# 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

S. J. Peake

Oceans and Habitat Management Branch
Fisheries and Oceans Canada
P.O. Box 5667
St. John's NL A1C 5X1

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# 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

by

S. J. Peake[1]

Oceans and Habitat Management Branch
Fisheries and Oceans Canada
P. O. Box 5667
St. John's, NL
A1C 5X1

[1] University of New Brunswick, Bag Service 4511, Fredericton, NB, Canada, E3B 6E1

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## ABSTRACT

This document presents a compilation of information relating to fish passage design criteria for a variety of species endemic to Newfoundland and Labrador. The primary focus is on swimming capacity, specifically sustained, prolonged, and burst swimming speeds as well as other physical and/or biological parameters that may influence fish passage. Over one hundred primary literature publications were consulted, and enough information was obtained to suggest velocity criteria for most species. However, data for several species was found to be scarce (or non-existent), and research dedicated to filling these information gaps and validating the applicability of forced swimming performance protocols to fish passage situations in the field are needed.



## RÉSUMÉ

Ce document présente une série de données relatives aux critères de conception des passes à poissons pour diverses espèces indigènes à Terre-Neuve-et-Labrador. Ces données concernent principalement la capacité natatoire, particulièrement en ce qui a trait à la nage intense et prolongée et aux pointes de vitesse, ainsi que d’autres paramètres physiques et biologiques susceptibles d’influencer le franchissement des passes à poissons. On a consulté plus d’une centaine de documents primaires et recueilli suffisamment de données pour en déduire des critères de vitesse pour la plupart des espèces. En revanche, pour plusieurs espèces, les données se sont avérées rares, voire inexistantes. Des recherches visant précisément à pallier ce manque de données, et à valider, sur le terrain, l’applicabilité des protocoles de performance de nage forcée aux passes à poissons, seront donc nécessaires.

# 1.0 GENERAL INTRODUCTION

The vast majority of information relating to swimming capacity and exercise physiology of fish has been generated by studying individuals forced to perform in swim tunnel respirometers (Hammer 1995). As a result of this work, it is generally accepted that the overall performance envelope can be divided into three main categories: sustained, prolonged, and burst (Beamish 1978). Sustained swimming occurs at relatively low speeds, and can be maintained for long periods (> 200 minutes) without interruption or failure as the energy used to support this activity is generated through aerobic metabolic pathways. The highest velocity that can be maintained aerobically is called maximum sustained speed. Prolonged swimming involves moderate speeds that require some anaerobic energy, and therefore eventually ends in swimming failure after 20 seconds to 200 min (Beamish 1978). Finally, high speed locomotion is classified as burst swimming, activity that is exclusively anaerobic in nature and relatively short-lived (< 20 s).

Critical swimming speed (Ucrit) is a special category of prolonged swimming first introduced by Brett (1964). The protocol is carried out on fish enclosed in a swim tunnel respirometer, during which subjects are forced to swim against a particular water velocity for a set time interval. Water velocity (and therefore swimming speed) is then increased by a set increment until the individual fails to swim for an entire time interval. Critical swimming speed is calculated as the sum of the penultimate velocity attained and a fraction of the velocity increment proportional to the time spent swimming at the final velocity relative to the full time interval (Hammer 1995). Although Ucrit has often been used to estimate maximum sustained speed, it has also been defined as the highest swimming speed that a fish can maintain for a period equal in magnitude to the time interval used in the test (Peake et al. 1997c). Time intervals as low as 2 min, and as high as 60 min are used in these trials, although values greater than 20 min are most common.

One of the practical applications of critical swimming speed data is related to the establishment of water velocity criteria for fishways and culverts (Jones et al. 1974). For example, if Ucrit (using 30 min time intervals) for a particular fish were found to be 50 cm/s, it would be expected that the animal could swim at 50 cm/s for periods up to 1800 s (30 min × 60 s/min). If velocity criteria for a 50 m long culvert were required, and if the fish were to swim for 30 min during the ascent, the speed of the individual relative to the ground would be 3.2 cm/s (5000 cm/1800 s). If the fish were to swim at 50 cm/s (i.e. critical swimming speed), water velocity in the culvert could not exceed 46.8 cm/s (50 cm/s – 3.2 cm/s), or the animal would fatigue prior to exiting the structure. Therefore, maximum allowable water velocity for that culvert would be 46.8 cm/s.

Although the validity of velocity criteria based on critical swimming speed data has rarely (if ever) been verified quantitatively for free-swimming fish, Peake and Farrell (2004) recently demonstrated that the relationship between swimming speed and endurance in respirometer-confined smallmouth bass (*Micropterus dolomieu*) did not hold for free-swimming fish in an experimental raceway. Further, Peake (2004a) recently demonstrated that velocity criteria based on Ucrit data underestimates (by at least 50%)

the maximum flow rate that can be stemmed by free-swimming smallmouth bass. The authors argue that the differences are associated with the confining nature of respirometers and the inability of fish within them to use their full range of energy saving strategies and gait transitions, suggesting that results for smallmouth bass are general and not species specific. If this is true, it can be expected that velocity criteria based on critical swimming speed data will be generally conservative; however, until more research is conducted, the degree to which these criteria need to be adjusted will remain unknown. However, it is the opinion of this author that critical swimming speed should allow conservative estimates of maximum allowable water velocity, as long as the values are not further reduced by allowing room for ground speed. As such, suggestions for water velocity criteria in this document are based on raw, unadjusted, critical speed data. Information on the relationship between swimming speed and fatigue time are also presented; however, these data are only used to support (or adjust) criteria based on critical speed information. It is suggested that these conservative criteria be adopted until research can be conducted on free-swimming fish in a manner similar to that employed by Peake (2004a).

## 2.0 GENERAL METHODOLOGY

This literature review focused primarily on gathering and summarizing information on swimming capacity of Newfoundland and Labrador fish species from the primary literature. Critical swimming speed separates the sustained and prolonged performance envelopes, and it was therefore considered the best available metric for establishing water velocity criteria in culverts. In compiling the data contained in the various Tables within this report, the critical swimming speed value presented generally represents the mean value minus one standard error or deviation, depending on the information provided. This allowed for a reasonably conservative estimate of Ucrit to be established for each study. If the study provided a model that would predict swimming performance over a range of fish sizes and water temperatures, calculations were made for several combinations and presented. Once the Ucrit data was compiled, with the corresponding length and temperature values (the primary factors that influence swimming capacity), they were sorted from the smallest fish to the largest. Then, each length value was subtracted from that of the smallest fish to establish a relative ranking. Then, the data were sorted according to water temperature (lowest to highest), and ranked as described for length. Length and temperature ranks were then added to establish an overall rank and these were given in the various Tables. Thus, the first entry in any Table represents a small fish that was tested at a low temperature. As swimming performance of this fish would be expected to be low relative to larger and/or warmer individuals, this first entry represents the most conservative data point. Velocity criteria based on this data point should allow passage for all fish ranked higher.

Endurance data from the primary literature was treated similarly and presented to support the velocity criteria suggested from the Ucrit data, or adjust it accordingly. Top swimming speeds were given, where available, to allow other data to be put into context.

# 3.0 SPECIES OF PRIMARY IMPORTANCE

## 3.1 BURBOT (*Lota lota*)

***Swimming Capacity***

A single research study documenting swimming capacity of juvenile and adult burbot was located, and the results of this study are summarized in Table 1. Mean critical swimming speed in this study was 39.1 cm/s (range: 36.4 to 40.8 cm/s) for fish having a mean length of 37.0 cm (range: 12.0 to 62.0 cm) at a mean water temperature of 12.0 °C. Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 35.0 cm/s or less should allow passage of burbot within the size range described above at 12.0 °C. No information on endurance or maximum swimming capacity of burbot was located.

***Fishway and Culvert Passage***

Schwalme et al. (1985) reported that a relatively large number of burbot (mean length: 57.4 cm) passed a vertical slot and two Denil fishways (10 and 20% slopes) on the Lesser Slave River. These fishways were relatively short (3 m) and contained moderate water velocities (23.0 to 68.0 cm/s in the vertical slot, 52.0 to 80.0 cm/s in the 10% Denil, and 75.0 to 107.0 cm/s in the 20% Denil). Although these fishways were very short, it is clear that burbot will ascend fishways regardless of configuration, slope, or water velocity, even when the latter exceeds their critical speed by a considerable degree (see above).

Slavik and Bartos (2002) also studied burbot movement past a fishway (mean water velocity: 10.0 cm/s) in the Czech Republic. The authors reported that spawning migrations in the fall were stimulated by an increase in discharge and a drop in water temperature. More burbot passed the fishway in other seasons, and passage generally coincided with a drop in discharge and a reduction in water depth within the structure.

Table 1. Minimum critical swimming speeds for burbot from the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 36.4 | 12.0 | 12.0 | 0.0 | Jones et al. (1974) |
| 37.3 | 17.0 | 12.0 | 5.0 | Jones et al. (1974) |
| 38.0 | 22.0 | 12.0 | 10.0 | Jones et al. (1974) |
| 38.5 | 27.0 | 12.0 | 15.0 | Jones et al. (1974) |
| 39.0 | 32.0 | 12.0 | 20.0 | Jones et al. (1974) |
| 39.4 | 37.0 | 12.0 | 25.0 | Jones et al. (1974) |
| 39.8 | 42.0 | 12.0 | 30.0 | Jones et al. (1974) |
| 40.1 | 47.0 | 12.0 | 35.0 | Jones et al. (1974) |

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 40.3 | 52.0 | 12.0 | 40.0 | Jones et al. (1974) |
| 40.6 | 57.0 | 12.0 | 45.0 | Jones et al. (1974) |
| 40.8 | 62.0 | 12.0 | 50.0 | Jones et al. (1974) |

### 3.2 AMERICAN EEL (*Anguilla rostrata*)

No swimming performance data for American eel was found in this literature search. However, Barbin and Krueger (1994) studied locomotory behaviour of elvers (4.9 to 6.4 cm) in a 1.5 m experimental flume, and noted that movement through the structure was impeded when water velocity exceeded 30.0 cm/s. As such, it is suggested that velocity criteria for elvers be set at approximately 20.0 cm/s to allow these animals to attain a reasonable ground speed while ascending culverts.

Whitfield and Kolenosky (1978) described a prototype eel fishway on the Saint Lawrence River, in Ontario, and noted that approximately 4 million adults passed through the structure during the four-year monitoring period. The fishway was installed in an ice chute on the hydroelectric dam and was outfitted with a trough and baffle system that slowed water velocity and provided rest pools. Slope was approximately 12 $^{o}$, and water velocity was quite high (255.0 cm/s). Attraction flow was provided by a pump.

### 3.3 LAKE CHUB (*Couesius plumbeus*)

No swimming performance or fishway/culvert passage data for lake chub was found in this literature search. However, Warren and Pardew (1998) studied passage of many minnow species in several culvert types and reported that culvert crossings were an order of magnitude lower than open box, ford crossings (gently sloping submerged roadbeds), and natural reaches. In addition, open box and ford crossings passed similar numbers of fish as did natural reaches. In general, water velocity at all crossings was inversely related to fish movement. Culverts had the highest water velocities (40.0 to 140.0 cm/s), followed by ford crossings (12.0 to 28.0 cm/s), and open box crossings (< 5.0 cm/s). As such, it is suggested that water velocity criteria for this species be set at 30.0 cm/s until swimming performance data can be obtained.

### 3.4 LONGNOSE DACE (*Rhinichthys cataractae*)

***Swimming Capacity***

Two research studies documenting swimming capacity of adult longnose dace were located, and the results of these studies are summarized in Table 2. Mean critical swimming speed of all fish among these studies was 61.8 cm/s (range: 26.0 to 76.0 cm/s) for fish having a mean length of 6.8 cm (range: 4.5 to 7.8 cm) at a mean water temperature of 12.8 °C (range: 5.0 to 24.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 65.0 cm/s or less should allow passage of most longnose dace within the size and temperature ranges described above. No information regarding swimming endurance or maximum swimming capacity of longnose dace could be found.

***Fishway and Culvert Passage***

No information was located on movements of longnose dace through fishways or culverts; however, Mullen and Burton (1995) reported that adults and juveniles in natural streams were segregated by water velocity. Adults typically dominated areas where water velocity exceeded 50.0 cm/s. Despite this, Gee and Northcote (1963) reported that both juvenile and adults given the choice of inhabiting channels containing water moving at 30.0, 60.0 or 90.0 cm/s consistently chose the lattermost. However, Mullen and Burton (1998) showed that segregation of juveniles and adults at water velocities in the range of 40.0 to 50.0 cm/s was due to active competition, and not differences in swimming capacity. As such, it is suggested that the proposed velocity criteria (65.0 cm/s) should not result in a velocity barrier for juveniles or adults of this species.

