Scientific Basis of Road-Stream Crossing Assessments in the Ashuelot River Watershed

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Executive Summary

There are more than 1000 road-stream crossings in the Ashuelot River watershed. Many of these are barriers to upstream movement of aquatic fauna and impediments to non-aquatic fauna that travel along stream corridors. Culverts are the greatest culprits, particularly those that are perched, undersized, too long, and made of unnatural materials such as steel and concrete. Physical dimensions of culverts can be precisely measured, and these measurements indicate the degree to which a structure is a barrier. An inventory of all road-stream crossings can indicate the level of fragmentation in a watershed.

This review focuses on the athleticism (leaping and swimming ability) and ecology of fish with regard to their ability to cross instream barriers and the potential consequences of impeded movement. A critical question was whether physical thresholds exist for species or groups of species, and if so, how can these thresholds be applied to culvert assessments and restoration in the Ashuelot River watershed. Given the range of athleticism of northeastern stream fauna and the effect of variable environmental conditions on performance (e.g., flow, temperature, etc.), I do not believe it is wise to use species-based physical thresholds to assess or design road-stream crossings. However, passage thresholds could be set according to the weakest species during the most challenging conditions (outside of natural events such as floods or droughts) to ensure that all species can surmount a barrier.

This conservative approach was been advocated by several scientists and managers, and this review endorses the recently published Massachusetts stream crossing standards, which are approved by the US Army Corps of Engineers:

1. All culverts must be embedded
2. All crossings are to be at least 1.2x the bankfull width of the stream
3. Natural substrate must be used
4. Water depth and velocity within the crossing must match conditions upstream and downstream
5. Crossings must have a minimum openness ratio

A consequence of adopting a conservative approach is that a large proportion of road-stream crossings will be classified as barriers. Upgrading or replacing culverts is expensive, and because funding for restoration is usually limited, there should be a way to further screen barriers to ensure that money is well spent. An ecological assessment of road-stream crossings is a second-tier screening tool to determine which barriers have the greatest ecological effects. An ecological assessment will likely align with watershed restoration goals more closely than a physical assessment. This review provides the scientific rationale for an ecological assessment based primarily on the biology, ecology, and habitat of stream and riparian fauna. I recommend an approach that uses landscape, habitat, and species variables that specifically relate to watershed restoration goals and conservation targets in the Ashuelot River watershed.

Together, a physical and ecological assessment of road-stream crossings can powerfully demonstrate the level of fragmentation in the Ashuelot River watershed, prioritize specific crossings for restoration, and provide the rationale for restoration that can be clearly communicated to stakeholders.

CHAPTER 1

Introduction

In 2000 there were nearly 4 million miles of public paved and unpaved roadways in the coterminous US (US Department of Transportation), not including private roadways (e.g., logging roads) or driveways; Trombulak and Frissell (2000) provide a figure of nearly 8.15 million miles of road lanes of all types. It is estimated that an additional 10,000 miles of roadways will be built annually in the US in the coming decade (Elvidge et al. 2004).

This transportation infrastructure cuts across natural ecosystems and has profound effects on natural communities and processes (Forman and Alexander 1998, Trombulak and Frissell 2000, Jones et al. 2000). Stream crossings have not been tallied, but there are probably several million bridges and culverts on fish-bearing streams, and tens of millions more on headwater streams that comprise more than 80 percent of the nation's stream network (Meyer et al. 2003). Based on GIS analysis, the Massachusetts Riverways Program estimated that 28,500 road and railroad crossings exist on Massachusetts fish-bearing streams, outnumbering dams by nearly 10:1.

Although many stream crossings are bridges that span the streambanks and may have minimal effect on the stream, most are culverts that constrict streamflow and have myriad physical, chemical, and biological effects. Some disrupt stream continuity by restricting natural movements of biota and creating unnatural habitat conditions that are detrimental to native species. Different species are challenged by barriers in different ways according to their behavior, life history, "athleticism" (ability to move through barriers of varying difficulty), and habitat requirements.

