed full passage were pool-and-weir fishways. The report outlined several design criteria guidelines for pool-and-weir fishways: 1) care should be taken to provide sufficient attraction flow to fishway entrances; 2) between-pool drop heights should be 0.2-0.3 m; 3) pool volume needs to be enough to dissipate the energy of water entering each pool; 4) an apron of slope 50-67% should be incorporated into each notch to both create submerged passaged conditions and reduce air entrainment that would otherwise impede upstream movement; 4) weir notches should be as wide as possible, although notch size (both width and depth) should be dictated by low flows (i.e., June Q60; Fisheries and Oceans Canada 2015) ; and 5) the depth of water in each notch should exceed or equal the drop height between pools (ASE UPEI 1997). The recommended between-pool drop heights outlined in ASE UPEI (1997) are consistent with other recommendations of 0.20-0.40 m (Conrad and Jansen 1983; Haché 1990). Additional construction guidelines for pool-and-weir fishways specific to Gaspereau include pool depths of at least 1 m, notch widths of at least 0.40-0.50 m located along the fishway walls, pool width at least 2 m, and pool lengths of 10-times the between-pool drop height (Haché 1990). Researchers also suggest a 50% slopes for aprons of baffles installed within culverts (e.g., Fisheries and Oceans Canada 2015).

The ideal fish passage structure should cause as little delay to migrating fish as possible. While considerable delays were noted for Rainbow Smelt, Alewife have been observed passing through Denil fishways in less than one minute, with some passing through in less than 10 seconds (Andrews 2014). The full-width, rock-ramp fishway studied by Franklin et al. (2012) passed Alewife in under one hour. However, at the bypass channel examined in that study, passage ranged from approximately 20 minutes to three days, although most fish passed in seven hours or less (Franklin et al. 2012). Delays may be a result of fish becoming disoriented within the fishways as a result of turbulent flows (see Behavioural Considerations section for Gaspereau).

If sections within a fishway are not of equal slope, then it may be useful to investigate passage rates at specific sections as a function of slope. For example, Franklin et al. (2012) compared slopes at different portions of two nature-like fishways and found that sections with slopes of 1.01 to 5.43% facilitated passage better than portions with slopes of 7.92 to 18.52%. In a study of both American Shad *Alosa sapidissima* and Blueback Herring, increasing slope was found to decrease passage at an Alaska steeppass and Denil fishway (Haro et al. 1999). Indeed, fishway slope was one of the primary factors identified in a review of variables affecting passage at fishways (Bunt et al. 2012). The distance a fish is required to swim through challenging flows likely has an impact on a fish's ability to ascend a given structure. For example, research suggests that Denil fishways less than 20 m in length may be most suitable for the passage of American Shad (Slatick and Basham 1985). The Denil fishway evaluations performed by Andrews (2014) corroborate this information as almost 75% of Alewife passed through Denil fishways less than 20 m in overall length.

In general, Gaspereau passage through fishways seems to be highly variable from a 0% passage efficiency noted in a pool-and-weir fishway (Andrews 2014) to 96.6% in a small Alaska steeppass fishway (Franklin et al. 2012). No specific passage efficiency information was found for Gaspereau movement through culverts; this represents a significant gap in our understanding of Gaspereau migrations into freshwater systems. However, Andrews (2014) posited that decreased attraction efficiency of one Denil fishway relative to a second nearby structure was related to Alewife being forced to ascend a long, dark culvert. Clearly, more research needs to address passage at culverts given the large number that are installed throughout Atlantic Canada.

SWIMMING PERFORMANCE

Katopodis and Gervais (2016) recently published a comprehensive literature review on swimming performance of various fish species. The authors assert that while much knowledge on swimming performance and biomechanics has been gained, far less is known about such metrics as time-to-fatigue and maximum distance of ascent at any given flow velocities. Unfortunately, this type of information would be useful to guide certain culvert and fishway designs. Nevertheless, some data do exist, which are summarized below.

Rainbow Smelt Swimming Performance

Only two studies have looked at the swimming performance of Rainbow Smelt. Griffiths (1979) used Great Lakes Rainbow Smelt to assess U_{crit} (i.e., critical swimming speeds) at 12°C water temperatures. U_{crit} values were 0.411 and 0.456 m s^{-1} for fish of lengths 13.0 and 16.0 cm, respectively, which would be considered spawning-sized smelt (Clément et al. 2012; Landsman and van den Heuvel, unpublished data). Furthermore, the 12°C temperature used for testing in Griffiths (1979) is observed during spawning migrations, albeit at the higher end of the temperature range during the migration (J.-B. Torterotot, N.E. Bergeron, and M. Clément. 2009. Evaluation of passage efficiency of Rainbow Smelt in a nature-like fishway. Unpublished report). Therefore, the measurements made by Griffiths could be applied in Atlantic Canada.

Rainbow Smelt that were allowed to acclimate to 5°C as well as 20°C and then tested at a common temperature of 10°C demonstrated significantly faster swimming speeds – two body lengths per second faster – when allowed to acclimate to the colder 5°C treatment (Woytanowski and Coughlin 2012). In years with particularly warm springs or fast warming periods following ice-out, the ability to successfully ascend a fishway or culvert may be compromised as the smelt's swimming ability diminishes at increasing temperatures. Temperature data for Prince Edward Island indicate that Rainbow Smelt may experience temperatures as low as 2°C up to at least 15°C (Landsman and van den Heuvel, unpublished data).

To supplement what information we could find for Rainbow Smelt specifically, our literature search was expanded to include other members within the Osmeriforme order. Swanson et al. (1998) studied the swimming performance of the Delta Smelt *Hypomesus transpacificus*. They demonstrated a mean U_{crit} of 27.6 +/- 5.1 cm s^{-1} and noted at least one swimming failure in 62% of the test subjects that coincided with a gait transition from 'stroke-and-glide' to more continuous swimming. The water velocity at the first non-fatigue related impingement within the swim flume increased with greater fish size, suggesting larger fish may be able to tolerate higher water velocities.

Another small-bodied smelt, the New Zealand Smelt *Retropinna retropinna*, was found capable of sustained swimming in a mean flow speed 0.19 m s^{-1} and bursting in a mean flow speed of 0.50 m s^{-1} (Mitchell 1989). Two other Osmeriformes, the Banded Kokopu *Galaxias fasciatus* and the Common Galaxias, were tested in the same study and were capable of sustained swimming at 0.19 m s^{-1} and bursting at a mean of 0.43 and 0.47 m s^{-1}, respectively. Overall, the swimming abilities were relatively weak, with fish apparently unable to produce velocities much above 0.50 m s^{-1}.

Gaspereau Swimming Performance

Alosids may be considered excellent swimmers, rivaling or exceeding the capabilities of even adult salmonids (Haro and Castro-Santos 2012). A recent swimming performance literature review lists Alewife and Blueback Herring as having a mean critical swimming speed of 2.890 m s^{-1} ± 0.835 (range 1.330-4.795 m s^{-1}) and 3.548 m s^{-1} ± 0.971 (range 1.799-4.870 m s^{-1}) (Katopodis and Gervais 2016; see also Figure 5). Alewife have been observed swimming in flows of 3.5 to 4.0 m s^{-1} (Stringham 1924; Dow 1962), with mean and maximum swim speeds in these flow velocities ranging from 3.96 to 4.54 m s^{-1} and from 4.47 to 6.01 m s^{-1}, respectively (Dow 1962). However, the distance swum under varying flow speeds may be a more relevant metric to fishway and culvert design. A rigorous study conducted by Haro et al. (2004) assessed distance of ascent under several different flow speeds. Their results indicated that distance ascended in flow speeds ranging from 1.5 to 3.5 m s^{-1} differed between Alewife and Blueback Herring, with Blueback Herring capable of swimming farther under these flow conditions than Alewife (Haro et al. 2004). Larger size and increasing water temperatures allowed Blueback Herring to swim farther distances, but neither effect was significant for Alewife (Haro et al. 2004). In general, both Alewife and Blueback Herring exhibit constant swim speeds despite varying flow velocities, a behaviour that should maximize distance of ascent (Castro-Santos 2005). Overall, swimming performance data should be used with caution as the swim flumes used for calculations may create laminar flow conditions not reflective of more heterogeneous flows observed in fishways and culverts (Haro et al. 2004).

Distance of ascent has also been calculated for the related American Shad. This species has been found to move up to 6.1 m at flows of 4.15 m s^{-1} (Weaver 1965) and 5 m at 4.5 m s^{-1} (Haro et al. 2004). These results indicate that flow velocities of 3.5 to 4 m s^{-1}, even if only experienced for a few meters, may create considerable problems for Shad moving past these areas (Larinier and Travade 2002). Based on data from Haro et al. (2004), similar conclusions could be drawn for Alewife and Blueback Herring.

LIFE HISTORY AND BEHAVIOURAL CONSIDERATIONS

Rainbow Smelt Life History and Behavioural Considerations

The life history characteristics of Rainbow Smelt may have a strong influence on their motivation to ascend culverts and fishways to access upstream spawning habitats. Ideal spawning habitats for Rainbow Smelt are found in rivers and consist of an “extended pool-riffle complex” with substrates ranging from small pebbles to 10-20 cm coarse cobble (Chase 2006). Habitats are often not far from the head of tide; more than 50% of spawning grounds in Maine’s coastal rivers were located from the head-of-tide to 200 m upstream (Chase 2006). As such, there may actually be little need for Rainbow Smelt to ascend fishways only to enter slow-moving lakes or ponds. Indeed, each of the study sites presented in this review are within or just beyond a 200 m distance of the head-of-tide and spawning was observed in each of the nature-like fishways presented in this review (Clément et al. 2012; Landsman and van den Heuvel unpublished data). Although passage at the fishways studied by Torterotot et al. (J.-B. Torterotot, N.E. Bergeron, and M. Clément. 2009. Evaluation of passage efficiency of Rainbow Smelt in a nature-like fishway. Unpublished report) and by Landsman and van den Heuvel (unpublished data) was relatively low, these structures should not be considered failures if their design resulted in the creation of suitable spawning habitat. Further research is needed to determine the ability of smelt to navigate through slow-moving lakes and ponds to access upstream spawning habitats.