Table 2. Minimum critical swimming speeds for longnose dace from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 66.0 | 7.8 | 5.0 | 3.3 | Facey & Grossman (1990) |
| 73.0 | 7.1 | 10.0 | 7.6 | Facey & Grossman (1990) |
| 76.0 | 7.8 | 10.0 | 8.3 | Facey & Grossman (1990) |
| 68.0 | 7.0 | 15.0 | 12.5 | Facey &Grossman (1990) |
| 26.0 | 4.5 | 24.0 | 19.0 | Nelson et al. (2003) |

### 3.5 PEARL DACE (*Margariscus margarita*)

No swimming performance or fishway/culvert passage data for pearl dace was found in this literature search; however, Warren and Pardew (1998) studied passage of many minnow species in several culvert types and reported that culvert crossings were an order of magnitude lower than open box, ford crossings (gently sloping submerged roadbeds), and natural reaches. In addition, open box and ford crossings passed similar numbers of fish as did natural reaches. In general, water velocity at all crossings was inversely related to fish movement. Culverts had the highest water velocities (40.0 to 140.0 cm/s), followed by ford crossings (12.0 to 28.0 cm/s), and open box crossings (< 5.0 cm/s). As such, it is suggested that water velocity criteria for this species be set at 30.0 cm/s until swimming performance data can be obtained.

### 3.6 NORTHERN PIKE (*Esox lucius*)

***Swimming Capacity***

A total of five research studies documenting swimming capacity of juvenile and adult northern pike were located, and the results of these studies are summarized in Tables 3 and 4. Mean critical swimming speed of all fish among these studies was 30.2 cm/s (range: 13.0 to 47.4 cm/s) for fish having a mean length of 28.5 cm (range: 2.0 to 62.0 cm) at a mean water temperature of 13.5 °C (range: 12.0 to 17.5 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 15.0 and 35.0 cm/s or less should allow passage of most juvenile and small adult northern pike, respectively. No information of swimming endurance of northern pike could be located; however, maximum swimming capacity appears to be at least 174.0 cm/s (Table 4).

***Fishway and Culvert Passage***

Very little information on passage ability of northern pike was located. Schwalme et al. (1985) reported that large numbers of northern pike (mean length: 44.1 cm) passed a vertical slot and two Denil fishways (10 and 20% slopes) on a weir on the Lesser Slave River. These fishways were relatively short (3 m) and contained moderate water velocities (23.0 to 68.0 cm/s in the vertical slot, 52.0 to 80.0 cm/s in the 10% Denil, and 75.0 to 107.0 cm/s in the 20% Denil). Obviously, these fishways were very short; however, it is clear that northern pike will ascend fishways regardless of configuration, slope, or water velocity, even when the latter exceeds their critical swimming speed by a considerable amount (see above).

Table 3. Minimum critical swimming speeds for northern pike from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 13.0 | 2.0 | 17.5 | 5.5 | Peake (2004 b) |
| 16.0 | 4.0 | 17.5 | 7.5 | Peake (2004 b) |
| 19.0 | 6.0 | 17.5 | 9.5 | Peake (2004 b)) |
| 19.2 | 12.0 | 12.0 | 10.0 | Jones et al. (1974) |
| 22.0 | 8.0 | 17.5 | 11.5 | Peake (2004 b) |
| 23.3 | 17.0 | 12.0 | 15.0 | Jones et al. (1974) |
| 26.8 | 22.0 | 12.0 | 20.0 | Jones et al. (1974) |
| 30.0 | 27.0 | 12.0 | 25.0 | Jones et al. (1974) |
| 33.0 | 32.0 | 12.0 | 30.0 | Jones et al. (1974) |
| 35.7 | 37.0 | 12.0 | 35.0 | Jones et al. (1974) |
| 38.3 | 42.0 | 12.0 | 40.0 | Jones et al. (1974) |
| 40.7 | 47.0 | 12.0 | 45.0 | Jones et al. (1974) |
| 43.1 | 52.0 | 12.0 | 50.0 | Jones et al. (1974) |
| 45.3 | 57.0 | 12.0 | 55.0 | Jones et al. (1974) |
| 47.4 | 62.0 | 12.0 | 60.0 | Jones et al. (1974) |

Table 4. The maximum swimming speeds that northern pike can attain in still water relative to fish length and water temperature, based on fast-start data from the primary

literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Reference |
|---|---|---|---|
| 174.0 | 20.7 | 15.0 | Webb (1978a) |
| 529.0 | 35.8 | 15.0 | Harper & Blake (1990) |
| 415.0 | 35.8 | 15.0 | Harper & Blake (1990) |
| 429.0 | 35.8 | 15.0 | Harper & Blake (1990) |
| 280.0 | 39.6 | 8.0 | Frith & Blake (1995) |

### 3.7 ARCTIC CHAR (*Salvelinus alpinus*)

***Swimming Capacity***

A total of five research studies documenting swimming capacity of juvenile and adult Arctic char were located, and the results of these studies are summarized in Tables 5 and 6. Mean critical swimming speed of all fish among these studies was 66.9 cm/s (range: 41.1 to 97.2 cm/s) for those having a mean length of 27.1 cm (range: 10.0 to 40.0 cm) at a mean water temperature of 9.8 °C (range: 5.0 to 15.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 40.0 and 65.0 cm/s should allow passage of juvenile and adult Artic char, respectively. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a (conservatively) long culvert (100 m). Endurance data collected indicates that adult Arctic char should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 85.0 cm/s (Table 6). Thus, if water velocity criteria for adults of this species are set at 65.0 cm/s (as recommended), an adult fish could attain a ground speed as high as 20.0 cm/s (85.0 – 65.0 cm/s), and still make it through the culvert. No information on the maximum swimming capacity or fishway/culvert passage of this species was located.

Table 5. Minimum critical swimming speeds for Arctic char from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 41.1 | 10.0 | 9.0 | 4.00 | Welch (1979) |
| 52.6 | 15.0 | 9.0 | 9.00 | Welch (1979) |
| 65.0 | 14.0 | 13.0 | 12.00 | Hunter & Scherer (1988) |
| 62.6 | 20.0 | 9.0 | 14.00 | Welch (1979) |
| 71.7 | 25.0 | 9.0 | 19.00 | Welch (1979) |
| 47.0 | 31.6 | 5.0 | 21.60 | Beamish (1980) |
| 80.0 | 30.0 | 9.0 | 24.00 | Welch (1979) |
| 48.0 | 31.6 | 10.0 | 26.60 | Beamish (1980) |

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 87.9 | 35.0 | 9.0 | 29.00 | Welch (1979) |
| 68.0 | 34.0 | 10.0 | 29.00 | Beamish (1980) |
| 97.2 | 34.3 | 12.0 | 31.30 | Jones et al. (1974) |
| 53.0 | 31.6 | 15.0 | 31.60 | Beamish (1980) |
| 95.3 | 40.0 | 9.0 | 34.00 | Welch (1979) |

Table 6. The maximum distance that Arctic char can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 51.0 | 34.0 | 10.0 | 6120.0 | Beamish (1980) |
| 68.0 | 34.0 | 10.0 | 2448.0 | Beamish (1980) |
| 85.0 | 34.0 | 10.0 | 459.0 | Beamish (1980) |
| 102.0 | 34.0 | 10.0 | 61.2 | Beamish (1980) |
| 136.0 | 34.0 | 10.0 | 12.2 | Beamish (1980) |

### 3.8 ADULT ATLANTIC SALMON (*Salmo salar*) IN SEAWATER

***Swimming Capacity***

Two research studies documenting swimming capacity of adult Atlantic salmon in seawater were located, and the results of these studies are summarized in Table 7. Mean critical swimming speed of all fish among these studies was 76.8 cm/s (range: 65.0 to 94.0 cm/s) for fish having a mean length of 39.2 cm (range: 34.0 to 44.0 cm) at a mean water temperature of 8.3 °C (range: 8.0 to 9.5 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to about 95.0 cm/s or less should allow passage of most adult Atlantic salmon within the size and temperature ranges described above. No information on endurance, maximum swimming capacity, or fishway/culvert passage of adult Atlantic salmon in seawater was located.

Table 7. Minimum critical swimming speeds for adult Atlantic salmon (in seawater) from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 94.0 | 34.0 | 9.5 | 1.5 | Wagner et al. (2003) |
| 75.0 | 38.0 | 8.0 | 4.0 | McKenzie et al. (1998) |
| 65.0 | 40.0 | 8.0 | 6.0 | McKenzie et al. (1998) |
| 75.0 | 40.0 | 8.0 | 6.0 | McKenzie et al. (1998) |
| 75.0 | 44.0 | 8.0 | 10.0 | McKenzie et al. (1998) |

## 3.9 ADULT ATLANTIC SALMON (*Salmo salar*) IN FRESHWATER

***Swimming Capacity***

Six research studies documenting swimming capacity of adult Atlantic salmon in freshwater were located, and the results of these studies are summarized in Tables 8 and 9. Mean critical swimming speed was 147.3 cm/s (range: 93.3 to 198.0 cm/s) for fish having a mean length of 48.6 cm (range: 35.9 to 57.5 cm) at 12.5 °C (range: 10.2 to 18.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to about 90.0 cm/s should allow passage of Atlantic salmon within size and temperature ranges described above. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a 100 m culvert. Endurance data collected indicates that adult Atlantic salmon should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 210.0 cm/s (Table 9). If water velocity criteria for this species were set at 90.0 cm/s (as recommended), a 52.0 cm fish could attain a ground speed as high as 130.0 cm/s (210.0 – 90.0 cm/s), and still make it through the culvert. No information on the maximum swimming capacity of adult Atlantic salmon in freshwater was located.

***Fishway and Culvert Passage***

Laine et al. (2002) monitored passage of adult Atlantic salmon on a Denil fishway on the River Kemijoki, in northern Finland. The authors noted that modifications to the fishway entrance that increased discharge through the fishway (1) reduced the amount of staging at the entrance, (2) increased the number of fish that passed the structure, and (3) increased the maximum size of adult salmon that used the fishway. Water velocities in this fishway were generally in the range of 100 to 120 cm/s (although the highest velocities were approximately 400 cm/s). Laine et al. (2002) also indicated that the number of adult Atlantic salmon that passed the fishways was positively correlated with the mean tailwater depth. Similar findings were reported by Thorstad et al. (2003).

Table 8. Minimum critical swimming speeds for adult Atlantic salmon (in freshwater) from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 93.3 | 35.9 | 10.2 | 0.0 | Wagner et al. (2003) |
| 155.0 | 45.0 | 12.0 | 10.9 | Beddow & McKinley (1999) |
| 120.0 | 47.0 | 10.4 | 11.3 | Ytrestoyl et al. (2001) |
| 170.0 | 57.5 | 12.0 | 23.4 | Booth et al. (1997) |
| 198.0 | 57.5 | 18.0 | 29.4 | Booth et al. (1997) |

Table 9. The maximum distance that adult Atlantic salmon (in freshwater) can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 60.0 | 52.0 | 4.0 | 6480.0 | Thorstad et al. (2000) |
| 110.0 | 52.0 | 4.0 | 8250.0 | Thorstad et al. (2000) |
| 130.0 | 52.0 | 4.0 | 5460.0 | Thorstad et al. (2000) |
| 150.0 | 52.0 | 4.0 | 3600.0 | Thorstad et al. (2000) |
| 170.0 | 52.0 | 4.0 | 2040.0 | Thorstad et al. (2000) |
| 190.0 | 52.0 | 4.0 | 342.0 | Thorstad et al. (2000) |
| 160.0 | 59.0 | 5.0 | 8640.0 | Thorstad et al. (1997) |
| 180.0 | 59.0 | 5.0 | 3240.0 | Thorstad et al. (1997) |
| 200.0 | 59.0 | 5.0 | 360.0 | Thorstad et al. (1997) |
| 210.0 | 59.0 | 5.0 | 504.0 | Thorstad et al. (1997) |

### 3.10 ATLANTIC SALMON (*Salmo salar*) KELTS

***Swimming Capacity***

A single research study documenting swimming capacity of Atlantic salmon kelts was located, and the results of this study is summarized in Tables 10 and 11. Mean critical swimming speed of all fish in this study was 107.3 cm/s (range: 92.7 to 121.9 cm/s) for fish having a mean length of 54.0 cm (range: 46.0 to 62.0 cm) at a mean water temperature of 5.0 °C. Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 90.0 cm/s or less (at 5.0 °C) should allow passage of Atlantic salmon kelts within the size range described above. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a (conservatively) long culvert (100 m). Endurance data collected indicates that Atlantic salmon kelts should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 110 cm/s (Table 11). If water velocity criteria for this species were set at 90.0 cm/s (as recommended), a 55 cm fish could attain a ground speed as high as 20.0 cm/s (110.0 – 90.0 cm/s), and still make it through the culvert. No information on the maximum swimming capacity or fishway/culvert passage of Atlantic salmon kelts was located.