The severity of effects depends on the nature of the barrier, the suite of species that use that portion of a stream, and both the local and regional environmental context. Environmental context is important because species, populations, communities, ecosystem processes, and physical habitat exhibit tremendous spatial and temporal variability within a watershed. The number of stream crossings, and the degree to which they individually and collectively restrict movement of species, provides an index of aquatic fragmentation in a watershed.

A good road-stream crossing assessment will provide the basis for restoration actions. Deciding which barriers have the greatest adverse effect on a species, species group, habitat, or natural community (generally referred to as "conservation target") is a critical step in that process. Defining the conservation target is a difficult decision that will greatly influence how we measure and assess crossings, prioritize crossings for potential restoration, allocate time and money for specific crossings, and demonstrate the effectiveness of restoration.

Unfortunately, there is often a mismatch between stated conservation targets, the criteria we use to target specific crossings, and the ultimate efficacy of conservation actions. This mismatch arises primarily because scientific understanding either does not exist yet or is not fully integrated into the management process. For example, there are virtually no scientific data on the athleticism of more than 80% of the native stream fishes in the northeastern United States or their ability to ascend stream crossings under relevant environmental conditions, yet managers are developing stream crossing standards to allow for fish passage. Unless managers use a conservative approach by adopting culvert criteria based on abilities of the weakest species, it is likely that stream crossing standards will continue to fragment streams. Lacking critical information, managers often have ambitious goals, marginal tools, and crude performance measures.

This document aims to review current scientific understanding of how aquatic and/or riparian species or species groups are challenged by human-made stream barriers, principally bridges and culverts. Pivotal questions addressed by this review are as follows:

- Given swimming ability, life history, and other factors, what physical thresholds are imposed on species or species groups by man-made barriers?
- What are the potential effects of limiting species movements with artificial barriers?
- What information can be used to prioritize specific stream crossings for restoration?

Information from this report will inform decisions on which crossings should be targeted to allow for natural flow, passage for aquatic and riparian species, and intact ecosystem function. Because ecological contexts differ, crossings slated for restoration will not necessarily be those that present the greatest physical barriers. This review focuses on barrier-based and ecosystem-based frameworks for assessing stream crossings, drawing on journal articles, gray literature, and expert interviews. It is hoped that an ecosystem-based assessment tool will help ensure that restoration actions have positive ecological effects, beyond simply the number of crossings replaced or the number of river miles reconnected. While this review is part of a field project assessing aquatic fragmentation in the Ashuelot River watershed in southeastern New Hampshire, it will also inform similar projects throughout the Connecticut River watershed and other northeastern US watersheds.

CHAPTER 2

Assessing Stream Crossings

2.1 OVERVIEW

Any man-made structure that crosses a stream (e.g., roads and railroads) has the potential to alter the flow of water, substrate conditions, and downstream transport of materials such as sediment and woody debris. Collectively, these can impede natural movement of species in the stream or along the stream corridor. Adverse effects are most pronounced in crossings that are small relative to the stream corridor, and whose design fails to provide conditions within the crossing that match natural conditions upstream and downstream. The greatest culprits are undersized culverts that concentrate streamflow into a small area, that are perched relative to normal stream elevation, and whose substrate is unnatural and not conducive to species movement.

Recent initiatives that assess stream crossings (mainly culverts) have measured physical attributes of each crossing (e.g., perch height, culvert size) and ranked the crossings according to a combination of physical conditions. This evaluation and ranking process can help identify the crossings most in need of restoration. Although culvert assessments usually measure a suite of physical attributes, this review focuses on features that have the greatest influence on species movement.

2.2 COMMON STREAM CROSSING PROBLEMS

Stream crossings impede animal movement for four basic reasons: they are either undersized, too shallow, perched, or too long.