It remains unclear whether the spawning noted by Clément et al. (2012) and Landsman and van den Heuvel (unpubl. data) in nature-like fishways was volitional or forced. Regardless, the high density of individuals within the fishways could create conditions favorable for egg crowding. Several studies suggest that egg crowding likely has an impact on the reproductive success of smelt (McKenzie 1947; Rothschild 1961; Buckley 1989). McKenzie (1964) studied the effect of egg density on Rainbow Smelt larvae production using pens that could include or exclude spawning adults. When smelt were given unlimited access to spawning habitat – simulating high-density spawning conditions conducive for egg crowding – they deposited nearly three times as many eggs as in areas with limited access. However, larvae production in the area with unlimited access was nearly half that of production in the area where access was restricted. Rothschild (1961) made similar findings where intermediate egg densities were found to produce the highest percentage of smelt larvae survival. Ideally, smelt can spread out over a large spatial area as they spawn. This could potentially relate to fishway design, such as for nature-like fishways. For instance, the bypass channel at Tuddy MacKinnon’s pond in Prince Edward Island is relatively narrow at only 3-4 m in width, whereas a rock-ramp nature-like fishway in a nearby system on the Pisquid River spans the entire river at approximately 8-10 m. Whether crowding in the narrower fishway is occurring to such a degree that it negatively impacts reproductive success remains unclear, but constructing something wider and with a larger spatial footprint would be to err on the side of caution and recommended.

Rainbow Smelt are known to migrate to spawning grounds at night (Langlois 1935; McKenzie 1947; Rothschild 1961; Scott and Scott 1988; Bradbury et al. 2004) and movements through fishways appear to largely follow this pattern (Figure 6; Landsman and van den Heuvel unpublished data). After moving through an area during the night, smelt may then drop back downstream during the day (Murawski et al. 1980). Furthermore, smaller males generally outnumber larger females on spawning grounds, although sex ratios change across the spawning run (Langlois 1935; McKenzie 1964; Murawski et al. 1980; Clément et al. 2012). Given movement patterns of smelt and the predominance of smaller males on spawning grounds, culverts and fishways should ensure both upstream and downstream movements as well as passage of all size classes and both sexes.

The use of light to modify behaviour has produced varying responses where some fish show an avoidance of the light source and others exhibit no response (see Popper and Carlson 1998). Strobes also proved successful at reducing the rate of entrainment as Rainbow Smelt moved downstream through dam turbines at the Oahe Dam, Lake Oahe, South Dakota (Hamel et al. 2008). There may also be applicable behavioural information from species related to Rainbow Smelt. For example, the Delta Smelt and the related Wakasagi *Hypomesus nipponensis* were subjects of a study examining the effects of photophase and light levels on swimming performance. The authors demonstrated that U_{crit} of delta smelt and wakasagi was significantly higher during daytime and under full light conditions than at night under full darkness (Young et al. 2004). They also showed that, for delta smelt, U_{crit} at night, but under illuminated conditions, was higher than night-full darkness measurements. U_{crit} values for wakasagi under night-light conditions were the highest of any treatment.

Other information relative to the behaviour of Rainbow Smelt may inform fishway or culvert design. First, smelt have been observed attempting to jump through small rapids and over rocks, though few appear successful (S. Landsman, personal observation). If smelt are required to jump, such as through the notches of pool-and-weir fishways, the jump height should be as minimal as possible. Second, smelt seem to favor zones of low velocities, often moving along the edges of rivers outside the thalweg (ASE UPEI 1997; Clement et al. 2012; S. Landsman, personal observation). Care should be taken to provide heterogeneous flows within culverts and fishways whenever possible.

Gaspereau Life History and Behavioural Considerations

Ascending fishways or culverts to access lentic habitats has been identified as a potential ecological trap, whereby fish passing through a structure do so only to access sub-optimal habitats (Cooke and Hinch 2013). For instance, if a fish that prefers spawning in shallow riffle habitat within a river then passes through a fishway and enters a lake, it may find locating suitable spawning habitat or mates difficult. This may apply to northern populations of Blueback Herring that tend to prefer fast moving rivers for spawning (Loesch 1987; Klauda et al. 1991). On the other hand, Alewife generally require lentic spawning habitats (Loesch 1987; Klauda et al. 1991). This information may be relevant when deciding on a culvert or fishway design. For instance, if a particular river contains a large spawning run of Blueback Herring, then constructing a nature-like fishway to provide spawning habitat for the species as well as passage for other fishes might be most appropriate. Conversely, in systems dominated by migratory Alewife, a technical fishway design over a nature-like fishway may be useful for allowing Alewife to access lentic habitats.

Studies focusing on movement patterns of Gaspereau and the related American Shad through fishways and during their migration period have revealed findings that may be pertinent to our understanding of how Gaspereau interact with fish passage structures. For example, several studies have shown diel periodicity in upstream movement patterns of Gaspereau. Movement generally takes place during daylight hours (Saila et al. 1972; Richkus 1974; Jessop and Parker 1988), but Gaspereau have also been observed moving upstream during low light periods (Kissil 1974; Perillo and Butler 2009). In contrast, Andrews (2014) found less activity at dawn or dusk relative to midday periods. Lighting fishways and culverts may thus be a cost-effective method of increasing passage efficiencies for Gaspereau (Andrews 2014). However, some evidence suggests passage may, to some degree, occur at night (Grote et al. 2014), particularly at higher temperatures (Richkus 1974).

As a schooling fish, Alewife passage may be partially influenced by the density of migrants moving through a fishway. Dominy (1973) reported that approximately 80 individuals min^{-1} passed through a large pool-and-weir fishway when densities were 75 individuals m^{-3} with fewer passing as the density of individuals moving through the fishway increased (Dominy 1973). A review of American Shad behavior through fish passage facilities by Larinier and Travade (2002) also noted intense schooling behavior of American Shad and suggested that fishway designs must avoid disrupting the schooling behavior of this species. Haro and Castro-Santos (2012) suggested that the weirs in pool-and-weir fishways might fragment schools of Shad, disrupting upstream movements through these types of fishways. Similarly, narrowing channels in fishways may also disrupt the integrity of schools (Haro and Castro-Santos 2012).

Flow conditions within fish passage structures have the potential to affect the behavior of fish attempting to move through them. Indeed, Gaspereau show preference for zones of reduced flow velocity and less turbulence (Collins 1952; Dominy 1973). The closely related American Shad also appeared to favor low velocities and turbulence (Talbot 1953; Haro and Kynard 1997), as sometimes observed in pool-and-weir fishways (Larinier and Travade 2002), suggesting that flow conditions through fish passage structures should emphasize low turbulence for American Shad (Larinier and Travade 2002) and likely for other alosids. Furthermore, Shad may not like to jump (Larinier and Travade 2002), making the plunging flows of pool-and-weir fishways unattractive to this species. Preference not to jump may also extend to Gaspereau as it has been suggested that Gaspereau cannot maneuver past obstructions with drop heights of 0.20-0.30 m (Atlantic States Marine Fisheries 1999).

Evidence exists to suggest the position of weir entrances and notches of fishways can affect passage of alosids through fishways. For example, Dominy (1973) compared two different entrance designs at a pool-and-weir fishway. One entrance was positioned at the waterline and the other was partly submerged. Alewife passed at a greater rate through the partly submerged entrance. Dominy (1973) attributed his finding to water levels exceeding the weir crest, enabling the Alewife to swim up and over the entrance weirs. Based on the description of the weir entrance provided by Dominy (1973), surface flows through the entrance may still have been present. American Shad prefer moving through orifices with surface flows rather than those that are completely submerged (Thompson and Gauley 1965; Monk et al. 1989; Larinier and Travade 2002), though a single study did indicate a near doubling of passage efficiency when presented with a submerged entrance at a Denil fishway (Slatick 1975).

Passage through fishways and culverts may not necessarily be conducted in a single try. Indeed, Alewife have been observed making multiple attempts to pass fishways (Franklin et al. 2012; Andrews 2014). This behavior may be related to Alewife becoming disoriented under confusing flow conditions, falling back downstream below the fishway, and then making another attempt to search for a path more conducive to upstream movement (Andrews 2014). Individuals attempting to make more passage attempts were found to pass more frequently than Alewife making fewer attempts (Andrews 2014). However, more attempts to pass a structure translates to more time spent fighting potentially high flows (Andrews 2014) and thus the physiological impact of this behavior could be substantial.