Table 10. Minimum critical swimming speeds for Atlantic salmon kelts from the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 92.7 | 46.0 | 5.0 | 0.0 | Booth et al. (1996) |
| 96.4 | 48.0 | 5.0 | 2.0 | Booth et al. (1996) |

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 100.0 | 50.0 | 5.0 | 4.0 | Booth et al. (1996) |
| 103.7 | 52.0 | 5.0 | 6.0 | Booth et al. (1996) |
| 107.3 | 54.0 | 5.0 | 8.0 | Booth et al. (1996) |
| 110.9 | 56.0 | 5.0 | 10.0 | Booth et al. (1996) |
| 114.6 | 58.0 | 5.0 | 12.0 | Booth et al. (1996) |
| 118.2 | 60.0 | 5.0 | 14.0 | Booth et al. (1996) |
| 121.9 | 62.0 | 5.0 | 16.0 | Booth et al. (1996) |

Table 11. The maximum distance that Atlantic salmon kelts can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 50.0 | 55.5 | 7.0 | 6000.0 | Booth et al. (1996) |
| 80.0 | 55.5 | 7.0 | 480.0 | Booth et al. (1996) |
| 110.0 | 55.5 | 7.0 | 330.0 | Booth et al. (1996) |
| 140.0 | 55.5 | 7.0 | 84.0 | Booth et al. (1996) |

### 3.11 ATLANTIC SALMON (*Salmo salar*) SMOLTS

***Swimming Capacity***

A total of four research studies documenting swimming capacity of Atlantic salmon smolts were located, and the results of these studies are summarized in Tables 12 through 14. Mean critical swimming speed of all fish among these studies was 101.5 cm/s (range: 41.6 to 162.0 cm/s) for fish having a mean length of 16.5 cm (range: 12.0 to 21.7 cm) at a mean water temperature of 11.9 °C (range: 5.0 to 19.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 65.0 cm/s or less should allow passage of Atlantic salmon smolts within the size and temperature ranges described above. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a (conservatively) long culvert (100 m). Endurance data collected indicates that Atlantic salmon smolts should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 121.0 cm/s (Table 13). If water velocity criteria for this species were set at 65.0 cm/s (as recommended), a 14.0 cm fish could attain a ground speed as high as 56.0 cm/s (121.0 – 65.0 cm/s), and still make it through the culvert. Maximum swimming capacity of Atlantic salmon smolts appears to be approximately 200.0 cm/s (Table 14).

Table 12. Minimum critical swimming speeds for Atlantic salmon smolts from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 64.4 | 16.5 | 5.0 | 4.5 | Booth et al. (1996) |
| 70.8 | 16.5 | 7.0 | 6.5 | Booth et al. (1996) |
| 100.8 | 12.0 | 12.8 | 7.8 | Peake et al. (1997c) |
| 103.0 | 12.4 | 12.8 | 8.2 | Peake et al. (1997c) |
| 77.1 | 16.5 | 9.0 | 8.5 | Booth et al. (1996) |
| 113.4 | 14.0 | 12.8 | 9.8 | Peake et al. (1997c) |
| 83.4 | 16.5 | 11.0 | 10.5 | Booth et al. (1996) |
| 41.6 | 21.7 | 7.0 | 11.7 | McCleave & Stred (1975) |
| 126.0 | 16.0 | 12.8 | 11.8 | Peake et al. (1997c) |
| 89.8 | 16.5 | 13.0 | 12.5 | Booth et al. (1996) |
| 146.0 | 18.5 | 12.0 | 13.5 | Peake et al. (1997b) |
| 138.6 | 18.0 | 12.8 | 13.8 | Peake et al. (1997c) |
| 162.0 | 19.4 | 12.0 | 14.4 | Peake et al. (1997b) |
| 96.1 | 16.5 | 15.0 | 14.5 | Booth et al. (1996) |
| 102.5 | 16.5 | 17.0 | 16.5 | Booth et al. (1996) |
| 108.8 | 16.5 | 19.0 | 18.5 | Booth et al. (1996) |

Table 13. The maximum distance Atlantic salmon smolts can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 108.0 | 14.0 | 14.0 | 972.0 | Peake et al. (1997c) |
| 113.0 | 14.0 | 14.0 | 678.0 | Peake et al. (1997c) |
| 121.0 | 14.0 | 14.0 | 363.0 | Peake et al. (1997c) |
| 169.0 | 14.0 | 14.0 | 10.1 | Peake et al. (1997c) |
| 55.0 | 17.5 | 7.0 | 6600.0 | Booth et al. (1996) |
| 55.0 | 17.5 | 14.0 | 6600.0 | Booth et al. (1996) |
| 55.0 | 17.5 | 17.0 | 6600.0 | Booth et al. (1996) |
| 95.0 | 17.5 | 7.0 | 1995.0 | Booth et al. (1996) |
| 95.0 | 17.5 | 14.0 | 2850.0 | Booth et al. (1996) |
| 95.0 | 17.5 | 17.0 | 7125.0 | Booth et al. (1996) |
| 135.0 | 17.5 | 7.0 | 162.0 | Booth et al. (1996) |
| 135.0 | 17.5 | 14.0 | 81.0 | Booth et al. (1996) |
| 135.0 | 17.5 | 17.0 | 1620.0 | Booth et al. (1996) |
| 175.0 | 17.5 | 7.0 | 420.0 | Booth et al. (1996) |
| 175.0 | 17.5 | 14.0 | 105.0 | Booth et al. (1996) |

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 175.0 | 17.5 | 17.0 | 1575.0 | Booth et al. (1996) |
| 195.0 | 17.5 | 7.0 | 117.0 | Booth et al. (1996) |
| 195.0 | 17.5 | 14.0 | 117.0 | Booth et al. (1996) |
| 195.0 | 17.5 | 17.0 | 117.0 | Booth et al. (1996) |
| 124.0 | 18.0 | 14.0 | 1116.0 | Peake et al. (1997c) |
| 129.0 | 18.0 | 14.0 | 774.0 | Peake et al. (1997c) |
| 137.0 | 18.0 | 14.0 | 411.0 | Peake et al. (1997c) |
| 185.0 | 18.0 | 14.0 | 11.1 | Peake et al. (1997c) |
| 140.0 | 22.0 | 14.0 | 1260.0 | Peake et al. (1997c) |
| 145.0 | 22.0 | 14.0 | 870.0 | Peake et al. (1997c) |
| 153.0 | 22.0 | 14.0 | 459.0 | Peake et al. (1997c) |
| 201.0 | 22.0 | 14.0 | 12.1 | Peake et al. (1997c) |

Table 14. The maximum swimming speed that Atlantic salmon smolts can attain in still water relative to fish length and water temperature, based on fast-start data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Reference |
|---|---|---|---|
| 200.0 | 16.5 | 5.0 | Booth et al. (1996) |

## 3.12 ATLANTIC SALMON (*Salmo salar*) PARR

***Swimming Capacity***

Eight independent research studies documenting the swimming (or holding) capacity of Atlantic salmon parr were located, and the results of these studies are summarized in Tables 15 and 16. Mean critical holding speed of all fish among these studies was 64.0 cm/s (range: 20.0 to 113.4 cm/s) for fish having a mean length of 8.9 cm (range: 4.5 to 14.2 cm) at a mean water temperature of 13.9 °C (range: 1.0 to 20.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 45.0 cm/s or less should allow passage of most Atlantic salmon parr within the size and temperature ranges described above. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a (conservatively) long culvert (100 m). Endurance data collected indicates that Atlantic salmon parr should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 38.0 cm/s (Table 16). If water velocity criteria for this species were set at 45.0 cm/s (as recommended above), this fish would probably not make it through the culvert. As such, water velocity criteria for Atlantic salmon parr should probably be reduced to reflect the critical swimming speed of the second ranked group (Table 16), which is 30.0 cm/s. This adjustment would allow fish to attain a reasonable ground speed (8 cm/s) and still pass the 100 m culvert. No information on the maximum swimming capacity or fishway/culvert passage of Atlantic salmon parr was located.

Table 15. Minimum critical swimming speeds for Atlantic salmon parr from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 45.0 | 7.5 | 1.0 | 3.0 | Rimmer et al. (1985) |
| 30.0 | 5.7 | 5.0 | 5.2 | Graham et al. (1996) |
| 40.0 | 7.2 | 5.0 | 6.7 | Graham et al. (1996) |
| 20.0 | 9.3 | 5.0 | 8.8 | Graham et al. (1996) |
| 35.0 | 4.5 | 12.0 | 11.0 | McDonald et al. (1998) |
| 50.6 | 5.0 | 12.0 | 11.5 | Peake et al. (1997c) |
| 41.0 | 5.5 | 12.0 | 12.0 | McDonald et al. (1998) |
| 52.0 | 6.5 | 12.0 | 13.0 | McDonald et al. (1998) |
| 56.8 | 7.0 | 12.0 | 13.5 | Peake et al. (1997c) |
| 54.2 | 5.0 | 14.0 | 13.5 | Peake et al. (1997c) |
| 63.0 | 9.0 | 12.0 | 15.5 | Peake et al. (1997c) |
| 60.4 | 7.0 | 14.0 | 15.5 | Peake et al. (1997c) |
| 57.8 | 5.0 | 16.0 | 15.5 | Peake et al. (1997c) |
| 44.8 | 9.3 | 12.5 | 16.3 | Stevens et al. (1998) |
| 78.0 | 12.2 | 10.5 | 17.2 | Arnold et al. (1991) |
| 69.2 | 11.0 | 12.0 | 17.5 | Peake et al. (1997c) |
| 66.6 | 9.0 | 14.0 | 17.5 | Peake et al. (1997c) |
| 64.0 | 7.0 | 16.0 | 17.5 | Peake et al. (1997c) |
| 61.4 | 5.0 | 18.0 | 17.5 | Peake et al. (1997c) |
| 49.0 | 13.6 | 10.0 | 18.1 | Lacroix et al. (2004) |
| 75.4 | 13.0 | 12.0 | 19.5 | Peake et al. (1997c) |
| 72.8 | 11.0 | 14.0 | 19.5 | Peake et al. (1997c) |
| 70.2 | 9.0 | 16.0 | 19.5 | Peake et al. (1997c) |
| 67.6 | 7.0 | 18.0 | 19.5 | Peake et al. (1997c) |
| 65.0 | 5.0 | 20.0 | 19.5 | Peake et al. (1997c) |
| 79.0 | 13.0 | 14.0 | 21.5 | Peake et al. (1997c) |
| 76.4 | 11.0 | 16.0 | 21.5 | Peake et al. (1997c) |
| 73.8 | 9.0 | 18.0 | 21.5 | Peake et al. (1997c) |
| 71.2 | 7.0 | 20.0 | 21.5 | Peake et al. (1997c) |
| 82.6 | 13.0 | 16.0 | 23.5 | Peake et al. (1997c) |
| 80.0 | 11.0 | 18.0 | 23.5 | Peake et al. (1997c) |
| 77.4 | 9.0 | 20.0 | 23.5 | Peake et al. (1997c) |
| 113.4 | 14.2 | 16.3 | 25.0 | Robertson et al. (2003) |
| 86.2 | 13.0 | 18.0 | 25.5 | Peake et al. (1997c) |
| 83.6 | 11.0 | 20.0 | 25.5 | Peake et al. (1997c) |
| 89.8 | 13.0 | 20.0 | 27.5 | Peake et al. (1997c) |

Table 16. The maximum distance that Atlantic salmon parr can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 38.0 | 5.0 | 12.0 | 66.5 | McDonald et al. (1998) |
| 67.2 | 5.0 | 12.5 | 4.0 | Peake et al. (1997c) |
| 50.0 | 5.5 | 12.0 | 12.5 | McDonald et al. (1998) |
| 38.0 | 6.0 | 12.0 | 256.0 | McDonald et al. (1998) |
| 50.0 | 6.5 | 12.0 | 40.0 | McDonald et al. (1998) |
| 72.2 | 7.0 | 12.5 | 4.3 | Peake et al. (1997c) |
| 50.0 | 7.5 | 12.0 | 80.0 | McDonald et al. (1998) |
| 77.2 | 9.0 | 12.5 | 4.6 | Peake et al. (1997c) |
| 82.2 | 11.0 | 12.5 | 4.9 | Peake et al. (1997c) |
| 87.2 | 13.0 | 12.5 | 5.2 | Peake et al. (1997c) |
| 92.2 | 15.0 | 12.5 | 5.5 | Peake et al. (1997c) |

### 3.13 BROOK TROUT (*Salvelinus fontinalis*)

***Swimming Capacity***

A total of five research studies documenting swimming capacity of juvenile and adult brook trout were located, and the results of these studies are summarized in Tables 17 and 18. Mean critical swimming speed of all fish among these studies was 58.7 cm/s (range: 7.6 to 184.1 cm/s) for fish having a mean length of 14.7 cm (range: 2.9 to 40.0 cm) at a mean water temperature of 12.9 °C (range: 5.0 to 15.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 30.0 and 50.0 cm/s or less should allow passage of most juvenile and adult brook trout, respectively. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a (conservatively) long culvert (100 m). Endurance data collected indicates that juvenile brook trout should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 48.0 cm/s (Table 18). If water velocity criteria for juveniles were set at 30.0 cm/s (as recommended), fish could attain a ground speed as high as 18.0 cm/s (48.0 – 30.0 cm/s), and still make it through the culvert. Adult brook trout should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 88.8 cm/s (Table 18). If water velocity criteria for this species were set at 50.0 cm/s (as recommended), fish could attain a ground speed as high as 38.8 cm/s (88.8 – 50.0 cm/s), and still make it through the culvert. Information on maximum swimming capacity of brook trout could not be found.