- **Undersized crossings** restrict natural stream flow, particularly during floods, causing scouring, erosion, high flow velocity, clogging, and ponding.
- **Shallow crossings** have water depths too low for many organisms to move through them and may lack appropriate bed material.
- **Perched crossings** are above the level of the stream bottom at the downstream end, or sometimes, well below the level of the stream bottom at the upstream end (i.e., an inlet drop). Perching can result from either improper installation or from years of downstream bed erosion.
- **Crossings with low openness ratio** (ratio of cross-sectional area to crossing length) may be behavioral barriers for some species, may not allow dry-land passage for others, and often have similar traits as undersized culverts.

These problems are expressed through a complex and dynamic suite of variables including water depth, flow velocity, flow heterogeneity, substrate conditions, retention and transport of materials (e.g., sediment and coarse particulate organic matter), and dry-land passage.

2.2.1 Low Flow

Low flow is a problem for species trying to swim through a stream crossing. Fish and other aquatic organisms need sufficient water depths to swim effectively, and some species need a strong flow of water to help direct upstream movement (called an "attraction flow"). Shallow depths and low water velocities may lead to stagnant conditions within the crossing and provide no navigable route for fish movement. Low flow problems are often associated with shallow crossings and perched crossings, and are made worse in crossings shaped to disperse flow evenly over a large area (e.g., flat concrete or large diameter culverts).

2.2.2 High Flow

Water velocity is usually higher in an undersized crossing than it is upstream or downstream. Over time, high flow degrades wildlife habitat, blocks animal movement, weakens the structural integrity of crossings, and causes scouring and erosion. During floods, undersized crossings may be filled with fast moving water and be impassable for terrestrial, semi-terrestrial, and aquatic species. Even during normal flows, dry land and shallow passage may not be provided because of the physical dimensions of culverts (i.e., height and width), possibly prohibiting movement of small mammals, amphibians, and reptiles.

2.2.3 Scouring and Erosion

High-velocity water may scour natural substrates in and downstream of the crossing, degrading habitat for fish and other wildlife. Scouring and erosion are most problematic in undersized crossings, particularly during floods when a large amount of water is forced through a small space.

Floodwater may (1) pond upstream of undersized crossings, (2) overtop and destroy roadways, (3) weaken the structural integrity of the crossing itself, and (4) scour sediments at the outlet and over time cause the crossing to become more perched and possibly undercut. Each of these processes contributes to greater instability of the stream channel, banks, and the crossing.

2.2.4 Clogging and Ponding

Some crossings—especially undersized ones—can become clogged by woody debris, leaves, and other material. Ponding results from the backup of water upstream of an undersized crossing. It may occur throughout the year, during seasonal high water or floods, or when crossings become clogged. Persistent ponding may lead to loss and fragmentation of lotic habitat, proliferation of non-indigenous species, shifts in the thermal regime and chemical nature of stream water, and creation of wetlands. It can also cause property damage, erosion of roadways, and bank erosion.

Costly routine maintenance may be required to prevent undersized crossings from being clogged, yet municipal road commissions and public works departments rarely have the resources to clean debris from all culverts. Jensen et al. (2001) determined that undersized culverts were much more likely to be plugged by beavers, and that installation of oversized culverts would discourage beavers and be more cost effective than trapping, periodically removing debris, or other options for managing beavers.

2.2.5 Unnatural Bed Materials

Culverts are generally constructed from steel plates, corrugated steel, corrugated aluminum, concrete, or plastic. These materials may not be appropriate for species that travel along the streambed, or they may interact with other hydraulic variables to create a barrier. In general, substrate (rocks and other material on the bed of the crossing) should match natural conditions to facilitate animal movement. Achieving suitable substrate conditions may require that culverts be embedded (sunk into streambed) and provided with natural substrates, or with artificial substrates that mimic natural substrates (i.e., baffles and weirs).

Although bed material is often a problem of design/construction (rather than a consequence of other problems), shallow crossings and perched crossings exacerbate effects of unnatural bed materials. For example, the flat concrete bottom of a box culvert may only become a problem for animal movement when water depth becomes too shallow or flow velocity is too high for species to swim through.