The ideal fish passage structure should be passable for both sexes and all sizes of a given species. For Gaspereau, and Alewife specifically, early parts of the migration may be dominated by males, with sex ratios evening out as the migration proceeds (Dominy 1973; Kissil 1974; Libby 1981), though in some cases sex ratios of migratory runs may be approximately equal (see citations within Libby 1981; Franklin et al. 2012). Eyler et al. (2002) reported male dominated migrations of both Alewife and Blueback Herring. There is also conflicting evidence of size selectivity at fishways. For instance, Andrews (2014) reported that longer fish passed more readily than smaller individuals, but Libby (1981) reported that larger individuals were selected against. Franklin et al. (2012) also found shorter maximum distance of ascent for longer fish. The apparent selection against larger fish may be related to turbulent flow conditions within fishways (Castro-Santos et al. 2009; Franklin et al. 2012), as larger fish have bigger surface areas that can interact with turbulent flows. It is also possible that the body shape of a laterally-compressed fish such as the Alewife and Blueback Herring may cause it to react poorly to turbulent flow conditions. Indeed, laterally-compressed fishes (i.e., Bluegill Sunfish *Lepomis macrochirus*) were found to take longer to correct body displacement following disturbances from a jet of water (Webb 2004).

PHYSIOLOGY CONSIDERATIONS

Few studies have assessed the physiological cost of navigating fish passage structures (Roscoe and Hinch 2010). What little evidence exists seems to suggest that passage through fishways may only impart moderate physiological changes on upstream migrants (e.g., Connor et al. 1964; Dominy 1971b; Schwalme et al. 1985; Pon et al. 2009) and that, at least in some species, physiological constraints may not be the limiting factor (Hatry et al. 2014).

Only a single study has examined changes to the blood physiology of Alewife moving upstream through a 65-cell pool-and-weir fishway on the Gaspereau River, Nova Scotia (Dominy 1971b). Lactic acid concentrations – an indicator of exhaustive exercise in fish (Kieffer 2000) – were quantified from blood samples taken from Alewife below, within, and above the fishway. The concentration of lactic acid was not significantly different for fish at either the entrance or 52nd cell of the fishway when compared to resting fish following passage or fish staging below the fishway entrance. However, lactic acid concentrations from Alewife sampled just below the first (of two) resting pools was significantly higher than rested fish. A drop in lactic acid concentrations by approximately 22% was noted for fish sampled above the second resting pool compared to those sampled below the first resting pool. This finding may underscore the importance of having multiple resting pools in a fishway.

Long-distance migrations require that fish have enough energy stores to travel to their spawning grounds, particularly when ceasing feeding during this time (e.g., McKeown 1984). Alewife lost upwards of 22% of lipid reserves during their upstream migrations and spent Alewife collected just before re-entry into saltwater lost 38% of lipid reserves (Crawford et al. 1986). Furthermore, lipid losses increased for late-migrating Alewife, likely as a result of higher water temperatures (Crawford et al. 1986). Lipid losses are likely to increase as fish are presented with more challenging flow conditions such as higher river slopes and faster water velocities, but encountering a fishway with design characteristics that impede upstream movement could also be highly problematic. If passing a fishway requires multiple attempts or extra time spent searching for the best path to move through the structure, then fish may expend an inordinate amount of energy trying to navigate the fishway. Fish may then find it difficult to reach their spawning grounds or interact with mates, potentially reducing their reproductive success.

RESEARCH GAPS AND RECOMMENDATIONS

Several research gaps common to both Rainbow Smelt and Gaspereau became evident after performing our literature review. First, more studies on fish passage at different fishways and culverts in the Maritimes are needed. Characteristics such as slope, length, drop height between weirs or sections, and flow speeds through the fishway should be catalogued. The approach taken by Franklin et al. (2012) to examine slopes of particular sections within a fishway and then relate passage efficiency to those areas should be adopted in future studies. This type of information is highly relevant to engineers. Second, it is evident that some structures do not perform well for both Rainbow Smelt and Gaspereau, possibly because their initial design was to facilitate passage of salmonids, but it would be important to understand if any modifications can be made to the existing structure or the river itself to increase the structure's performance (e.g., modifications made to the pool-and-weir fishway at Warren's Pond, Hillsborough River, Prince Edward Island; Harris et al. 2012). This becomes important given the number of fishways and culverts currently installed throughout the Maritimes. Third, understanding the specific flow paths chosen as fish ascend structures may guide fishway and culvert design; for instance, Powers et al. (1997) and Light et al. (Light, J.T., Peterson, N.P., and Simmons, R.K. 2013. Passage of native Cutthroat Trout through small culverts on steep slopes: What are the limits? Unpublished presentation) reported juvenile Coho Salmon *Oncorhynchus kisutch* and wild Cutthroat Trout *Oncorhynchus clarkia* used the outer, low velocity boundary layer of a corrugated culvert to ascend the structure. For each species, the flow velocity in the boundary layer itself needed to be 1 m s^{-1} or less to enable passage. Finally, once sufficient information has been gathered relative to the passage needs of both Rainbow Smelt and Gaspereau, we recommend having a cohesive framework and regulations for implementing appropriate fishway and culvert designs in the region. Biologists should work closely with engineers and consultants to apply their strategies.

RAINBOW SMELT RESEARCH GAPS AND RECOMMENDATIONS

This literature review revealed a paucity of information related to Rainbow Smelt fish passage and swimming performance. As such, the effectiveness of mitigation strategies and conservation efforts may be limited by this lack of information. Given the importance managers are beginning to place on Rainbow Smelt relative to passage around dams and through culverts, it is clear more studies need to focus on this species. What information is available, including preliminary data presented by Landsman and van den Heuvel, seems to suggest that heterogeneous flow conditions such as those found in nature-like fishways may facilitate passage through structures. We recommend biologists and engineers aim to design structures with minimally challenging flow and hydraulic conditions.

To begin, biologists should assess passage at culverts and fishways of various designs (e.g., box and perched culverts, pool-and-weir and nature-like fishways). It will be important to characterize the design elements (e.g., slope, length, weir drop height) at fishways that may pass Rainbow Smelt so that engineers can incorporate those elements into future builds. Based on the limited information available relative to Rainbow Smelt passage through culverts, we suspect culverts pose a serious problem to upstream movements. Any opportunity to modify existing structures (e.g., addition of baffles) should be seized. Overall, study designs that incorporate manipulations of different design elements (e.g., entrance positions, weir drop height) could prove useful for the future construction of fishways and culverts in the region.

Rainbow Smelt are often viewed as the poorest swimming anadromous species to visit Maritimes rivers. This appears largely based on anecdotal observations of swimming performance relative to other species, given that only two swimming-related studies have ever used Rainbow Smelt as the focal species. One may therefore conclude that a natural progression in Rainbow Smelt research might include future studies assessing swimming performance under varying conditions. While we do not necessarily disagree with this, caution should be taken when deciding whether to apply findings from those types of studies to fishway or culvert designs. Calculating swimming performance metrics in swim tunnels or other low-turbulence structures, such as open-channel experimental flumes, may have little application to fishway or culvert designs. Roughness elements within fishways and culverts (e.g., rocks, woody debris) can create turbulence that fish may use to decrease swimming-related energy costs as they move upstream (e.g., Liao et al. 2003a, 2003b; Liao 2007). Therefore, swimming performance data may only be applicable to particular types of fishways (e.g., Alaskan steeppass) or culverts (e.g., box) (Haro et al. 2004). Indeed, Nelson et al. (2002) advocate that some swimming performance metrics (e.g., U_{crit}) do not assess the natural swimming ability of a fish.

If swimming performance is assessed, then we recommend comparisons be made between or among groups to understand what types of individuals or what environmental conditions (e.g., temperature) may affect Rainbow Smelt passage. It is well established that small body size often translates to slower overall swimming speeds (e.g., Webb et al. 1984; Videler and Wardle 1991; Hammer 1995) and thus it is likely that the smelt's small body size is a constraint on its ability to swim well through fast flow conditions. Another well-established relationship is the increase in swimming performance with increasing temperatures, though it should be noted that performance declines above a species-specific temperature threshold (e.g., Brett 1971; Beamish 1978; Hammer 1995). The opposite pattern may be shown in Rainbow Smelt as cold acclimation resulted in improved swimming performance for this species (Woytanowski and Coughlin 2012). Testing spawning-sized adults and water temperatures reflective of the migratory period should be considered priorities.

It may also be prudent to adjust our definition of what constitutes a successful fishway. Castro-Santos et al. (2009) describe the ideal fishway as a structure that makes a dammed stretch of river completely transparent to migrating fish, enabling any individual of any species and size free passage around an obstacle. However, engineers and biologist rarely, if ever, succeed at accomplishing this. Therefore, this type of mitigation strategy may, to some, be viewed as a failure. Nevertheless, if a fishway can double as habitat, such as nature-like fishways, then we may be able to at least partially offset habitat losses above impassable obstructions. In the case of Rainbow Smelt that were observed spawning within nature-like fishways, one could make the argument that the implementation of this type of fish passage structure was successful, despite the relatively low passage efficiencies summarized within this review.

One major difference between Rainbow Smelt and Alewife is their preference for stream-based spawning habitat. This begs the question: do the impoundments that smelt enter after ascending fishways act as ecological traps? If they do enter ponds and lakes, can they navigate through them to access upstream, riverine spawning habitat? If they cannot, then this poses an interesting conundrum for biologists. Should conservation efforts focus on improving passage or on creating suitable spawning habitat? Until we have a better understanding of a smelt's ability to navigate through slow-moving bodies of water, we recommend biologists and engineers construct low gradient nature-like fishways that provide heterogeneous flow conditions to promote upstream movement and that double as spawning habitat.

Visual observations of Rainbow Smelt behaviour within nature-like fishways indicates that this species is quite adept at seeking out areas of low flow velocities, often moving upstream along the extreme outer edges of the fishways. Some individuals do, however, attempt to navigate through the fastest flows mid-channel, and will attempt to jump over small rapids. This information may be pertinent to engineers because creating fish passage structures with flow heterogeneity may enable passage of smelt better than structures producing uniform flows. Understanding the specific flow paths Rainbow Smelt follow as they ascend a fishway or culvert will be important data for biologists and engineers to incorporate into future designs.