***Fishway and Culvert Passage***

In one of the few primary literature studies found that actually evaluated fish passage ability in actual culverts, Belford and Gould (1989) reported that brook trout (21.1 to 30.8 cm) could swim distances of 10, 30, 50, 70, and 90 m against bottom water velocities up to 96.0, 80.0, 74.0, 70.0, and 67.0 cm/s, respectively. These results agreed well with other field reports on brook trout passage from the grey literature (Saltzman and Koski 1971;

Lauman 1976; Travis and Tilsworth 1986). Thus, water velocity criteria for a 100 m culvert suggested above for juvenile and adults (30.0 and 50.0 cm/s, respectively) should be suitable for this species.

Table 17. Minimum critical swimming speeds for brook trout from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| **Ucrit (cm/s)** | **Length (cm)** | **Temp. (°C)** | **Rank** | **Reference** |
|---|---|---|---|---|
| 9.0 | 8.2 | 5.0 | 5.3 | Beamish (1980) |
| 7.6 | 2.9 | 12.7 | 7.7 | Stillwell & Benfey (1997) |
| 30.0 | 5.0 | 12.0 | 9.1 | McDonald et al. (1998) |
| 32.0 | 5.5 | 12.0 | 9.6 | McDonald et al. (1998) |
| 12.0 | 8.2 | 10.0 | 10.3 | Beamish (1980) |
| 42.0 | 6.5 | 12.0 | 10.6 | McDonald et al. (1998) |
| 21.5 | 4.0 | 15.0 | 11.1 | Beamish (1980) |
| 52.0 | 7.5 | 12.0 | 11.6 | McDonald et al. (1998) |
| 62.0 | 8.5 | 12.0 | 12.6 | McDonald et al. (1998) |
| 72.0 | 9.5 | 12.0 | 13.6 | McDonald et al. (1998) |
| 49.1 | 10.0 | 12.7 | 14.8 | Peake et al. (1997c) |
| 28.9 | 8.0 | 15.0 | 15.1 | Beamish (1980) |
| 22.0 | 8.2 | 15.0 | 15.3 | Beamish (1980) |
| 47.2 | 10.4 | 15.0 | 17.5 | Beamish (1980) |
| 34.4 | 12.0 | 15.0 | 19.1 | Beamish (1980) |
| 71.6 | 15.0 | 12.7 | 19.8 | Peake et al. (1997c) |
| 39.0 | 16.0 | 15.0 | 23.1 | Beamish (1980) |
| 94.1 | 20.0 | 12.7 | 24.8 | Peake et al. (1997c) |
| 42.9 | 20.0 | 15.0 | 27.1 | Beamish (1980) |
| 116.6 | 25.0 | 12.7 | 29.8 | Peake et al. (1997c) |
| 46.4 | 24.0 | 15.0 | 31.1 | Beamish (1980) |
| 139.1 | 30.0 | 12.7 | 34.8 | Peake et al. (1997c) |
| 49.6 | 28.0 | 15.0 | 35.1 | Beamish (1980) |
| 161.6 | 35.0 | 12.7 | 39.8 | Peake et al. (1997c) |
| 184.1 | 40.0 | 12.7 | 44.8 | Peake et al. (1997c) |

Table 18. The maximum distance that brook trout can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| **Speed (cm/s)** | **Length (cm)** | **Temp. (°C)** | **Distance (m)** | **Reference** |
|---|---|---|---|---|
| 50.0 | 5.5 | 12.0 | 12.5 | McDonald et al. (1998) |
| 50.0 | 6.5 | 12.0 | 40.0 | McDonald et al. (1998) |

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 50.0 | 7.5 | 12.0 | 80.0 | McDonald et al. (1998) |
| 28.5 | 8.0 | 14.0 | 2567.0 | Peake et al. (1997c) |
| 29.6 | 8.0 | 14.0 | 2219.4 | Peake et al. (1997c) |
| 30.9 | 8.0 | 14.0 | 1854.0 | Peake et al. (1997c) |
| 32.6 | 8.0 | 14.0 | 1466.4 | Peake et al. (1997c) |
| 35.0 | 8.0 | 14.0 | 1048.9 | Peake et al. (1997c) |
| 37.5 | 8.0 | 20.0 | 3377.0 | Peake et al. (1997c) |
| 38.6 | 8.0 | 20.0 | 2894.4 | Peake et al. (1997c) |
| 39.0 | 8.0 | 14.0 | 585.4 | Peake et al. (1997c) |
| 39.9 | 8.0 | 20.0 | 2394.0 | Peake et al. (1997c) |
| 41.6 | 8.0 | 20.0 | 1871.4 | Peake et al. (1997c) |
| 44.0 | 8.0 | 20.0 | 1318.9 | Peake et al. (1997c) |
| 48.0 | 8.0 | 20.0 | 720.4 | Peake et al. (1997c) |
| 57.9 | 8.0 | 14.0 | 34.7 | Peake et al. (1997c) |
| 66.9 | 8.0 | 20.0 | 40.1 | Peake et al. (1997c) |
| 69.3 | 16.0 | 14.0 | 6239.0 | Peake et al. (1997c) |
| 70.4 | 16.0 | 14.0 | 5279.4 | Peake et al. (1997c) |
| 71.7 | 16.0 | 14.0 | 4302.0 | Peake et al. (1997c) |
| 73.4 | 16.0 | 14.0 | 3302.4 | Peake et al. (1997c) |
| 75.8 | 16.0 | 14.0 | 2272.9 | Peake et al. (1997c) |
| 78.3 | 16.0 | 20.0 | 7049.0 | Peake et al. (1997c) |
| 79.4 | 16.0 | 20.0 | 5954.4 | Peake et al. (1997c) |
| 79.8 | 16.0 | 14.0 | 1197.4 | Peake et al. (1997c) |
| 80.7 | 16.0 | 20.0 | 4842.0 | Peake et al. (1997c) |
| 82.4 | 16.0 | 20.0 | 3707.4 | Peake et al. (1997c) |
| 84.8 | 16.0 | 20.0 | 2542.9 | Peake et al. (1997c) |
| 88.8 | 16.0 | 20.0 | 1332.4 | Peake et al. (1997c) |
| 98.7 | 16.0 | 14.0 | 59.2 | Peake et al. (1997c) |
| 107.7 | 16.0 | 20.0 | 64.6 | Peake et al. (1997c) |
| 110.1 | 24.0 | 14.0 | 9911.0 | Peake et al. (1997c) |
| 111.2 | 24.0 | 14.0 | 8339.4 | Peake et al. (1997c) |
| 112.5 | 24.0 | 14.0 | 6750.0 | Peake et al. (1997c) |
| 114.2 | 24.0 | 14.0 | 5138.4 | Peake et al. (1997c) |
| 116.6 | 24.0 | 14.0 | 3496.9 | Peake et al. (1997c) |
| 119.1 | 24.0 | 20.0 | 10721.0 | Peake et al. (1997c) |
| 120.2 | 24.0 | 20.0 | 9014.4 | Peake et al. (1997c) |
| 120.6 | 24.0 | 14.0 | 1809.4 | Peake et al. (1997c) |
| 121.5 | 24.0 | 20.0 | 7290.0 | Peake et al. (1997c) |
| 123.2 | 24.0 | 20.0 | 5543.4 | Peake et al. (1997c) |
| 125.6 | 24.0 | 20.0 | 3766.9 | Peake et al. (1997c) |
| 129.6 | 24.0 | 20.0 | 1944.4 | Peake et al. (1997c) |
| 139.5 | 24.0 | 14.0 | 83.7 | Peake et al. (1997c) |
| 148.5 | 24.0 | 20.0 | 89.1 | Peake et al. (1997c) |

### 3.14 LAKE TROUT (*Salvelinus namaycush*)

***Swimming Capacity***

Two research studies documenting swimming capacity of juvenile lake trout were located, and the results of these studies are summarized in Table 19. Mean critical swimming speed of all fish among these studies was 38.4 cm/s (range: 19.0 to 74.2 cm/s) for fish having a mean length of 10.6 cm (range: 3.0 to 12.0 cm) at a mean water temperature of 9.9 °C (range: 5.0 to 15.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 20.0 cm/s or less should allow passage of most juvenile lake trout within the size and temperature ranges described above. No information regarding swimming endurance, maximum swimming capacity, or fishway/culvert passage of lake trout could be found.

Table 19. Minimum critical swimming speeds for lake trout from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| **Ucrit (cm/s)** | **Length (cm)** | **Temp. (°C)** | **Rank** | **Reference** |
|---|---|---|---|---|
| 20.0 | 3.0 | 9.5 | 4.5 | Beamish (1980) |
| 19.0 | 11.5 | 5.0 | 8.5 | Beamish (1980) |
| 25.0 | 12.0 | 5.0 | 9.0 | Beamish (1980) |
| 25.0 | 7.5 | 9.5 | 9.0 | Beamish (1980) |
| 26.0 | 11.5 | 10.0 | 13.5 | Beamish (1980) |
| 74.2 | 11.8 | 10.0 | 13.8 | Beamish et al. (1989) |
| 74.2 | 11.8 | 10.0 | 13.8 | Beamish et al. (1989) |
| 74.2 | 11.8 | 10.0 | 13.8 | Beamish et al. (1989) |
| 27.5 | 12.0 | 10.0 | 14.0 | Beamish (1980) |
| 27.0 | 11.5 | 15.0 | 18.5 | Beamish (1980) |
| 30.0 | 12.0 | 15.0 | 19.0 | Beamish (1980) |

### 3.15 LAKE WHITEFISH (*Coregonus clupeaformis*)

***Swimming Capacity***

Two research studies documenting swimming capacity of juvenile and adult lake whitefish were located, and the results are summarized in Tables 20 and 21. Mean critical swimming speed in this study was 57.2 cm/s (range: 34.1 to 70.6 cm/s) for fish having a mean length of 28.9 cm (range: 6.0 to 48.0 cm) at a mean water temperature of 11.8 °C (range: 5.0 to 17.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 40.0 and 55.0 cm/s or less should allow passage of juvenile and adult lake whitefish, respectively. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a (conservatively) long culvert (100 m). Endurance data collected indicates that lake whitefish greater than 12 cm in length should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 69.0 cm/s (Table 21). If water velocity criteria for juveniles were set at 40.0 cm/s (as recommended), fish could attain ground speeds as high as 29.0 cm/s (69.0 – 40.0 cm/s), and still make it through the culvert. Adult fish could attain a ground speed of about 14.0 cm/s during an ascent, indicating that 55.0 cm/s is a reasonable velocity criteria for this species. Maximum swimming capacity of lake whitefish could not be found.

***Fishway and Culvert Passage***

Schwalme et al. (1985) reported that a few lake whitefish (mean length: 43.5 cm) passed a vertical slot and two Denil fishways (10 and 20% slopes) on the Lesser Slave River. These fishways were relatively short (3 m) and contained moderate water velocities (23.0 to 68.0 cm/s in the vertical slot, 52.0 to 80.0 cm/s in the 10% Denil, and 75.0 to 107.0 cm/s in the 20% Denil). Although these fishways were very short, it is clear that lake whitefish will ascend fishways regardless of configuration, slope, or water velocity.

Table 20. Minimum critical swimming speeds for lake whitefish from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 34.1 | 6.0 | 12.0 | 7.0 | Jones et al. (1974) |
| 43.4 | 12.0 | 12.0 | 13.0 | Jones et al. (1974) |
| 50.1 | 18.0 | 12.0 | 19.0 | Jones et al. (1974) |
| 55.4 | 24.0 | 12.0 | 25.0 | Jones et al. (1974) |
| 57.0 | 34.0 | 5.0 | 28.0 | Bernatchez & Dodson (1985) |
| 59.8 | 30.0 | 12.0 | 31.0 | Jones et al. (1974) |
| 65.5 | 34.0 | 12.0 | 35.0 | Bernatchez & Dodson (1985) |
| 63.8 | 36.0 | 12.0 | 37.0 | Jones et al. (1974) |
| 62.6 | 34.0 | 17.0 | 40.0 | Bernatchez & Dodson (1985) |
| 67.3 | 42.0 | 12.0 | 43.0 | Jones et al. (1974) |
| 70.6 | 48.0 | 12.0 | 49.0 | Jones et al. (1974) |

Table 21. The maximum distance that lake whitefish can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 63.0 | 12.6 | 12.0 | 328.9 | Bernatchez & Dodson (1985) |

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 74.0 | 12.8 | 12.0 | 53.3 | Bernatchez & Dodson (1985) |
| 69.0 | 12.8 | 12.0 | 186.3 | Bernatchez & Dodson (1985) |
| 59.0 | 12.8 | 12.0 | 754.0 | Bernatchez & Dodson (1985) |
| 68.0 | 34.0 | 12.0 | 1358.6 | Bernatchez & Dodson (1985) |
| 102.0 | 34.0 | 12.0 | 97.9 | Bernatchez & Dodson (1985) |
| 75.0 | 34.1 | 5.0 | 175.5 | Bernatchez & Dodson (1985) |
| 75.0 | 34.1 | 12.0 | 900.0 | Bernatchez & Dodson (1985) |
| 55.0 | 34.4 | 5.0 | 1296.9 | Bernatchez & Dodson (1985) |
| 90.0 | 34.6 | 12.0 | 226.8 | Bernatchez & Dodson (1985) |
| 63.0 | 35.0 | 5.0 | 536.8 | Bernatchez & Dodson (1985) |

### 3.16 ROUND WHITEFISH (*Prosopium cylindraceum*)

No swimming performance or fishway/culvert passage data for round whitefish was found in this literature search. As such, it is suggested that water velocity criteria for this species be set according to that proposed for lake whitefish (40.0 and 55.0 cm/s for juveniles and adults, respectively) until swimming performance data for this species can be obtained.