2.3 MEASURING BARRIERS

Hydraulic and structural measurements of stream crossings provide the basis for regulations and construction standards, whereas most of the problems discussed in section 2.2 are symptoms of poor design and are often difficult to quantify. Hydraulic and structural analysis can be complex and should be performed by qualified engineers, yet there are several basic measurements that can indicate the degree to which a stream crossing impedes animal movement. These include outlet drop, outlet perch, culvert slope, culvert length, culvert material, and culvert dimensions (width and openness) in relation to stream size. For reasons discussed in Chapter 4, descriptions of stream habitat and photographs of reaches upstream and downstream of crossings may provide important information for assessing crossings and later deciding which ones to replace.

2.3.1 Outlet Drop and Perch

Outlet drop is the elevation difference between the culvert outlet and the tailwater control (Figure 1, P3-P5). The outlet drop represents the lead-up to a culvert, and could potentially represent a jump, velocity, endurance, or depth barrier. A low outlet drop means there is a low gradient lead-up to the culvert, preferably a resting pool where fish can gather strength and leap from. A high outlet drop means that a species may encounter fast water and shallow depths for some distance before even reaching the culvert, possibly decreasing its likelihood of surmounting additional challenges of getting into, and swimming through, a culvert. Less commonly, there may be an "inlet drop" where the streambed is well above the culvert inlet on the upstream end, which can be a potent jump barrier if the outlet drop and the distance of the culvert are also challenging; only the strongest fish would be able to meet that three-fold challenge.

Outlet perch is the elevation of the culvert outlet minus the elevation of the downstream water (Figure 1, P3-P4). This is essentially the vertical distance a species must ascend to get into the culvert, and is therefore generally considered a jump barrier. The outlet perch will always be equal to or less than the outlet drop. Outlet perch and