Another behavioural consideration that could form the basis of a future study is the effect light may have on passage through culverts or fishways. The work by Young et al. (2004) is intriguing as it showed swimming performance for two osmerid species was higher when light was present, regardless of hour of the day. It remains unclear what affect light levels may have on Rainbow Smelt, but if the results of Young et al. (2004) in fact do apply to Rainbow Smelt, then the placement of lights in culverts or at fishways could facilitate passage. Additionally, Sands and Chang (2002) recommended lighting culverts that become completely submerged during high tides.

Lessons from Rainbow Smelt passage at fishways could potentially be applied to culvert designs in systems containing smelt. For example, if heterogeneous flow conditions within nature-like fishways facilitate passage, then open-bottom arch-style culverts that maintain the river's natural substrate may be important to consider. The Department of Fisheries and Oceans favor these culvert designs whenever installing them is possible (Fisheries and Oceans 2012). Increasing the roughness inside culverts is another method of creating heterogeneous flow conditions and can be accomplished by installing baffles, adding rocks, or creating corrugations within culverts (Savoie and Haché 2002). Baffles should be installed in culverts that exceed a slope of 0.5% (PEI 2006) and guidelines suggest that the same recommended between-pool drop height of 0.15 m (for Rainbow Smelt specifically) applied to pool-and-weir fishways should also apply to baffle installation in culverts (Savoie and Haché 2002). Rainbow Smelt successfully passed through a pool-and-weir fishway with drop heights at or close to the recommended 0.15 m, which lends support to the culvert baffle guidelines. Guidelines further recommend that baffles be spaced a minimum of 1.8 m apart with the first baffle positioned no greater than 1.25 m from the downstream entrance (Savoie and Haché 2002; Fisheries and Oceans 2012). Biologists in the Maritimes have established several other general design guidelines for culverts including an embedded depth of 20% to 45% the diameter of the culvert (Savoie and Haché 2002; PEI 2006; Fisheries and Oceans 2012) and a downstream plunge pool with a width and length two and three times, respectively, the diameter of the culvert (PEI 2006). For more information regarding culvert design guidelines see Savoie and Haché (2002), PEI (2006), Fisheries and Oceans (2012), and Fisheries and Oceans (2015).

GASPEREAU RESEARCH GAPS AND RECOMMENDATIONS

Gaspereau passage efficiencies range from 0% to 97% with lowest passage associated with a dilapidated pool-and-weir fishway. The variation in passage efficiencies highlights the need to continue assessing more structures. The goal of this research should be to identify a set of design criteria that could be applied to future fishway installations, although researchers should be cautious about drawing conclusions from data obtained during only a single year. Therefore, biologists should strive to conduct multi-year studies that encompass as many fishways as possible. As with studies using Rainbow Smelt, research projects that can incorporate manipulation of different design elements (e.g., Dominy 1973) may be the most useful for informing future fishway and culvert construction projects.

Passage through fishways is a complex interaction among environmental variables, swimming performance, and fish behaviour. The effect of different hydraulic conditions within fishways on passage efficiency is a research gap that should be addressed. For example, the relationship between variables such as air entrainment or water clarity and passage success requires further investigation (Haro et al. 1999). Studying the fine-scale movement patterns in relation to flow conditions within fishways may yield important information relative to the specific flow velocities Gaspereau seek as they move through structures.

The effect of migration delay on Gaspereau – as well as Rainbow Smelt – remains uncertain. Research indicates Alewife make multiple attempts to pass through structures (e.g., Franklin et al. 2012; Andrews 2014), which likely reduces energy supplies with each subsequent attempt. Theoretically, fish that expend too much energy traversing a fishway or culvert may experience decreased reproductive success if not enough energy can be allocated to reaching spawning grounds or seeking out mates. If this occurs, then it is reasonable to suggest that the fishway design is flawed. The effect of migratory delay at fishways and culverts on reproductive success requires further investigation.

Our review also revealed no studies assessing Gaspereau passage at culverts. This finding was surprising given the number of culvert installations in Atlantic Canada. Monitoring culvert passage could easily be achieved with minimal equipment costs by tracking PIT tagged fish and only using two antennas (with one multi-antenna reader) to monitor movements. This design would allow a researcher to track individual fish and assess entrance as well as passage efficiencies. As with fishways, characteristics such as length and slope should be catalogued. Eventually, patterns should emerge as to what factors of culvert designs facilitate passage. Similar to Rainbow Smelt, culverts with baffles may facilitate passage of Gaspereau; drop height between each pool should be 0.20 m (Savoie and Haché 2002). We consider the lack of culvert passage studies a significant research gap and we recommend that studying passage through culverts becomes a priority.

REFERENCES

ASE Consultants and the University of Prince Edward Island (ASE UPEI). 1997. Impact of impoundments and their suitability for resident and anadromous fish species on Prince Edward Island: Final Report Vol. I. v-154 pp.

Andrews, S.N. 2014. Fishways efficiency and passage behaviour of alewife in three fishways on Tantramar Marsh near Amherst, Nova Scotia. Masters Thesis, Acadia University, Wolfville, Nova Scotia. 105 pp.

Atlantic States Marine Fisheries Commission. 1999. Amendment 1 to the interstate fishery management plan for Shad and river herring. Fish Manage Rep No. 35 of the Atlantic States Marine Fisheries Commission. 77 pp.

Bradbury, I.R., Campana, S.E., Bentzen, P., and Snelgrove, P.V. 2004. Synchronized hatch and its ecological significance in rainbow smelt *Osmerus mordax* in St. Mary's Bay, Newfoundland. Limnol. Oceanogr. 49: 2310-2315.

Brett, J.R. 1971. Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of sockeye salmon (*Oncorhynchus nerka*). Amer Zool 11: 99-113.

Buckley, J.L. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North Atlantic) - rainbow smelt. U.S. Fish Wildl. Serv. Biol. Rep. 82: 11 pp.

Bunt, C.M. 2001. Fishway entrance modifications enhance fish attraction. Fish. Manag. Ecol. 8: 95-105.

Bunt, C.M., Castro-Santos, T., and Haro, A. 2012. Performance of fish passage structures at upstream barriers to migration. River Res. Appl. 28: 457-478.

Castro-Santos, T. 2005. Optimal swim speeds for traversing velocity barriers: an analysis of volitional high-speed swimming behavior of migratory fishes J. Exp. Biol. 208: 421-432.

Castro-Santos, T., Cotel, A., and Webb, P.W. 2009. Fishway evaluations for better bioengineering. *In* Challenges for Diadromous Fishes in a Dynamic Global Environment. Edited by A.J. Haro, K.L. Smith, R.A. Rulifson, C.M. Moffitt, R.J. Klauda, M.J. Dadswell, R.A. Cunjak, J.E. Cooper, K.L. Beal, and T.S. Avery. American Fisheries Society, Bethesda, MD.

Caudill, C.C., Daigle, W.R., Keefer, M.L., Boggs, C.T., Jepson, M.A., Burke, B.J., Zabel, R.W., Bjornn, T.C., and Peery, C.A. 2007. Slow dam passage in adult Columbia River salmonids associated with unsuccessful migration: delayed negative effects of passage obstacles or condition-dependent mortality? Can. J. Fish. Aquat. Sci. 64: 979-995.

Clement, M., Torterotot, J-B., and Bergeron, N.E. 2012. Evaluation of rainbow smelt passage in a nature-like fishway. In Fourth North American Workshop on Rainbow Smelt: Extended Abstract Proceedings. Edited by C.H. Wood, C. Enterline, K. Mills, B.C. Chase, G. Verreault, J. Fischer, and M.H. Ayer. Massachusetts Division of Marine Fisheries Technical Report TR-51. pp. 54-60.

Collins, G.B. 1952. Factors influencing the orientation of migrating anadromous fishes. U.S. Fish. Wildl. Serv. Fish. Bull. 73: 373-396.

Connor, A.R., Elling, C.H., Black, E.C., Collins, G.B., Gauley, J.R., and Trevor-Smith, E. 1964. Changes in glycogen and lactate levels in migrating salmonid fishes ascending experimental endless fishways. J. Fish. Res. Board Can. 21: 255-290.

Conrad, V., and Jansen, H. 1983. Refinements in design of fishways for small watersheds. Paper presented at the Northeast Fish and Wildlife Conference, Dover, Vermont, USA, 15-18 May. 26 pp.

Cooke, S., Paukert, C., and Hogan, Z. 2012. Endangered river fish: factors hindering conservation and restoration. Endang. Species Res. 17: 179-191.

Cooke, S.J., and Hinch, S.G. 2013. Improving the reliability of fishway attraction and passage efficiency estimates to inform fishway engineering, science, and practice. Ecol. Eng. 58: 123-132.

Dominy, C.L. 1971a. Evaluation of a pool and weir fishway for passage of Alewives (*Alosa pseudoharengus*) at White Rock, Gaspereau River, Nova Scotia. Canada Dep. of Fisheries and Forestry. Fish. Serv. Progr. Rep. No 3. 22 pp.

Dominy, C.L. 1971b. Changes in blood lactic acid concentrations in Alewives (*Alosa pseudoharengus*) during passage through a pool and weir fishway. J. Fish. Res. Board Can. 28: 1215-1217.

Dominy, C.L. 1973. Effect of entrance-pool weir elevation and fish density on passage of Alewives *Alosa pseudoharengus* in a pool and weir fishway. Trans. Amer. Fish. Soc. 102: 398-404.