### 3.17 MOTTLED SCULPIN (*Cottus bairdi*)

***Swimming Capacity***

A single research study documenting swimming capacity of adult mottled sculpin was located, and the results of this study is summarized in Table 22. Mean critical swimming speed in this study was 32.5 cm/s (range: 28.0 to 38.0 cm/s) for fish having a mean length of 6.7 cm (range: 6.3 to 7.1 cm) at a mean water temperature of 10.0 $^{o}$C (range: 5.0 to 15.0 $^{o}$C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that a 100 m culvert containing water velocities up to 30.0 cm/s or less should allow passage of most adult mottled sculpin within the size and temperature ranges described above. No information regarding swimming endurance, maximum swimming capacity, or fishway/culvert passage of mottled sculpin could be found.

Table 22. Minimum critical swimming speeds for mottled sculpin from the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 28.0 | 6.3 | 5.0 | 0.0 | Facey & Grossman (1990) |
| 28.0 | 6.6 | 10.0 | 5.3 | Facey & Grossman (1990) |
| 36.0 | 7.1 | 10.0 | 5.8 | Facey & Grossman (1990) |
| 38.0 | 6.6 | 15.0 | 10.3 | Facey & Grossman (1990) |

### 3.18 SLIMY SCULPIN (*Cottus cognatus*)

***Swimming Capacity***

A single research study documenting swimming capacity of adult slimy sculpin was located, and the results of this study are summarized in Table 23. No information on critical swimming speed could be located; however, the maximum swimming speed of 7.8 cm individuals appears to be approximately 55.0 cm/s. Suggested velocity criteria for slimy sculpin was 30.0 cm/s, and based on its maximum speed, this appears to be reasonable for this species.

Table 23. The maximum swimming speed that slimy sculpin can attain in still water relative to fish length and water temperature, based on fast-start data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 55.0 | 7.8 | 15.0 | 0 | Webb (1978a) |

### 3.19 RAINBOW SMELT (*Osmerus mordax*)

***Swimming Capacity***

A single research study documenting swimming capacity of juvenile and adult rainbow smelt was located, and the results of this study are summarized in Table 24. Mean critical swimming speed in this study was 38.2 cm/s (range: 30.1 to 45.6 cm/s) for fish having a mean length of 11.5 cm (range: 7.0 to 16.0 cm) at a mean water temperature of 10.0 °C. Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 30.0 and 40.0 cm/s or less (at a temperature of 10.0 °C) should allow passage of most juvenile and adult rainbow smelt, respectively. No information regarding swimming endurance, maximum swimming capacity, or fishway/culvert passage of alewife could be found.

Table 24. Minimum critical swimming speeds for rainbow smelt from the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 30.1 | 7.0 | 10.0 | 0.0 | Griffiths (1979) |
| 36.0 | 10.0 | 10.0 | 3.0 | Griffiths (1979) |
| 41.1 | 13.0 | 10.0 | 6.0 | Griffiths (1979) |
| 45.6 | 16.0 | 10.0 | 9.0 | Griffiths (1979) |

### 3.20 NINESPINE STICKLEBACK (*Pungitius pungitius*)

No swimming performance or fishway/culvert passage data for ninespine stickleback was found in this literature search. As such, it is suggested that water velocity criteria for this species be set according to that proposed for threespine stickleback (20.0 cm/s; see below) until swimming performance data for this species can be obtained.

### 3.21 THREESPINE STICKLEBACK (*Gasterosteus aculeatus*)

***Swimming Capacity***

A total of six independent research studies documenting the swimming capacity of juvenile and adult threespine stickleback were located, and the results of these studies are summarized in Tables 25 through 27. Mean critical swimming speed of all fish among these studies was 29.8 cm/s (range: 19.0 to 38.0 cm/s) for fish having a mean length of 6.6 cm (range: 6.3 to 7.1 cm) at a mean water temperature of 10.4 °C (range: 5.0 to 15.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 25.0 cm/s or less should allow passage of most adult threespine stickleback. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a (conservatively) long culvert (100 m). Endurance data collected indicates that adult threespine stickleback should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 23.0 cm/s (Table 26). This means that velocity criteria should be slightly lower (about 20.0 cm/s) than that dictated by critical speed data. Maximum swimming capacity of juvenile and adult threespine stickleback appears to be approximately 50.0 and 70.0 cm/s, respectively (Table 27).

Table 25. Minimum critical swimming speeds for threespine stickleback from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 28.0 | 6.3 | 5.0 | 0.0 | Facey & Grossman (1990) |
| 28.0 | 6.6 | 10.0 | 5.3 | Facey & Grossman (1990) |
| 38.0 | 6.6 | 10.0 | 5.3 | Facey & Grossman (1990) |
| 19.0 | 6.3 | 12.0 | 7.0 | Schaarschmidt & Jurss (2003) |
| 36.0 | 7.1 | 15.0 | 10.8 | Facey & Grossman (1990) |

Table 26. The maximum distance that threespine stickleback can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| Speed (cm/s) | Length cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 26.4 | 4.4 | 20.0 | 80.0 | Whoriskey & Wootton (1987) |
| 23.0 | 4.6 | 20.0 | 6620.0 | Whoriskey & Wootton (1987) |
| 18.8 | 4.7 | 20.0 | 5410.0 | Whoriskey & Wootton (1987) |
| 33.6 | 4.8 | 20.0 | 0.0 | Whoriskey & Wootton (1987) |
| 24.5 | 4.9 | 20.0 | 5920.0 | Whoriskey & Wootton (1987) |
| 20.0 | 5.0 | 20.0 | 5760.0 | Whoriskey & Wootton (1987) |
| 30.0 | 5.0 | 20.0 | 27.0 | Whoriskey & Wootton (1987) |
| 35.0 | 5.0 | 20.0 | 21.0 | Whoriskey & Wootton (1987) |
| 30.5 | 6.0 | 9.5 | 439.2 | Taylor & McPhail (1986) |
| 30.0 | 6.0 | 9.5 | 342.0 | Taylor & McPhail (1986) |
| 31.0 | 6.2 | 9.5 | 223.2 | Taylor & McPhail (1986) |

Table 27. The maximum swimming speeds that threespine stickleback can attain in still water relative to fish length and water temperature, based on fast-start data from the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 57.0 | 3.8 | 8.0 | 2.7 | Guderley et al. (2001) |
| 47.0 | 1.1 | 19.4 | 11.4 | Garenc et al. (1999) |
| 67.9 | 2.7 | 19.4 | 13.0 | Garenc et al. (1999) |
| 85.4 | 6.0 | 17.0 | 13.9 | Taylor & McPhail (1986) |
| 61.8 | 6.0 | 17.0 | 13.9 | Taylor & McPhail (1986) |
| 131.4 | 5.9 | 19.4 | 16.2 | Garenc et al. (1999) |
| 59.7 | 2.1 | 24.0 | 17.0 | Garenc et al. (1999) |
| 68.0 | 3.9 | 23.0 | 17.8 | Guderley et al. (2001) |
| 77.3 | 3.1 | 24.0 | 18.0 | Garenc et al. (1999) |
| 91.8 | 6.6 | 24.0 | 21.5 | Garenc et al. (1999) |

### 3.22 ATLANTIC STURGEON (*Acipenser oxyrhynchus*)

No swimming performance or passage data for Atlantic sturgeon was found. As such, it is suggested that water velocity criteria for this species be set according to data collected for lake sturgeon (*Acipenser fulvescens*) by Peake et al. (1997b). These authors suggested that water velocity in a 100 m culvert be set at approximately 1 body length per second (e.g. 15 cm/s for a 15 cm fish etc.).

## 3.23 LONGNOSE SUCKER (*Catostomus catostomus*)

***Swimming Capacity***

A single research study documenting swimming capacity of juvenile and adult longnose sucker was located, and the results of this study is summarized in Table 28. Mean critical swimming speed in this study was 62.7 cm/s (range: 23.0 to 91.4 cm/s) for fish having a mean length of 29.0 cm (range: 4.0 to 54.0 cm) at a mean water temperature of 12.0 °C. Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 35.0 and 60.0 cm/s or less (at 12.0 °C) should allow passage of most juvenile and adult longnose sucker, respectively. No information regarding swimming endurance or maximum swimming capacity of longnose sucker could be found.

***Fishway and culvert passage***

Schwalme et al. (1985) reported that large numbers of longnose sucker (mean length: 43.5 cm) passed a vertical slot fishway on a weir on the Lesser Slave River, although fewer numbers moved past the two Denil fishways (10 and 20% slopes). These fishways were relatively short (3 m) and contained moderate water velocities (23.0 to 68.0 cm/s in the vertical slot, 52.0 to 80.0 cm/s in the 10% Denil, and 75.0 to 107.0 cm/s in the 20% Denil). Although these fishways were very short, it is clear that longnose sucker will ascend fishways. However, the apparent preference of this species for the vertical slot configuration suggests they exhibit a behavioural avoidance of highly turbulent water (Denil fishways tend to be turbulent), or that they were deterred by the relatively high water velocities in the Denil fishways.

Slatick and Basham (1985) also studied passage of longnose sucker through several fishways on the Columbia River. The authors reported observing several fish moving through a 7.9 m long fishway with slopes of 24.0 and 27.8%, and an 15.2 m structure with a 28.7% slope. However, no fish successfully passed a 20.1 m structure with a 27.3% slope (Slatick and Basham 1985). Although water velocities were not given in this study, it is apparent that fishway slope has little effect on passage, while length does appear to have an effect on passage efficiency of this species.

Table 28. Minimum critical swimming speeds for longnose sucker from the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 23.0 | 4.0 | 12.0 | 0.0 | Jones et al. (1974) |
| 35.3 | 9.0 | 12.0 | 5.0 | Jones et al. (1974) |
| 44.7 | 14.0 | 12.0 | 10.0 | Jones et al. (1974) |
| 52.5 | 19.0 | 12.0 | 15.0 | Jones et al. (1974) |
| 59.4 | 24.0 | 12.0 | 20.0 | Jones et al. (1974) |

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 65.7 | 29.0 | 12.0 | 25.0 | Jones et al. (1974) |
| 71.5 | 34.0 | 12.0 | 30.0 | Jones et al. (1974) |
| 76.9 | 39.0 | 12.0 | 35.0 | Jones et al. (1974) |
| 82.0 | 44.0 | 12.0 | 40.0 | Jones et al. (1974) |
| 86.8 | 49.0 | 12.0 | 45.0 | Jones et al. (1974) |
| 91.4 | 54.0 | 12.0 | 50.0 | Jones et al. (1974) |

## 3.24 WHITE SUCKER (*Catostomus commersoni*)

***Swimming Capacity***

A single research study documenting swimming capacity of juvenile and adult white sucker was located, and the results of this study is summarized in Table 29. Mean critical swimming speed in this study was 61.6 cm/s (range: 47.6 to 74.2 cm/s) for fish having a mean length of 27.5 cm (range: 17.0 to 38.0 cm) at a mean water temperature of 12.0 °C (range: 12.0 to 12.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 45.0 and 60.0 cm/s or less should allow passage of most juvenile and adult white sucker, respectively. No information regarding swimming endurance or maximum swimming capacity of white sucker could be found.

***Fishway and culvert passage***

Schwalme et al. (1985) also reported that large numbers of white sucker (mean length: 42.6 cm) passed a vertical slot fishway on a weir on the Lesser Slave River, although fewer numbers moved past the two Denil fishways (10 and 20% slopes). These fishways were relatively short (3 m) and contained moderate water velocities (23.0 to 68.0 cm/s in the vertical slot, 52.0 to 80.0 cm/s in the 10% Denil, and 75.0 to 107.0 cm/s in the 20% Denil). Although these fishways were very short, it is clear that white sucker will ascend fishways. However, the apparent preference of this species for the vertical slot configuration suggests they, like longnose sucker, exhibit a behavioural avoidance of highly turbulent water, or were deterred by the relatively high water velocities in the Denil fishways.