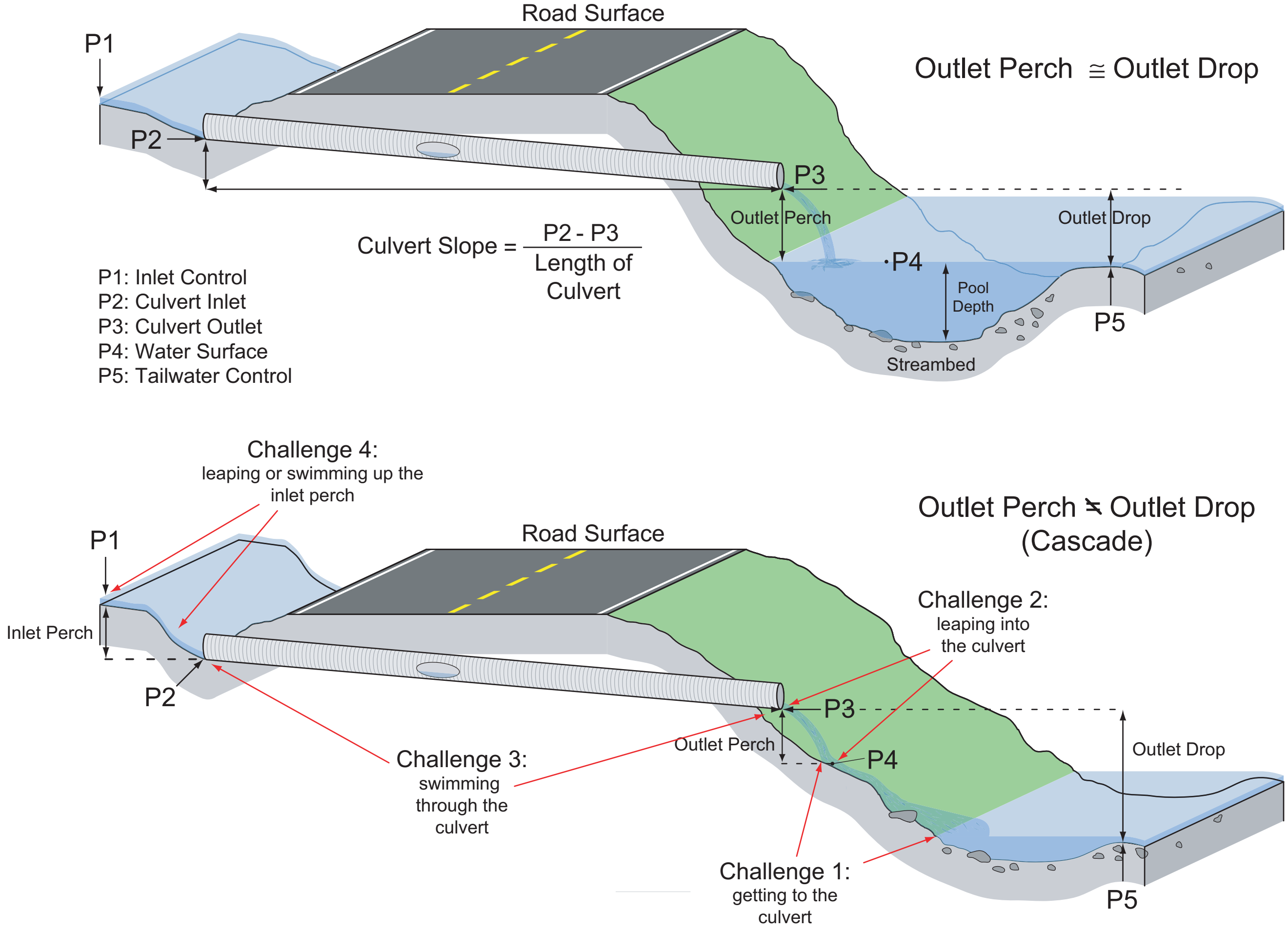

Figure 1. Culvert measurements and challenges facing aquatic animals for culverts that are perched and those with a cascade leading up to the culvert outlet.

outlet drop will be comparable if the tailwater control creates a nearly level tailwater that extends to the culvert outlet (i.e., pool). The distinction between outlet drop and outlet perch only becomes important when they are significantly different, indicating that species have a two-fold challenge of reaching the culvert and then leaping into the culvert. In some instances, the tailwater control may actually be higher than the culvert outlet and possibly the culvert inlet, indicating that the culvert is backwatered and is likely neither a depth nor velocity barrier for fish but could pose problems for other wildlife species (e.g., turtles and mammals).

Outlet drops and perches usually result from culverts that are installed too high above the stream, from downstream bed scouring and erosion that lower the streambed relative to the culvert outlet (e.g., scour pools), and from crossings that are sited in steeper terrain. A common way to fix this problem is to install sills downstream to raise the tailwater elevation, or to reinstall crossings so that they are sunk deeper into the streambed.

2.3.2 Culvert Slope and Length

Culvert slope is the elevation gain of the pipe (Figure 1, P2-P3) divided by the length of the culvert. This value may be multiplied by 100 to express it as a percentage. Culvert slope may indicate the degree to which a culvert acts as a velocity barrier to species movement, since water will flow more quickly through a steeper culvert. Culvert slope and length indicate the combined effects of a velocity and exhaustion barrier, since some fast swimmers can only maintain speeds for a short distance (or alternatively, some slow swimmers can maintain enough speed for a longer distance). Engineers are usually advised to examine outlet velocities—and adopt special crossing designs—when the culvert gradient approaches or exceeds 4% (Washington Department of Fish and Wildlife (WDFW) 2003)).

2.3.3 Culvert Material

Substrate at the entrance, exit, and within a stream crossing may affect species movement by affecting the velocity and depth of water. Culverts are generally constructed from structural steel plates, corrugated steel, corrugated aluminum, concrete, or plastic. Corrugated culverts may create small velocity refuges that small fish can use as resting areas. Smooth concrete or steel provide virtually no velocity refuge, and instead promote uniform flow that species must overcome in one burst. This may be particularly difficult when the water is shallow or when velocity is very high.