Dow, R.L. 1962. Swimming speed of river herring *Pomolobus pseudoharengus* (Wilson). J. Conseil 27: 77-80.

Dynesius, M., and Nilsson, C. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266: 753-762.

Eyler, S.M., Vogel, L.E., and Margraf, F.J. 2002. Effectiveness of a fish passage facility for anadromous river herring recruitment. Proc. Annu. Conf. Southeast. Assoc. Fish and Wildl. Agencies: 56: 55-64.

Fary, J., and Golden, M. 1998. Maryland fish passage program 1998 monitoring report. Dep. Nat. Resour. Annapolis, Md. 12pp.

Fisheries and Oceans Canada. 2012. Guidelines of Fisheries and Oceans Canada for the design of watercourse crossings in Quebec. Fisheries and Oceans Canada, Fish Habitat Management Division, Mont-Joli, Québec, Canada. 47 pp. + appendices.

Fisheries and Oceans Canada. 2015. Guidelines for the design of fish passage for culverts in Nova Scotia. Fisheries Protection Program, Maritimes Region, 95 pp.

Franklin, A.E., Haro, A., Castro-Santos, T., and Noreika, J. 2012. Evaluation of nature-like and technical fishways for the passage of Alewives at two coastal streams in New England. Trans. Amer. Fish. Soc. 141: 624-637.

Griffiths, J.S. 1979. Effects of size and temperature on sustained swimming speeds of Great Lakes fishes. Ontario Hydro Res. Div. Rep. 37 pp.

Grote, A.B., Bailey, M., Zydlewski, J.D., and Hightower, J.E. 2014. Multibeam sonar (DIDSON) assessment of American Shad (*Alosa sapidissima*) approaching a hydroelectric dam. Can. J. Fish. Aquat. Sci. 71: 545-558.

Haché, D. 1990. Fish passage guidelines for small watersheds in the Gulf Region. Dept. Fish. Oceans Canada, Hab. Manage. Div., Gulf Region. 35 + ii pp.

Hall, C.J., Jordaan, A., and Frisk, M.G. 2011. The historic influence of dams on diadromous fish habitat with a focus on river herring and hydrologic longitudinal connectivity. Landscape Ecol. 26: 95-107.

Hamel, M.J., Brown, M.L., and Chipps, S.R. 2008. Behavioral responses of rainbow smelt to in situ strobe lights. N. Am. J. Fish. Manage. 28: 394-401.

Hammer, C. 1995. Fatigue and exercise tests with fish. Comp Biochem Physiol A 112: 1-20.

Haro, A., and Castro-Santos, T. 2012. Passage of American Shad: paradigms and realities. Mar. Coast. Fish. 4: 252-261.

Haro, A., Castro-Santos, T., Noreika, J., and Odeh, M. 2004. Swimming performance of upstream migrant fishes in open-channel flow: a new approach to predicting passage through velocity barriers. Can. J. Fish. Aquat. Sci. 61: 1590-1601.

Haro, A.J., and Kynard, B. 1997. Video evaluation of passage efficiency of American Shad and sea lamprey in a modified Ice Harbor fishway. N. Am. J. Fish. Manage. 17: 981-987.

Haro, A., Odeh, M., Castro-Santos, T., and Noreika, J. 1999. Effect of slope and headpond on passage of American Shad and blueback herring through simple Denil and deepened Alaska steeppass fishways. N. Am. J. Fish. Manage. 19: 51-58.

Harris, M., Dupuis, T., Guignion, D., and MacFarlane, R. 2012. Technical manual for watershed management on Prince Edward Island. Prepared for the PEI Watershed Alliance, PE. 261 pp.

Hatry, C., Thiem, J.D., Binder, T.R., Hatin, D., Dumont, P., Stamplecoskie, K.M., Molina, J.M., Smokorowski, K.E., and Cooke, S.J. 2014. Comparative physiology and relative swimming performance of three redhorse (*Moxostoma* spp.) species: associations with fishway passage success. Physiol. Biochem. Zool. 87: 148-159.

Jackson, S.D. 2003. Design and construction of aquatic organism passage at road-stream crossings: ecological considerations in the design of river and stream crossings. In Proceedings of the International Conference of Ecology and Transportation. Center for Transportation and the Environment, North Carolina State University, Raleigh. pp. 20-29.

Jessop, B.M., and Parker, H.A. 1988. The alewife in the Gaspereau River, Kings County, Nova Scotia, 1982-1984. Can. Manuscr. Rep. Fish. Aquat. Sci. No. 1992: 29 pp.

Jones, W.J. 1999. Establishment of river herrings in a southern Delaware impoundment: evaluation of fish passage and predation. M.S. Thesis, Univ. Md., Eastern Shore, Princess Anne. 181pp.

Katopodis, C. 1992. Introduction to fishway design. Freshwater Institute, Central and Arctic Region, Department of Fisheries and Oceans, Winnipeg, MB. 68 pp.

Katopodis, C., Kells, J.A., and Acharya, M. 2001. Nature-Like and Conventional Fishways: Alternative Concepts? Can. Water. Resour. J. 26: 211-232.

Katopodis, C., and Williams, J.G. 2012. The development of fish passage research in a historical context. Ecol. Eng. 48: 8-18.

Katopodis, C. and Gervais, R. 2016. Fish swimming performance database and analyses. Fish. Oceans Can. Sci. Advis. Sec. Res. Doc. 2016/002. vi + 550 pp.

Kieffer, J.D. 2000. Limits to exhaustive exercise in fish. Comp. Biochem. Physiol. A 126: 161-179.

Kissil, G.W. 1974. Spawning of the anadromous alewife, *Alosa pseudoharengus*, in Bride Lake, Connecticut. Trans. Amer. Fish. Soc. 103: 312-317.

Klauda, R.J., Fischer, S.A., Hall Jr., L.W., and Sullivan, J.A. 1991. Alewife and blueback herring, *Alosa pseudoharengus* and *Alosa aestivalis*. In Habitat Requirements for Chesapeake Bay Living Resources. Edited by S.L. Funderburk, J.A. Mihursky, S.J. Jordan, and D. Riley. Chesapeake Bay Program, Annapolis, Maryland. pp. 10.1–10.29.

Langlois, T.H. 1935. Notes on the Spawning Habits of the Atlantic Smelt. Copeia 1935: 141-142.

Larinier, M. 2002a. Fish passage through culverts, rock weirs and estuarine obstructions. Bull. Fr. Pêche Piscic. 364: 119-134.

Larinier, M. 2002b. Biological factors to be taken into account in the design of fishways, the concept of obstructions to upstream migration. Bull. Fr. Pêche Piscic. 364: 28-38.

Larinier, M., and Travade, F. 2002. The design of fishways for Shad. Bull. Fr. Pêche. Piscic. 364: 135-146.

Liao, J.C. 2003a. Fish exploiting vortices decrease muscle activity. Science 302: 1566-1569.

Liao, J.C. 2003b. The Karman gait: novel body kinematics of rainbow trout swimming in a vortex street. J. Exp. Biol. 206: 1059-1073.

Liao, J.C. 2007. A review of fish swimming mechanics and behaviour in altered flows. Philos. T. R. Soc. B 362: 1973-1993.

Libby, D.A. 1981. Difference in sex ratios of the anadromous alewife, *Alosa pseudoharengus*, between the top and bottom of a fishway at Damariscotta Lake, Maine. U.S. Nat. Mar. Fish. Serv. Fish. Bull. 79: 207-211.

Limburg, K.E., and Waldman, J.R. 2009. Dramatic declines in North Atlantic diadromous fishes. BioScience 59: 955-965.

Loesch, J.G. 1987. Overview of life history aspects of anadromous Alewives and blueback herring in freshwater habitats. In Common strategies of anadromous and catadromous fishes. Edited by M.J. Dadswell, R.J. Klauda, C.M. Moffitt, R.L. Saunders, R.A. Rulifson, and J.E. Cooper. American Fisheries Society, Bethesda, MD. pp. 89-103.

MacDonald, J.I., and Davies, P.E. 2007. Improving the upstream passage of two galaxiid fish species through a pipe culvert. Fish. Manag. Ecol. 14: 221-230.

Mallen-Cooper, M., and Brand, D.A. 2007. Non-salmonids in a salmonid fishway: What do 50 years of data tell us about past and future fish passage? Fish. Manag. Ecol. 14: 319-332.

Malmqvist, B., and Rundle, S. 2002. Threats to the running water ecosystems of the world. Environ. Conserv. 29: 134-153.

Martin, J.D. 1984. Atlantic salmon and alewife passage through a pool and weir fishway on the Magaguadavic River, New Brunswick, during 1983. Can. Manuscr. Rep. Fish. Aquat. Sci. 1776: iii–11.

McKenzie, R.A. 1964. Smelt life history in the Miramichi River, New Brunswick. Can. Dept. Fish. Oceans Rep. 144. Department Fisheries and Oceans Canada.

McKenzie, R.A. 1947. The effect of crowding of smelt eggs on the production of larvae. Fish. Res. Board Can. Prog. Rep. Atlantic Coast Sta. 39: 11-13.

McKeown, B.A. 1984. Fish Migration (Physiology Chapter). Timber Press, Portland, Oregon.

Mitchell, C.P. 1989. The swimming performance of some native freshwater fishes. New Zeal. J. Mar. Fresh. Res. 23: 181-187.

Monk, B., Weaver, D., Thompson, C., and Ossiander, F. 1989. Effects of flow and weir design on the passage behaviour of American Shad and salmonids in an experimental fish ladder. N. Am. J. Fish. Manage. 9: 60-67.