Slatick and Basham (1985) also studied passage of white sucker through several fishways on the Columbia River. The authors reported observing several fish moving through a 7.9 m long fishway with slopes of 24.0 and 27.8%, and an 15.2 m structure with a 28.7% slope. However, no fish successfully passed a 20.1 m structure with a 27.3% slope (Slatick and Basham 1985). Although water velocities were not given in this study, it is apparent that fishway slope has little effect on passage, while length does appear to have an effect on passage efficiency of this species.

Bunt et al. (1999) studied passage of radio-tagged adult white sucker through two Denil fishways on the Grand River (Ontario) and reported that passage efficiency was 38%. Numbers of fish that ascended dropped exponentially with water velocity, and the maximum value that still allowed passage was 96.0 cm/s. This indicates that velocity criteria suggested above (60.0 cm/s) should not create a velocity barrier for this species.

Low passage efficiency was blamed on distracting flows near the fishway entrances.

Table 29. Minimum critical swimming speeds for white sucker from the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| **Ucrit (cm/s)** | **Length (cm)** | **Temp. (°C)** | **Rank** | **Reference** |
|---|---|---|---|---|
| 47.6 | 17.0 | 12.0 | 0.0 | Jones et al. (1974) |
| 52.1 | 20.0 | 12.0 | 3.0 | Jones et al. (1974) |
| 56.3 | 23.0 | 12.0 | 6.0 | Jones et al. (1974) |
| 60.2 | 26.0 | 12.0 | 9.0 | Jones et al. (1974) |
| 63.9 | 29.0 | 12.0 | 12.0 | Jones et al. (1974) |
| 67.5 | 32.0 | 12.0 | 15.0 | Jones et al. (1974) |
| 70.9 | 35.0 | 12.0 | 18.0 | Jones et al. (1974) |
| 74.2 | 38.0 | 12.0 | 21.0 | Jones et al. (1974) |

## 4.0 SPECIES OF SECONDARY INTEREST

### 4.1 ATLANTIC TOMCOD (*Microgadus tomcod*)

No information on swimming capacity of Atlantic tomcod was located. However, Bergeron et al. (1998) studied movements of this species in Sainte-Anne River in Quebec and concluded that upstream migration was impeded when water velocities in the river exceeded 30.0 cm/s. As such, it is recommended that this value be adopted as a guideline for water velocity criteria in culverts and fishways until swimming performance data can be obtained.

### 4.2 ALEWIFE (*Alosa psuedoharengus*)

***Swimming Capacity***

A single research study documenting swimming capacity of juvenile and adult alewife was located, and the results of this study are summarized in Table 30. Mean critical swimming speed in this study was 48.7 cm/s (range: 43.0 to 53.0 cm/s) for fish having a mean length of 10.0 cm (range: 5.0 to 15.0 cm) at a mean water temperature of 12.0 °C. Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 40.0 and 50.0 cm/s or less (at 15.0 °C) should allow passage of most juvenile and adult alewife, respectively. No information regarding swimming endurance, maximum swimming capacity, or fishway/culvert passage of alewife could be found.

Table 30. Minimum critical swimming speeds for alewife from the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 43.0 | 5.0 | 12.0 | 0.0 | Griffiths (1979) |
| 49.0 | 10.0 | 12.0 | 5.0 | Griffiths (1979) |
| 53.0 | 15.0 | 12.0 | 10.0 | Griffiths (1979) |

### 4.3 AMERICAN SHAD (*Alosa sapidissima*)

No swimming performance data was located for American shad, indicating that research is needed on the locomotory capacity of this species. As such, it is suggested that water velocity criteria for this species be set according to data collected for alewife (40.0 and 50.0 cm/s for juvenile and adult American shad, respectively).

American shad have been observed migrating through Denil fishways on the Columbia River (Slatick and Basham 1985). The authors reported observing several hundred fish moving through a 7.9 m long fishway with slopes of 24.0 and 28.7%, and an 11.9 m structure with a 23.3% slope. It was further reported that a few American shad passed through 15.2 m Denil fishway (slope: 28.7%); however, no fish successfully passed a 20.1 m structure with a 27.3% slope (Slatick and Basham 1985). Although water velocities were not given, it is apparent that fishway slope has little effect on passage, while length does appear to have an effect on passage efficiency of this species.

Moser et al. (2000) studied passage efficiency of adult American shad through a navigation lock and a fishway on the Cape Fear River, in North Carolina. The authors concluded that passage efficiency through the locks was greatest when attraction flows in excess of the natural discharge were provided at the entrance. It was also noted that relatively few American shad used the fishway. Poor attraction flow, turbulence at the entrance, excessive slope, and lack of resting pools were implicated as likely causes of the problem. Similar findings for this species were reported by Barry and Kynard (1986) and Haro et al. (1999).

Haro and Kynard (1997) studied passage efficiency of American shad in a modified ice harbour fishway using an underwater video camera system. The authors reported that American shad ascended and descended the fishway exclusively through the surface weirs, and that movement coincided with decreasing light levels in the evening. Haro and Kynard (1997) concluded that passage efficiency was low, and suggested that high mean water velocity (up to 200 cm/s), air entrainment, and turbulence disrupted migratory motivation and visual/rheotactic orientation. Similar findings for this species were reported by Monk et al. (1989).

## 4.4 BANDED KILLIFISH (*Fundulus diaphanus*)

### *Swimming Capacity*

Two research studies documenting swimming capacity of adult banded killifish were located, and the results of these studies are summarized in Tables 31 and 32. Mean critical swimming speed of all fish among these studies was 33.4 cm/s (range: 25.2 to 39.2 cm/s) for fish having a mean length of 6.7 cm (range: 6.0 to 8.2 cm) at a mean water temperature of 19.3 °C (range: 10.0 to 25.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 25.0 cm/s or less should allow passage of most banded killifish within the size and temperature ranges described above. No information regarding swimming endurance of banded killifish could be found; however, maximum swimming capacity appears to be approximately 90.0 cm/s (Table 32).

Table 31. Minimum critical swimming speeds for banded killifish from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 25.2 | 6.0 | 10.0 | 0.0 | DiMichelle & Powers (1982) |
| 39.2 | 6.0 | 25.0 | 15.0 | DiMichelle & Powers (1982) |
| 35.7 | 8.2 | 23.0 | 15.2 | Kolok & Sharkey (1997) |

Table 32. The maximum swimming speeds that banded killifish can attain in still water relative to fish length and water temperature, based on fast-start data from the literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Reference |
|---|---|---|---|
| 90.0 | 6.0 | 10.0 | Johnson & Bennett (1995) |
| 85.0 | 6.0 | 35.0 | Johnson & Bennett (1995) |

### 4.5 MUMMICHOG (*Fundulus heteroclitus*)

No swimming performance or fishway/culvert passage data for the mummichog was found in this literature search. As such, it is suggested that water velocity criteria for this species be set according to that proposed for banded killifish (25.0 cm/s) until swimming performance data for this species can be obtained.

### 4.6 SEA LAMPREY (*Petromyzon marinus*)

***Swimming Capacity***

Two research studies documenting swimming capacity of juvenile and adult sea lamprey were located, and the results of these studies are summarized in Tables 33 and 34. Mean critical swimming speed of all fish among these studies was 78.7 cm/s for fish having a mean length of 60.6 cm at a mean water temperature of 15.0 °C. Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 75.0 cm/s or less (at 15.0 °C) should allow passage of adult sea lamprey. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a (conservatively) long culvert (100 m). Endurance data collected indicates that juvenile sea lamprey should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 30.0 cm/s (Table 34). Water velocity criteria based on critical swimming speed for juveniles is not available, and as such, it is suggested that these criteria be set at 30.0 cm/s for juvenile fish based on the available endurance data. Maximum swimming capacity of sea lamprey could not be located.

### *Fishway and Culvert Passage*

Haro and Kynard (1997) studied passage efficiency of sea lamprey in a modified ice harbour fishway using an underwater video camera system. The authors reported that this species ascended and descended the fishway through the surface weirs and the submerged orifices, and that movement occurred primarily at night. Haro and Kynard (1997) concluded that passage efficiency was low, and suggested that high mean water velocities (up to 200 cm/s), air entrainment, and turbulence disrupted migratory motivation and visual/rheotactic orientation .

Table 33. Minimum critical swimming speed for sea lamprey from the primary literature.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 78.7 | 60.6 | 15.0 | 0 | Mesa et al. (2003) |

Table 34. The maximum distance that sea lamprey can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 30.0 | 12.3 | 5.0 | 38.7 | Beamish (1974) |
| 30.0 | 12.3 | 15.0 | 76.2 | Beamish (1974) |
| 60.0 | 12.3 | 5.0 | 5.6 | Beamish (1974) |
| 60.0 | 12.3 | 15.0 | 11.0 | Beamish (1974) |
| 30.0 | 14.8 | 5.0 | 256.1 | Beamish (1974) |
| 30.0 | 14.8 | 15.0 | 503.9 | Beamish (1974) |
| 60.0 | 14.8 | 5.0 | 37.1 | Beamish (1974) |
| 60.0 | 14.8 | 15.0 | 73.0 | Beamish (1974) |

## 4.7 BROWN TROUT (*Salmo trutta*)

### *Swimming Capacity*

A total of six research studies documenting swimming capacity of juvenile and adult brown trout were located, and the results of these studies are summarized in Tables 35 through 37. Mean critical swimming speed of all fish among these studies was 82.5 cm/s (range: 35.8 to 145.6 cm/s) for fish having a mean length of 16.1 cm (range: 5.0 to 35.0 cm) at a mean water temperature of 8.3 °C (range: 5.0 to 15.0 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 35.0 and 70.0 cm/s or less should allow passage of most juvenile and adult brown trout, respectively. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a (conservatively) long culvert (100 m). Endurance data collected indicates that juvenile brown trout should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 25.8 cm/s (Table 36). This means that velocity criteria (based on critical speed data) for these small fish may need to be dropped slightly (to about 20.0 cm/s) to allow fish to attain a reasonable ground speed and not become fatigued prior to reaching the end of the culvert. Adult brown trout should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 101.5 cm/s (Table 36). If water velocity criteria for this species were set at 70.0 cm/s (as recommended), adult fish could attain a ground speed as high as 31.5 cm/s (101.5 – 70.0 cm/s), and still make it through the culvert. Maximum swimming capacity of brown trout appears to be approximately 130.0 cm/s (Table 37).

***Fishway and Culvert Passage***

Laine et al. (2002) monitored passage of adult brown trout on a Denil fishway on the River Kemijoki, in northern Finland. The authors noted that sea-run brown trout routinely used the fishway, even though water velocities (100 to 120 cm/s, and as high as 400 cm/s) generally exceeded their critical swimming speed (see above). This suggests that the suggested velocity criteria for adult brown trout (70.0 cm/s) should allow passage through culverts. Aarestrup et al. (2003) also studied passage of adult sea-run brown trout (> 30 cm) through a nature-like bypass channel in a small Danish stream. The bypass channel was 130 m long with a gradient of 1.6%. Water velocity in the channel averaged 140 cm/s, with local maxima in the range of 195 cm/s. The authors reported an attraction efficiency of 91%, although only 55% of those actually passed through the entire channel. Nevertheless, it is clear that this species is capable of moving considerable distances against water moving at speeds in excess of the suggested culvert velocity criteria (70.0 cm/s).

Jensen and Aass (1995) studied migration of adult brown trout through a fishway in eastern Norway and found that there were upper and lower discharge rates that impeded passage. When discharges over the dam exceeded 180 $m^3$/s, fish had difficulty locating the fishway entrance, and when rates dropped below 20 $m^3$/s, fish had difficulty entering the structure. Clearly fishway and culvert entrances must be designed such that appropriate attraction flows are present. However, competing flows need to be minimized and entrances must be designed such that the structures are navigable when discharge is low.

Laine (1990) studied movement of juvenile and adult brown trout in a vertical slot fishway in northern Finland. The author noted that fish readily ascended the structure, even though it contained water velocities as high as 140 cm/s. It was also found that the brown trout could spend a considerable amount of time in the fast moving water and appeared to move through the upper portion of the fishway faster than the lower section. Learning behaviour was cited as a possible reason for this. Again, these data indicate that brown trout should have no trouble ascending culverts containing water moving at 70.0 cm/s or less.

In one of the few primary literature studies found that actually evaluated fish passage ability in actual culverts, Belford and Gould (1989) reported that brown trout (22.2 to 43.0 cm in length) could swim distances of 10, 30, 50, 70, and 90 m against bottom water velocities up to 96.0, 80.0, 74.0, 70.0, and 67.0 cm/s, respectively. These results agreed well with other field reports on brown trout passage from the grey literature (Saltzman and Koski 1971; Lauman 1976; Travis and Tilsworth 1986). Thus, water velocity criteria for a 100 m culvert suggested above for adults (70.0 cm/s) should be suitable for this species.