2.3.4 Culvert Dimensions

The size and shape of a stream crossing, relative to the size and nature of the stream, strongly influence whether it will impede animal movement. Barriers may result from stream crossings that are too large, too small, or that fail to account for long-term natural processes such as channel migration and sediment transport.

- Any shape/size that disperses flow over a large area can lead to a depth barrier during low flow periods. Examples are cement-bottom box culverts or oversized pipe culverts. Good stream crossings have a low flow channel to allow for year-round passage.
- Any shape/size that concentrates flow into a small area can create a depth or velocity barrier during high flow periods. Examples are any type of undersized culverts and culverts with a narrow width (no matter what height).

Openness, or the ratio of the cross sectional area to crossing length, is another important measurable aspect of stream crossings. Crossings with a low openness ratio are more tunnel-like and may be an insurmountable physical or behavioral barrier for many species. Optimum openness ratios for Massachusetts stream crossings are at least 0.5 m with a minimum height of 1.2 m (Massachusetts Riverways Program 2005). Crossings should ideally be wider than the bankfull width of a stream and span the banks to allow for dry-land wildlife passage for most of the year. Bankfull width is the width of the stream at bankfull discharge, and bankfull discharge is the dominant discharge associated with channel formation and sediment transport and strongly corresponds to the 2-year flood (Magilligan and Nislow 2001). Bankfull width is determined by examining natural hydrology of a stream system and perhaps considering stream height at 50-year or 100-year flood events.

CHAPTER 3

Biological Basis for Assessing Barriers

3.1 OVERVIEW

Fish are the primary biological basis for assessing whether a stream crossing is a barrier primarily because we know most about them and because they are common conservation targets. Species and life stages will have different passage thresholds due to jumping ability, swimming speed, stamina, and other aspects of their physiology. Specific studies have not been conducted for the majority of northeastern stream fishes, nor are most studies conducted under relevant environmental conditions.

Thus, the biological basis for characterizing barriers in northeastern streams can only be inferred from studies conducted elsewhere, on species presumed similar to northeastern species. Guidance may also be taken from controlled (i.e., laboratory) experiments, although these exclude many variables. The March 2006 version of the Massachusetts River and Stream Crossing Standards cautions, "Given the large number of species that make up river and stream communities and the almost complete lack of information about swimming abilities and passage requirements for most organisms, it is impractical to use a species-based approach for designing road crossings."

Nevertheless, this chapter summarizes available information to provide a basic understanding of the "state of the science" of stream crossing assessments based on species' performance. It focuses on four types of barriers: (1) jump barriers, (2) velocity and exhaustion barriers, (3) depth barriers, and (4) behavioral barriers. These factors interact with each other and constantly change, so the concept of "barrier" must be qualified with statements about species, time of the year, and other contextual parameters.

Even though existing information is sparse, it can be applied to practical management in the Northeast through a conservative approach to barrier assessments. Management will provide greatest benefit to species assemblages and stream continuity by understanding the needs and abilities of the weakest "athletes" during the most challenging conditions. A conservative approach negates the need for exhaustive scientific investigation on athleticism of all species.

Table 1 lists common and Latin names of northeastern stream fish, as well as stream-dwelling amphibians, reptiles, and invertebrates that may also be conservation targets. Many of these species are mentioned throughout the text; common names are used and readers should refer to Table 1 for Latin names.

3.2 JUMP BARRIER

Perched stream crossings can impede fish movement, yet the biological evidence is tenuous for most species and under most relevant environmental conditions. Existing data on leaping performance are biased toward trout and salmon, and most studies were conducted under controlled (i.e., laboratory) conditions.

Brandt et al. (2005) found that waterfall height and fish size strongly affected jumping performance of YOY (young of the year) brook trout. Plunge pool depth and waterfall width affected jumping performance to a lesser extent. The only combinations of height and plunge pool depth that fish did *not* ascend (among waterfall heights of 2-24 cm and plunge pool depths of 8-18 cm) were waterfalls higher than 16 cm with 8 cm plunge pools, and waterfalls higher than 22 cm with 10 cm plunge pools. Probabilities of fish jumping the waterfall increased with the size of the fish.