Moring, J. 2005. Recent trends in anadromous fishes. In The Decline of Fisheries Resources in New England: Evaluating the Impact of Overfishing, Contamination, and Habitat Degradation. Edited by R. Buschbaum, J. Pederson, and W.E. Robinson. MT Sea Grant College Program Massachusetts Institute of Technology, Cambridge, MA. pp. 25-42.

Murawski, S.A., Clayton, G.R., Reed, R.J., and Cole, C.F. 1980. Movements of spawning rainbow smelt, *Osmerus mordax*, in a Massachusetts estuary. Estuaries 3: 308-314.

Nelson, J., Gotwalt, P., Reidy, S., and Webber, D. 2002. Beyond Ucrit: matching swimming performance tests to the physiological ecology of the animal, including a new fish "drag strip." Comp. Biochem. Physiol. A 133: 289-302.

Nilsson, C., Reidy, C.A., Dynesius, M., and Revenga, C. 2005. Fragmentation and flow regulation of the world's large river systems. Science 308: 405-408.

Peake, S.J. 2008. Swimming performance and behaviour of fish species endemic to Newfoundland and Labrador: a literature review for the purpose of establishing design and water velocity criteria for fishways and culverts. Can. Manuscr. Rep. Fish. Aquat. Sci. 2843: 52 pp.

Prince Edward Island (PEI) Department of Communities, Land and Environment. 2006. Prince Edward Island watercourse and wetland alteration guidelines. Online. Accessed 28 March 2015. URL: http://www.gov.pe.ca/photos/original/eef_wet_alter_3.pdf

Perillo, J.A., and Butler, L.H. 2009. Evaluating the use of Fairmount Dam fish passage facility with application to anadromous fish restoration in the Schuylkill River, Pennsylvania. J. Pa. Acad. Sci. 83: 24-33.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., and Stromberg, J.C. 1997. The natural flow regime. BioScience 47: 769-784.

Pon, L.B., Hinch, S.G., Cooke, S.J., Patterson, D.A., and Farrell, A.P. 2009. Physiological, energetic and behavioural correlates of successful fishway passage of adult sockeye salmon *Oncorhynchus nerka* in the Seton River, British Columbia. J. Fish. Biol. 74: 1323-1336.

Popper, A.N., and Carlson, T.J. 1998. Application of sound and other stimuli to control fish behavior. Trans. Amer. Fish. Soc. 127: 673-707.

Powers, P.D., Bates, K., Burns, T., Gowen, B., and Whitney, R. 1997. Culvert hydraulics related to upstream juvenile salmonid passage. Washington State Department of Fish and Wildlife, Lands and Restoration Services Program, Project 982740, Olympia.

Richkus, W.A. 1974. Factor influencing the seasonal and daily patterns of alewife (*Alosa pseudoharengus*) migration in a Rhode Island river. J. Fish. Res. Board. Can. 31: 1485-1497.

Roscoe, D.W., and Hinch, S.G. 2010. Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish Fish. 11: 12-33.

Rothschild, B.J. 1961. Production and survival of eggs of the American smelt, *Osmerus mordax* (Mitchell), in Maine. Trans. Amer. Fish. Soc. 90: 42-48.

Saila, S.B., Polgar, T.T., Sheehy, D.J., and Flowers, J.M. 1972. Correlations between alewife activity and environmental variables at a fishway. Trans. Amer. Fish. Soc. 101: 583-594.

Savoie, R., and Haché, D. 2002. Design Criteria for Fish Passage in New or Retrofit Culverts in the Maritime Provinces, Canada. Dept. Fish. Oceans Canada, Moncton, New Brunswick, iv. + 38 pp. + 2 appendices.

Schwalme, K., Mackay, W.C., and Lindner, D. 1985. Suitability of vertical slot and Denil fishways for passing north-temperate, nonsalmonid fish. Can. J. Fish. Aquat. Sci. 42: 1815-1822.

Scott, W.B., and Scott, M.G. 1988. Atlantic fishes of Canada. Can. B. Fish. Aquat. Sci. 219: 731 pp.

Slatick, E. 1975. Laboratory evaluation of a Denil-type steeppass fishway with various entrance and exit conditions for passage of adult salmonids and American Shad. Mar. Fish. Rev. 37: 17-26.

Slatick, E., and Basham, L.R. 1985. The effect of Denil fishway length on passage of some nonsalmonid fishes. Mar. Fish. Rev. 47: 83-85.

Swanson, C., Young, P.S., and Cech, J.J. 1998. Swimming performance of delta smelt: maximum performance, and behavioral and kinematic limitations on swimming at submaximal velocities. J. Exp. Biol. 201: 333-345.

Stringham, E. 1924. The maximum speed of freshwater fishes. Amer. Nat. 58: 156-161.

Talbot, G.B. 1953. Passage of Shad at the Bonneville fishways. U.S. Fish Wildl. Serv. Fish. Bull. 94.

Thiem, J.D., Binder, T.R., Dumont, P., Hatin, D., Hatry, C., Katopodis, C., Stamplecoskie, K.M., and Cooke, S.J. 2013. Multispecies fish passage behaviour in a vertical slot fishway on the Richelieu River, Quebec, Canada: fishway community passage. River Res. Appl. 29: 582-592.

Thompson, C.S., and Gauley, J.R. 1965. Laboratory evaluation of the 1-on-10 slope Ice Harbor fishway design. U.S. Fish Wildl. Serv. Spec. Sci. Rep. 509: 20 pp.

Videler, J.J., and Wardle, C.S. 1991. Fish swimming stride by stride: speed limits and endurance. Rev. Fish Biol. Fish. 1: 23-40.

Weaver, C.R. 1965. Observations of the swimming ability of adult American Shad (*Alosa sapidissima*). Trans. Amer. Fish. Soc. 94: 382-385.

Webb, P.W., Kostecki, P.T., and Stevens, E.D. 1984. The effect of size and swimming speed on locomotor kinematics of rainbow trout. J. Exp. Biol. 109: 77-95.

Woytanowski, J.R., and Coughlin, D.J. 2013. Thermal acclimation in rainbow smelt, *Osmerus mordax*, leads to faster myotomal muscle contractile properties and improved swimming performance. Biol. Open 2: 343-350.

Young, P.S., Swanson, C., and Cech, J.J. 2004. Photophase and illumination effects on the swimming performance and behavior of five California estuarine fishes. Copeia 2004: 479-487.

TABLES

Table 1. Summarized passage information for Passive Induced Transponder (PIT) tagged Rainbow Smelt at five fishways and one culvert located in Prince Edward Island, Canada. The references are as follows: [1] Landsman and van den Heuvel unpublished data 2015; [2] Landsman and van den Heuvel unpublished data 2014; [3] Torterotot et al. (2009) and Clément et al. (2012).

Structure Type	Location	Structure Length (m)	Slope (%)	Drop Height Between Baffles/Weirs/Culvert Entrance (m)	Fish Size Range (mm)	Total Number Tagged	% Passage (# pass/#enter)
Nature-Like Rock Ramp[1]	Wheatley River	108.3	1.5	na	134-267	179	41.2[a] (41/98)
Box culvert[2]	Glenfinnan River	24.2	1.4	0.30[c]	141-240	340	33.2[b] (113/340)
Pool-and-weir fishway[2]	Glenfinnan River	9.8	16.0	0.16 – 0.29	141-240	340	0 (0/0)
Pool-and-weir fishway[1]	Hillsborough River	6.1	13.1	0.09 – 0.21	134-204	450	13.2[a] (5/38)
Nature-Like Bypass Channel[2]	Glenfinnan River	60.6	2.4	na	141-240	340	26.5[a] (9/34)
Nature-Like Rock Ramp[2]	Pisquid River	53.5	2.3	0.11 – 0.26	150-260	1,001	23.6[a] (65/236)
Nature-Like Rock Ramp[3]	Pisquid River	53.5	2.3	0.11 – 0.26	129-240	465	6.0[a] (6/106)

[a] of those entering the structure; [b] of the total tagged; [c] culvert is in tidal section of river, measurement made at low tide

Table 2. Summarized passage information for PIT tagged Alewife and Blueback Herring. Note: the study by Haro et al. (1999) was under experimental conditions versus natural stream conditions in Franklin et al. (2012) and Andrews (2014). CAFRC = Conte Anadromous Fish Research Center. The references are as follows: [1] Franklin et al. (2012); [2] Andrews (2014); [3] Haro et al. (1999).