Table 35. Minimum critical swimming speeds for brown trout from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 35.8 | 5.0 | 5.0 | 0.0 | Peake et al. (1997c) |
| 40.4 | 5.0 | 7.0 | 2.0 | Peake et al. (1997c) |
| 45.0 | 5.0 | 9.0 | 4.0 | Peake et al. (1997c) |
| 59.8 | 10.0 | 5.0 | 5.0 | Peake et al. (1997c) |
| 49.6 | 5.0 | 11.0 | 6.0 | Peake et al. (1997c) |
| 64.4 | 10.0 | 7.0 | 7.0 | Peake et al. (1997c) |
| 69.0 | 10.0 | 9.0 | 9.0 | Peake et al. (1997c) |
| 83.8 | 15.0 | 5.0 | 10.0 | Peake et al. (1997c) |
| 73.6 | 10.0 | 11.0 | 11.0 | Peake et al. (1997c) |
| 88.4 | 15.0 | 7.0 | 12.0 | Peake et al. (1997c) |
| 93.0 | 15.0 | 9.0 | 14.0 | Peake et al. (1997c) |
| 55.0 | 16.0 | 10.0 | 16.0 | Pedersen & Malte (2004) |
| 97.6 | 15.0 | 11.0 | 16.0 | Peake et al. (1997c) |
| 131.8 | 25.0 | 5.0 | 20.0 | Peake et al. (1997c) |
| 136.4 | 25.0 | 7.0 | 22.0 | Peake et al. (1997c) |
| 141.0 | 25.0 | 9.0 | 24.0 | Peake et al. (1997c) |
| 145.6 | 25.0 | 11.0 | 26.0 | Peake et al. (1997c) |
| 76.0 | 35.0 | 5.0 | 30.0 | Day & Butler (1996) |
| 81.0 | 34.0 | 15.0 | 39.0 | Day & Butler (1996) |

Table 36. The maximum distance that brown trout can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 22.4 | 2.9 | 10.5 | 51.4 | Colquhoun et al. (1984) |
| 36.6 | 3.5 | 5.5 | 2.5 | Ojanguren & Brana (2000) |
| 36.6 | 3.5 | 10.0 | 4.2 | Ojanguren & Brana (2000) |
| 36.6 | 3.5 | 15.0 | 4.6 | Ojanguren & Brana (2000) |
| 36.6 | 3.5 | 17.0 | 7.6 | Ojanguren & Brana (2000) |
| 36.6 | 3.5 | 19.0 | 10.1 | Ojanguren & Brana (2000) |
| 36.6 | 3.5 | 21.0 | 3.2 | Ojanguren & Brana (2000) |
| 36.6 | 3.5 | 26.0 | 2.6 | Ojanguren & Brana (2000) |

| Speed (cm/s) | Length (cm) | Temp. (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 31.6 | 4.5 | 17.0 | 12.6 | Ojanguren & Brana (2003) |
| 25.8 | 5.0 | 5.5 | 1627.4 | Peake et al. (1997c) |
| 27.0 | 5.0 | 5.5 | 1457.8 | Peake et al. (1997c) |
| 28.4 | 5.0 | 5.5 | 1276.8 | Peake et al. (1997c) |
| 30.1 | 5.0 | 5.5 | 1082.2 | Peake et al. (1997c) |
| 32.2 | 5.0 | 5.5 | 870.3 | Peake et al. (1997c) |
| 35.3 | 5.0 | 5.5 | 635.4 | Peake et al. (1997c) |
| 40.5 | 5.0 | 5.5 | 364.8 | Peake et al. (1997c) |
| 61.0 | 5.0 | 5.5 | 36.6 | Peake et al. (1997c) |
| 36.6 | 7.0 | 5.5 | 5.1 | Ojanguren & Brana (2000) |
| 36.6 | 7.0 | 10.0 | 24.2 | Ojanguren & Brana (2000) |
| 36.6 | 7.0 | 15.0 | 38.8 | Ojanguren & Brana (2000) |
| 36.6 | 7.0 | 17.0 | 26.8 | Ojanguren & Brana (2000) |
| 36.6 | 7.0 | 19.0 | 19.1 | Ojanguren & Brana (2000) |
| 36.6 | 7.0 | 21.0 | 30.9 | Ojanguren & Brana (2000) |
| 36.6 | 7.0 | 26.0 | 9.7 | Ojanguren & Brana (2000) |
| 31.6 | 10.0 | 17.0 | 158.0 | Ojanguren & Brana (2003) |
| 86.8 | 15.0 | 5.5 | 5470.4 | Peake et al. (1997c) |
| 88.0 | 15.0 | 5.5 | 4751.8 | Peake et al. (1997c) |
| 89.4 | 15.0 | 5.5 | 4021.8 | Peake et al. (1997c) |
| 91.1 | 15.0 | 5.5 | 3278.2 | Peake et al. (1997c) |
| 93.2 | 15.0 | 5.5 | 2517.3 | Peake et al. (1997c) |
| 96.3 | 15.0 | 5.5 | 1733.4 | Peake et al. (1997c) |
| 101.5 | 15.0 | 5.5 | 913.8 | Peake et al. (1997c) |
| 122.0 | 15.0 | 5.5 | 73.2 | Peake et al. (1997c) |
| 147.8 | 25.0 | 5.5 | 9313.4 | Peake et al. (1997c) |
| 149.0 | 25.0 | 5.5 | 8045.8 | Peake et al. (1997c) |
| 150.4 | 25.0 | 5.5 | 6766.8 | Peake et al. (1997c) |
| 152.1 | 25.0 | 5.5 | 5474.2 | Peake et al. (1997c) |
| 154.2 | 25.0 | 5.5 | 4164.3 | Peake et al. (1997c) |
| 157.3 | 25.0 | 5.5 | 2831.4 | Peake et al. (1997c) |
| 162.5 | 25.0 | 5.5 | 1462.8 | Peake et al. (1997c) |
| 183.0 | 25.0 | 5.5 | 109.8 | Peake et al. (1997c) |

Table 37. The maximum swimming speeds that brown trout can attain in still water relative to fish length and water temperature, based on fast-start data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp. (°C) | Reference |
|---|---|---|---|
| 130.0 | 4.5 | 17.0 | Ojanguren & Brana (2003) |
| 160.0 | 10.0 | 17.0 | Ojanguren & Brana (2003) |

## 4.8 PINK SALMON (*Oncorhynchus gorbuscha*)

### *Swimming Capacity*

A single research study documenting swimming capacity of adult pink salmon was located, and the results of this study are summarized in Table 38. Data pertaining to critical swimming speed or maximum swimming capacity could not be found; however, endurance data suggest that adult fish should be able to pass a 100 m culvert assuming they are not forced to exceed a swimming speed of 148.5 cm/s (Table 38). It is suggested that water velocity criteria for this species be set at about 100.0 cm/s, which leaves a considerable range of ground speeds available (up to 48.5 cm/s).

### *Fishway and Culvert Passage*

Hinch et al. (2002) studied swimming patterns and behaviour of migrating pink salmon in the Fraser River, British Columbia. The authors conceded that swimming performance data for this species is very scarce, but used information from sockeye salmon (*Oncorhynchus nerka*) to estimate that sustained swimming in adults occurred at speeds up to 125 cm/s, while prolonged swimming speeds ranged from 126.0 to 160.0 cm/s and burst swimming occurred at speeds higher than 160.0 cm/s. The authors reported that mean swimming speed during upstream migration was about 110.0 cm/s, indicating that this species is capable of moving long distances at swimming speeds in excess of the velocity criteria suggested above (100.0 cm/s).

Table 38. The maximum distance that pink salmon can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| **Speed (cm/s)** | **Length (cm)** | **Temp. (°C)** | **Distance (m)** | **Reference** |
|---|---|---|---|---|
| 82.5 | 55.0 | 20.0 | 14850.0 | Brett (1982) |
| 104.5 | 55.0 | 20.0 | 4075.5 | Brett (1982) |
| 126.5 | 55.0 | 20.0 | 759.0 | Brett (1982) |
| 148.5 | 55.0 | 20.0 | 356.4 | Brett (1982) |

## 4.9 RAINBOW TROUT (*Oncorhynchus mykiss*)

### *Swimming Capacity*

Thirty-one independent research studies documenting the swimming capacity of juvenile and adult rainbow trout were located, and the results of these studies are summarized in Tables 39 through 41. Mean critical swimming speed of all fish among these studies was 56.4 cm/s (range: 22.8 to 111.6 cm/s) for fish having a mean length of 15.5 cm (range: 6.8 to 41.0 cm) at a mean water temperature of 12.9 °C (range: 5.0 to 22.6 °C). Assuming that unadjusted critical swimming speed can be used as a conservative estimate of maximum allowable velocity, it is suggested that culverts containing water velocities up to 35.0 and 60.0 cm/s or less should allow passage of most juvenile and adult rainbow trout, respectively. It is also suggested that endurance data (where available) be used to confirm that these criteria are reasonable for passage through a (conservatively) long culvert (100 m). Endurance data collected indicates that juvenile rainbow trout should be able to ascend a 100 m culvert as long as they are not forced to exceed a swimming speed of about 38.0 cm/s (Table 40). If water velocity criteria for juveniles were set at 35.0 cm/s (as recommended above), these fish would be able to move through the culvert while attaining a ground speed of 3.0 cm/s (38.0 – 35.0 cm/s). Adult rainbow trout should be able to ascend most culverts as long as they are not forced to exceed a swimming speed of about 88.8 cm/s (Table 40). If water velocity criteria for adults were set at 60.0 cm/s (as recommended above), these fish would be able to move through the culvert while attaining a ground speed of 28.8 cm/s (88.8 – 60.0 cm/s). Maximum swimming capacity of juvenile and adult rainbow trout is approximately 125.0 and 200.0 cm/s, respectively (Table 41).

***Fishway and Culvert Passage***

In one of the few primary literature studies found that actually evaluated fish passage ability in actual culverts, Belford and Gould (1989) reported that rainbow trout (16.1 to 47.0 cm in length) could swim distances of 10, 30, 50, 70, and 90 m against bottom water velocities up to 96.0, 80.0, 74.0, 70.0, and 67.0 cm/s, respectively. These results agreed well with other field reports on rainbow trout passage from the primary (Weaver 1963; Collins et al. 1962) and grey literature (Saltzman and Koski 1971; Lauman 1976; Travis and Tilsworth 1986). Thus, water velocity criteria for a 100 m culvert suggested above for juveniles and adults (35.0 and 60.0 cm/s, respectively) should be suitable for this species.

Table 39. Minimum critical swimming speeds for rainbow trout from various sources in the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close together represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| **Ucrit (cm/s)** | **Length (cm)** | **Temp. (°C)** | **Rank** | **Reference** |
|---|---|---|---|---|
| 38.5 | 9.4 | 5.0 | 2.6 | Facey & Grossman (1990) |
| 43.0 | 8.5 | 6.0 | 2.7 | Peake et al. (1997a) |
| 65.0 | 7.8 | 10.0 | 6.0 | Facey & Grossman (1990) |
| 75.2 | 9.0 | 10.0 | 7.2 | Hawkins & Quinn (1996) |
| 51.4 | 9.1 | 10.0 | 7.3 | Gamperl et al. (1991) |
| 66.6 | 9.1 | 10.0 | 7.3 | Russell (1980) |
| 58.0 | 9.7 | 10.0 | 7.9 | Facey & Grossman (1990) |
| 22.8 | 8.7 | 11.0 | 7.9 | Brown et al. (1999) |
| 45.0 | 9.8 | 10.0 | 8.0 | Myrick & Cech (2000) |
| 52.0 | 11.8 | 10.0 | 9.9 | Myrick & Cech (2000) |
| 37.5 | 6.8 | 15.1 | 10.1 | Wilson & Wood (1992) |
| 62.8 | 9.6 | 12.5 | 10.3 | Wood et al. (1996) |
| 65.9 | 10.9 | 11.9 | 11.0 | Beamish (1978) |
| 52.0 | 7.8 | 15.0 | 11.0 | Facey & Grossman (1990) |
| 42.9 | 12.1 | 11.0 | 11.3 | Anderson et al. (1997) |
| 28.4 | 8.3 | 15.0 | 11.5 | Gregory & Wood (1999) |
| 57.6 | 12.0 | 12.0 | 12.2 | Waiwood & Beamish (1978) |

| Ucrit (cm/s) | Length (cm) | Temp. (°C) | Rank | Reference |
|---|---|---|---|---|
| 45.2 | 9.0 | 15.0 | 12.2 | Alsop & Wood (1997) |
| 37.7 | 9.1 | 15.0 | 12.3 | Gregory & Wood (1999) |
| 50.0 | 10.4 | 14.0 | 12.6 | Myrick & Cech (2000) |
| 37.4 | 9.8 | 15.0 | 13.0 | Gregory & Wood (1999) |
| 50.0 | 11.0 | 14.0 | 13.2 | Myrick & Cech (2000) |
| 44.2 | 10.5 | 15.0 | 13.7 | Gregory & Wood (1999) |
| 53.0 | 8.5 | 18.0 | 14.7 | Peake et al. (1997a) |
| 43.4 | 12.5 | 14.1 | 14.8 | Beamish (1978) |
| 45.0 | 10.3 | 19.0 | 17.5 | Myrick & Cech (2000) |
| 52.0 | 10.8 | 19.0 | 18.0 | Myrick & Cech (2000) |
| 52.3 | 11.8 | 22.4 | 22.4 | Beamish (1978) |
| 79.3 | 12.5 | 22.6 | 23.3 | Beamish (1978) |
| 104.5 | 20.0 | 16.5 | 24.7 | Ye & Randall (1991) |
| 67.9 | 32.8 | 6.0 | 27.0 | Jain et al. (1997) |
| 47.1 | 27.5 | 12.0 | 27.7 | Mitton & McDonald (1994) |
| 66.5 | 33.5 | 8.0 | 29.7 | Keen & Farrell (1994) |
| 58.1 | 29.2 | 15.0 | 32.4 | Beamish (1978) |
| 63.8 | 38.4 | 6.0 | 32.6 | Jain et al. (1997) |
| 111.6 | 35.8 | 11.0 | 35.0 | Anderson et al. (1997) |
| 58.4 | 41.0 | 6.0 | 35.2 | Jain et al. (1997) |
| 69.1 | 31.0 | 16.0 | 35.2 | Shingles et al. (2001) |