Structure Type	Location	Structure Length (m)	Slope (%)	Drop Height Between Baffles / Weirs / Culvert Entrance (m)	Fish Size Range (mm)	[a] % Passage (# pass / #enter)
Alosa pseudoharengus						
Rock-ramp nature-like fishway [1]	Town Brook, Massachusetts, USA	32	4.2	212-263	400	94.2 (97/103)
Pool-and-weir fishway [1]	East River, Massachusetts, USA	14	14.3	201-271	393	21.4 (6/28)
Step-pool bypass channel [1]	East River, Massachusetts, USA	48	7.1	201-271	393	40.6 (86/212)
Alaska steeppass fishway [1]	East River, Massachusetts, USA	3	9.6	201-271	393	96.6 (141/146)
Alaska steeppass fishway [1]	East River, Massachusetts, USA	3	29.6	201-271	393	94.5 (86/91)
Denil fishway [2]	Amherst Marsh, Nova Scotia, Canada	16.03	11.9	--	374	74.6 (88/118)
Denil fishway [2]	Missiquash, Nova Scotia, Canada	13.1	17.5	--	416	73.7 (157/213)
Pool-and-weir fishway [2]	Front Lake, Nova Scotia, Canada	10.4	17.3	--	406	0.51 (1/197)
Experimental Denil [3]	CAFRC, Massachusetts USA	7.6	12.5, 16.7 [b]	205-290	462	1.0 [c], 3.0 [d]
Alosa aestivalis						
Experimental Alaska steeppass	CAFRC, Massachusetts, USA	7.6	12.5, 16.7 [b]	205-290	462	1.0 [c], 4.0 [d]

[a] of those entering the structure; [b] authors also varied height of the headpond; [c] low headpond height; [d] low headpond height

FIGURES

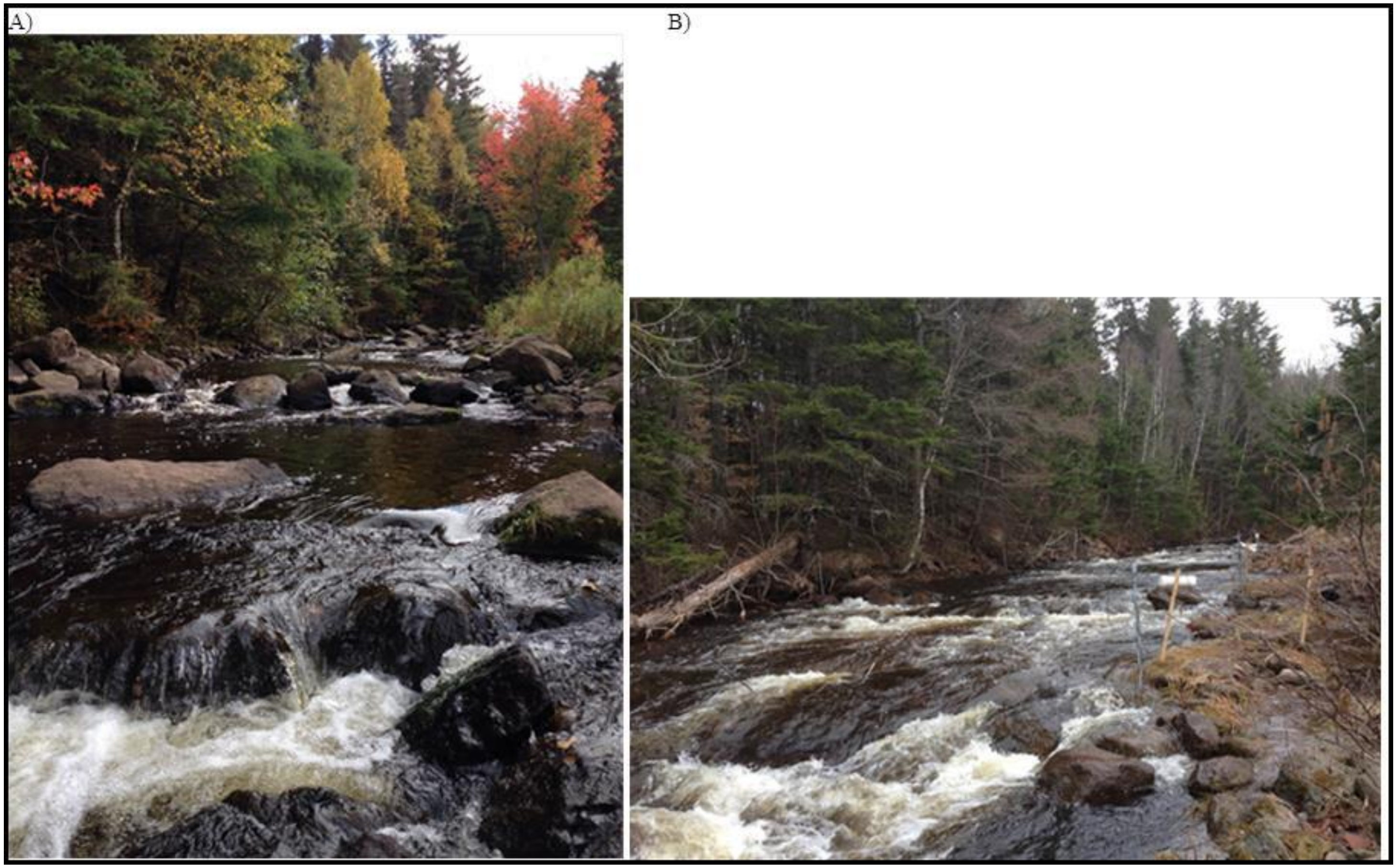

Figure 1. View looking upstream at a rock-ramp nature-like fishway (slope 2.2%, drop heights at rock weirs ranging from 0.13-0.26 m) located on the Pisquid River, Pisquid, Prince Edward Island. The large R250 boulders were placed in the fishway in an attempt to improve passage following the unpublished report by Torterotot et al. (2009). Photo A taken during low water in the fall of 2014, while Photo B shows water levels through the fishway during the Rainbow Smelt migration in 2014. Photos by Sean Landsman.

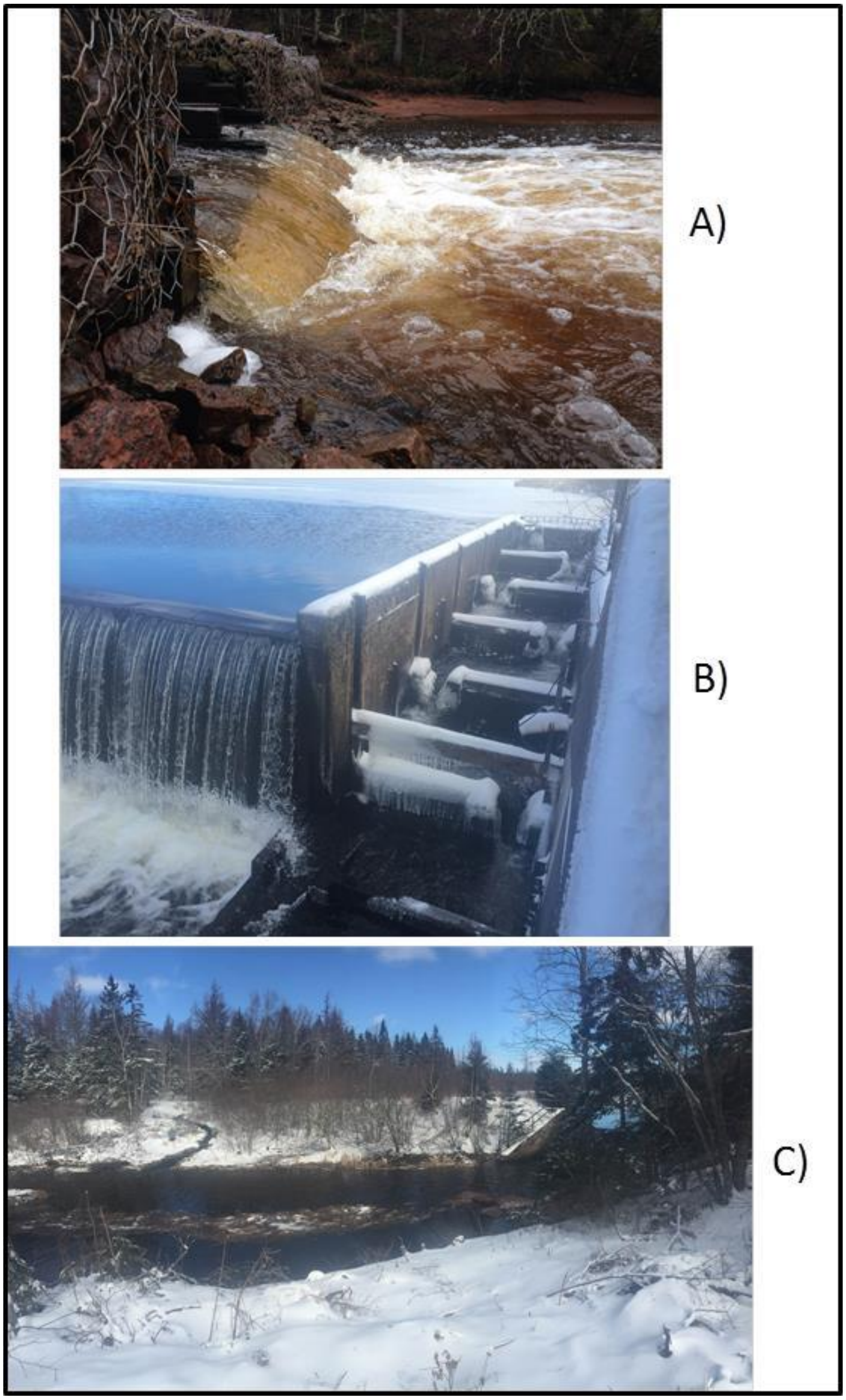

Figure 2. Side profile (A) of the outlet of a box culvert (24.2 m long, 1.4% slope) at the head-of-tide on the Glenfinnan River, Prince Edward Island Canada. The photo was taken on a low tide and shows a drop of 0.3-0.5 m to the holding pool below the culvert. Also shown are the pool-and-weir (B) and nature-like bypass channel (C; far shoreline) fishways. Photos by Sean Landsman.