Table 40. The maximum distance that rainbow trout can swim at various speeds in still water relative to fish length and water temperature, based on endurance data from the primary literature.

| Speed (cm/s) | Length (cm) | Temp (°C) | Distance (m) | Reference |
|---|---|---|---|---|
| 40.0 | 5.7 | 13.0 | 72.0 | McFarlane et al. (2001) |
| 38.0 | 6.0 | 12.0 | 22.8 | McDonald et al. (1998) |
| 39.0 | 6.0 | 14.0 | 19.5 | Mitton & McDonald (1994) |
| 70.0 | 6.0 | 6.0 | 21.0 | Nahhas et al. (1982) |
| 38.0 | 7.0 | 12.0 | 53.2 | McDonald et al. (1998) |
| 57.0 | 7.0 |  | 158.0 | Hollis et al. (1999) |
| 38.0 | 8.0 | 12.0 | 95.0 | McDonald et al. (1998) |
| 38.0 | 9.0 | 12.0 | 152.0 | McDonald et al. (1998) |
| 38.0 | 10.0 | 12.0 | 190.0 | McDonald et al. (1998) |
| 63.0 | 10.0 |  | 63.0 | Hollis et al. (2000) |
| 39.0 | 12.0 | 14.0 | 210.6 | Mitton & McDonald (1994) |
| 66.6 | 22.2 | 10.0 | 6993.0 | Russell (1980) |
| 88.8 | 22.2 | 10.0 | 319.7 | Russell (1980) |
| 111.0 | 22.2 | 10.0 | 33.3 | Russell (1980) |
| 57.0 | 27.0 | 12.0 | 762.0 | Mellas & Haynes (1985) |

Table 41. The maximum swimming speeds that rainbow trout can attain in still water relative to fish length and water temperature, based on fast-start data from the primary literature. All values are ranked in relation to the smallest fish tested at the lowest water temperature (i.e. the first table entry). Two rankings that are close to each other represent data from similar sized fish tested at similar water temperatures. Ranks that are far apart represent fish of different size and/or tested at different water temperatures.

| **Speed (cm/s)** | **Length (cm)** | **Temp. (°C)** | **Rank** | **Reference** |
|---|---|---|---|---|
| 85.0 | 13.3 | 5.6 | 4.2 | Webb (1978b) |
| 120.0 | 9.1 | 10.0 | 4.4 | Gamperl et al. (1991) |
| 135.0 | 13.3 | 9.9 | 8.5 | Webb (1978b) |
| 153.0 | 9.6 | 15.0 | 9.9 | Webb (1976) |
| 150.0 | 13.3 | 15.0 | 13.6 | Webb (1978b) |
| 121.0 | 15.0 | 15.0 | 15.3 | Webb (1976) |
| 188.7 | 22.2 | 10.0 | 17.5 | Russell (1980) |
| 155.0 | 13.3 | 19.9 | 18.5 | Webb (1978b) |
| 137.0 | 18.5 | 15.0 | 18.8 | Webb (1978b) |
| 167.0 | 20.4 | 15.0 | 20.7 | Webb (1976) |
| 140.0 | 13.3 | 25.0 | 23.6 | Webb (1978b) |
| 175.0 | 24.2 | 15.0 | 24.5 | Webb (1976) |
| 181.0 | 29.6 | 15.0 | 29.9 | Webb (1976) |
| 244.0 | 29.6 | 15.0 | 29.9 | Harper & Blake (1990) |

### 4.10 BLACKSPOTTED STICKLEBACK (*Gasterosteus wheatlandi*)

No swimming performance or fishway/culvert passage data for blackspotted stickleback was found in this literature search. As such, it is suggested that water velocity criteria for this species be set according to that proposed for threespine stickleback (20.0 cm/s) until swimming performance data for this species can be obtained.

### 4.11 FOURSPINE STICKLEBACK (*Apeltes quadracus*)

No swimming performance or fishway/culvert passage data for fourspine stickleback was found in this literature search. As such, it is suggested that water velocity criteria for this species be set according to that proposed for threespine stickleback (20.0 cm/s) until swimming performance data for this species can be obtained.

# 5.0 GENERAL DISCUSSION

As mentioned previously, research on the cutting edge of fish exercise performance and physiology are beginning to question the validity of speed/endurance models generated from forced performance tests, and the utility of critical swimming speed for establishing water velocity criteria in culverts and fishways. However, until additional research is conducted on free-swimming fish, Ucrit data represent the best information available and should be used to *conservatively* estimate maximum allowable water velocities. It is also worth noting that the vast majority of research papers collected in this review were measuring swimming capacity for reasons not associated with fish passage. As such, it cannot be expected that the various methodologies employed should unilaterally result in field applicable data. Clearly, new approaches to determining swimming capacity of real fish in the real world are required.

Nevertheless, velocity criteria compiled in this literature review are generally in line with those suggested by Katopodis (1994) for general subcarangiform swimmers. For example, models described by this author indicate that 20 to 50 cm fish should pass a 100 m culvert if water velocities are below about 50 to 90 cm/s, respectively, a range of values that fit well with those suggested by this review (Tables 42 and 43). This agreement is not unexpected, as models developed by Katopodis (1994) are based on critical speed data generated from fish confined in swim tunnel respirometers (Table 44).

In general, research on passage efficiency of fish in existing culverts and fishways indicate that most problems are associated with high water velocities and turbulence at the entrance. The former is particularly problematic at fishway entrances, where flow is influenced by baffles and other internal infrastructure, and where competing flows are generally present. Unfortunately, many problems with fishways have been identified, but very few studies have been conducted to solve these problems and/or quantitatively assess their relative importance. Water velocity appears to be the primary issue associated with culverts, although very little focused research has been conducted on fish passage through these structures, despite their number and potential to block migratory routes.

Table 42. A summary of suggested water velocity criteria for species listed as primarily important in terms of fish passage associated with the Trans-Labrador highway.

| **Species** | **Life stage** | **Suggested Velocity Criteria (cm/s)** | **Page** |
|---|---|---|---|
| Burbot | juvenile | 35.0 | 4 |
| | adult | 35.0 | 4 |
| American eel | juvenile | 20.0 | 5 |
| Lake chub | adult | 30.0* | 5 |
| Longnose dace | adult | 65.0 | 5 |
| Pearl dace | adult | 30.0* | 6 |
| Northern pike | juvenile | 15.0 | 7 |
| | adult (small) | 35.0 | 7 |
| Arctic charr | juvenile | 40.0 | 8 |
| | adult | 65.0 | 8 |
| Atlantic salmon | adult (seawater) | 95.0 | 9 |
| | adult (freshwater) | 90.0 | 10 |
| | kelts | 90.0 | 11 |
| | smolts | 65.0 | 12 |
| | parr | 30.0 | 14 |
| Brook trout | juvenile | 30.0 | 16 |
| | adult | 50.0 | 16 |
| Lake trout | juvenile | 20.0 | 19 |
| Lake whitefish | juvenile | 40.0 | 19 |
| | adult | 55.0 | 19 |
| Round whitefish | juvenile | 40.0* | 21 |
| | adult | 55.0* | 21 |
| Mottled sculpin | adult | 30.0 | 21 |
| Slimy sculpin | adult | 30.0 | 22 |
| Rainbow smelt | juvenile | 30.0 | 22 |
| | adult | 40.0 | 22 |
| Ninespine stickleback | adult | 20.0* | 23 |
| Threespine stickleback | juvenile | 20.0 | 23 |
| | adult | 20.0 | 23 |
| Atlantic sturgeon | juveniles | 15.0* | 24 |
| | sub-adults | 35.0* | 24 |
| | adults | 110.0* | 24 |

| Species | Life stage | Suggested Velocity Criteria (cm/s) | Page |
|---|---|---|---|
| Longnose sucker | juvenile | 35.0 | 25 |
| | adult | 60.0 | 25 |
| White sucker | juvenile | 45.0 | 26 |
| | adult | 60.0 | 26 |

*estimated from data for another related species (see text)

Table 43. A summary of suggested water velocity criteria for species listed as secondarily important in terms of fish passage associated with the Trans-Labrador Highway.

| Species | Life stage | Suggested Velocity Criteria (cm/s) | Page |
|---|---|---|---|
| Atlantic tomcod | adult | 30.0 | 28 |
| Alewife | juvenile | 40.0 | 28 |
| | adult | 50.0 | 28 |
| American shad | juvenile | 40.0* | 28 |
| | adult | 50.0* | 28 |
| Banded killifish | adult | 25.0 | 29 |
| Mummichog | adult | 25.0* | 30 |
| Sea lamprey | juvenile | 30.0 | 30 |
| | adult | 75.0 | 30 |
| Brown trout | juvenile | 20.0 | 31 |
| | adult | 70.0 | 31 |
| Pink salmon | adult | 100.0 | 35 |
| Rainbow trout | juvenile | 35.0 | 35 |
| | adult | 60.0 | 35 |
| Blackspotted stickleback | adult | 20.0* | 38 |
| Fourspine stickleback | adult | 20.0* | 38 |

*estimated from data for another related species (see text)

Table 44. A summary of models describing the relationship between critical swimming speed (Y), fish length (X), and water temperature (Z) for representative species.

| Species | Length (X) | Temp (Z) | Regression | Reference |
|---|---|---|---|---|
| **PRIMARY** | | | | |
| Burbot | 12.0 – 62.0 | 12.0 | $Y = 30.6X^{0.07}$ | Jones et al. (1974) |
| Northern pike | 12.0 – 62.0 | 12.0 | $Y = 4.9X^{0.55}$ | Jones et al. (1974) |
| Atlantic salmon parr | 3.5 – 6.5 | 11.0 – 13.0 | $Y = 4.10X^{1.36}$ | McDonald et al. (1998) |
| | 4.8 – 12.4 | 12.3 – 20.5 | $Y = 13.5 + 3.1X + 1.8Z$ | Peake et al. (1997c) |
| Atlantic salmon smolts | 12.4 – 18.0 | 12.8 – 16.3 | $Y = 25.2 + 6.3X$ | Peake et al. (1997c) |
| | 15.0 – 25.0 | 5.0 – 9.0 | $Y = 48.6 + 3.2Z$ | Booth et al. (1996) |
| Atlantic salmon kelts | 48.0 – 62.0 | 5.0 – 9.0 | $Y = 9.0 + 1.8X$ | Booth et al. (1996) |
| Brook trout | 5.3 – 9.4 | 11.0 – 13.0 | $Y = 3.53X^{1.33}$ | McDonald et al. (1998) |
| | 7.1 – 40.5 | 12.7 – 20.0 | $Y = 4.0 + 4.5X$ | Peake et al. (1997c) |
| | 4.0 – 27.0 | 15 | $\log y = 1.1 + 0.43\log X$ | Beamish (1980) |
| Lake whitefish | 6.0 – 51.0 | | $Y = 18.2X^{0.35}$ | Bernatchez & Dodson (1985) |
| Rainbow smelt | 7.0 – 16.3 | 10.0 | $Y = 11.45X^{0.504}$ | Griffiths (1979) |
| Longnose sucker | 4.0 – 53.0 | 7.0 – 19.0 | $Y = 11.03X^{0.53}$ | Jones et al. (1974) |
| White sucker | 17.0 – 37.0 | 12.0 – 19.0 | $Y = 10.03X^{0.55}$ | Jones et al. (1974) |
| **SECONDARY** | | | | |
| Alewife | 4.6 – 15.0 | 15 | $Y = 31.7X^{0.193}$ | Griffiths 1979) |
| Brown trout | 5.2 – 26.0 | 5.5 – 12.5 | $Y = 0.2 + 4.8X + 2.3Z$ | Peake et al. (1997c) |

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