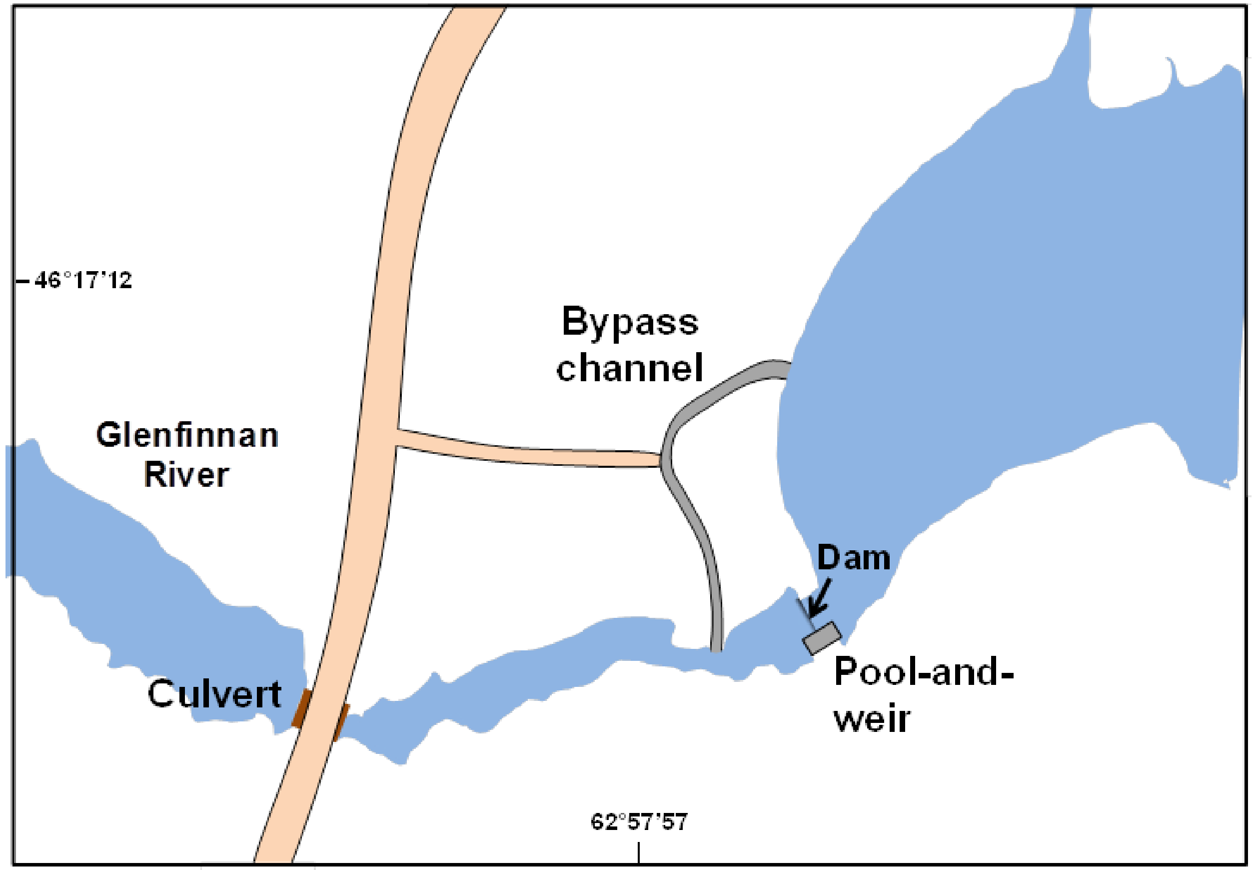

Figure 3. Schematic of the Tuddy MacKinnon dam, culvert, nature-like bypass channel, and pool-and-weir fishway complex. The bypass channel and pool-and-weir fishways are independent of each other and provide two separate paths into the pond. Schematic not-to-scale.

Figure 4. View looking upstream at a small 4-cell pool-and-weir fishway with a slope of 13.1% and weir drop heights ranging from 0.08-0.21 m located on the Hillsborough River, Cherry Hill, Prince Edward Island. Photo by Sean Landsman.

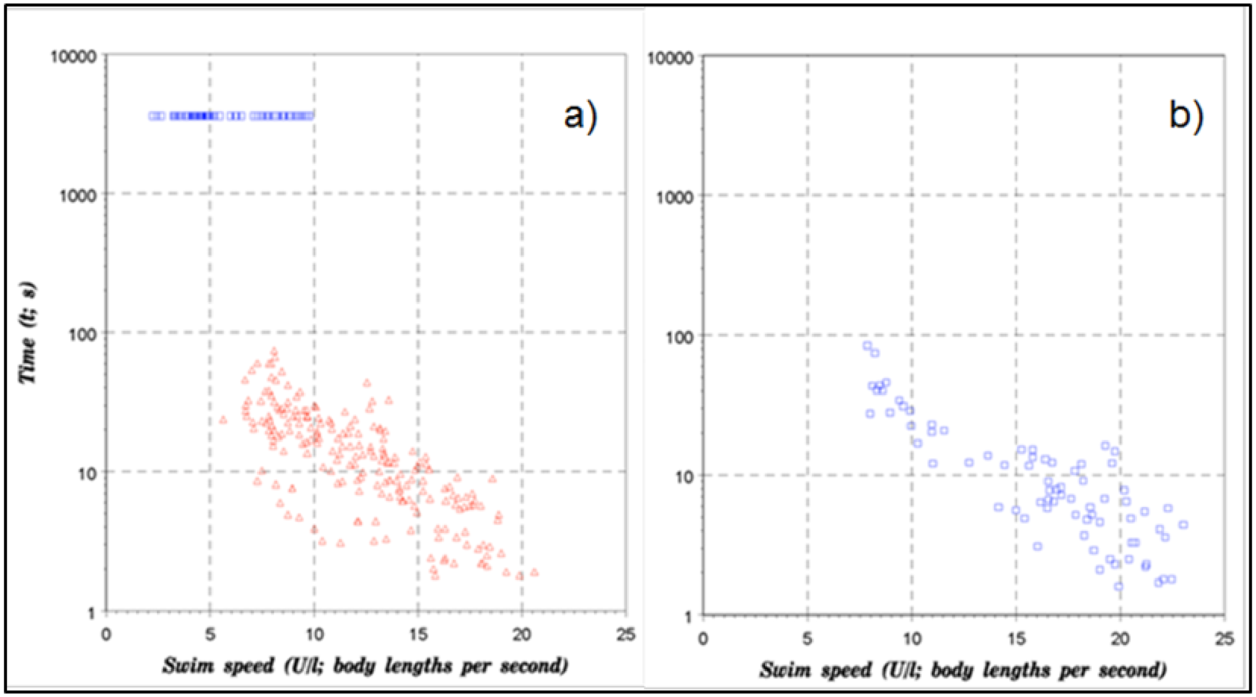

Figure 5. Swim speed by duration for Alewife (a; left panel) using data from Griffiths (1979; blue squares) and Castro-Santos (2005; red triangles) and Blueback Herring (b; right panel) using data from Castro-Santos (2005; blue squares) (Katopodis and Gervais 2016).

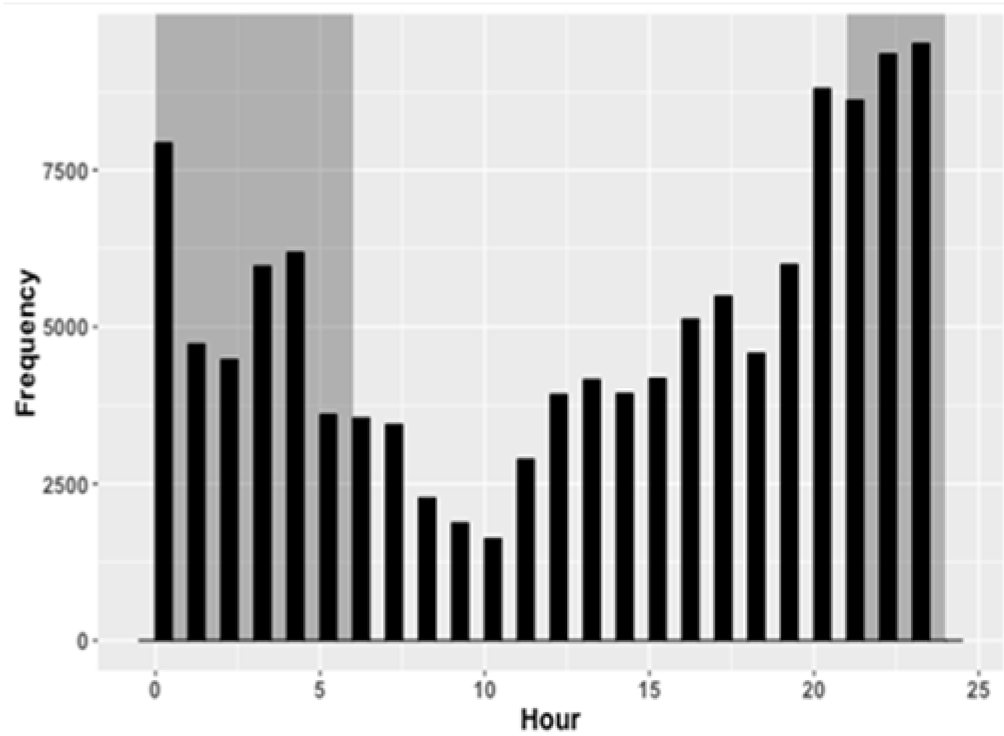

Figure 6. Diel patterns of Passive Induce Transponder (PIT) tag detections of Rainbow Smelt ascending a nature-like fishway on the Wheatley River, Prince Edward Island. Data presented are the pooled detection frequencies at each hour of the day across the monitoring period from 14 May to 25 May, 2015. Shaded vertical rectangles represent night periods. (Landsman and van den Heuvel unpublished data).