Not surprisingly, jumping ability of adult brook trout is also limited by the same three factors: waterfall height, plunge pool depth, and fish size. Kondratieff and Myrick (2006) examined jumping performance of three size classes (10-15 cm, 15-20 cm, and >20 cm) of brook trout at different heights and plunge pool depths. The smallest size class could jump 63.5 cm waterfalls from 50 cm plunge pools. Larger fish could jump 73.5 cm waterfalls provided the plunge pool was at least 40 cm deep. Fish did not jump waterfalls 43.5 cm or more in height from a plunge pool of 10 cm. In other words, a shallow plunge pool greatly reduces the height that brook trout can jump.

There is evidence of brook trout ascending taller waterfalls under natural conditions. Myrick and Kondratieff

Table 1. Northeastern stream fauna commonly considered in stream barrier studies.

Group and Common Name	Latin Name
FISH	
Salmonidae	
Rainbow Trout	*Oncorhynchus mykiss*
Atlantic Salmon	*Salmo salar*
Brown Trout	*Salmo trutta*
Brook Trout	*Salvelinus fontinalis*
Cyprinidae	
Lake Chub	*Couesius plumbeus*
Silvery Minnow	*Hybognathus regius*
Common Shiner	*Luxilus cornutus*
Pearl Dace	*Margariscus margarita*
Golden Shiner	*Notemigonus crysoleucas*
Bridle Shiner	*Notropis bifrenatus*
Spottail Shiner	*Notropis hudsonius*
Redbelly Dace	*Phoxinus eos*
Finescale Dace	*Phoxinus neogaeus*
Blacknose Dace	*Rhinichthys atratulus*
Longnose Dace	*Rhinichthys cataractae*
Creek Chub	*Semotilus atromaculatus*
Fallfish	*Semotilus corporalis*
Catostomidae	
White Sucker	*Catostomus commersoni*
Longnose Sucker	*Catostomus catostomus*
Creek Chubsucker	*Erimyzon oblongus*
Centrarchidae	
Rock Bass	*Ambloplites rupestris*
Banded Sunfish	*Enneacanthus obesus*
Redbreasted Sunfish	*Lepomis auritus*
Pumpkinseed Sunfish	*Lepomis gibbosus*
Bluegill	*Lepomis macrochirus*
Smallmouth Bass	*Micropterus dolomieu*
Largemouth Bass	*Micropterus salmoides*
Percidae	
Tessellated Darter	*Etheostoma olmstedi*
Swamp Darter	*Etheostoma fusiforme*
Yellow Perch	*Perca flavescens*
Anguillidae	
American Eel	*Anguilla rostrata*
FISH (continued)	
Ictaluridae	
Brown Bullhead	*Ameiurus nebulosus*
Yellow Bullhead	*Ameiurus natalis*
Esocidae	
Chain Pickerel	*Esox niger*
Cottidae	
Slimy Sculpin	*Cottus cognatus*
Lotidae	
Burbot	*Lota lota*
Umbridae	
Central Mudminnow	*Umbra limi*
Clupeidae	
American shad	*Alosa sapidissima*
River Herring	*Alosa sp.*
Petromyzontidae	
Sea Lamprey	*Petromyzon marinus*
American Brook Lamprey	*Lampetra appendix*
SALAMANDERS	
Spring Salamander	*Gyrinophilus porphyriticus*
Two-lined Salamander	*Eurycea bislineata*
Northern Dusky Salamander	*Desmognathus fuscus*
TURTLES	
Wood Turtle	*Clemmys insculpta*
Painted Turtle	*Chrysemys picta*
INVERTEBRATES	
Freshwater Mussels	
Brook floater	*Alasmidonta varicosa*
Dwarf wedgemussel	*Alasmidonta heterodon*
Triangle Floater	*Alasmidonta undulata*
Creeper	*Strophitus undulatus*
Eastern Pondmussel	*Ligumia nasuta*
Eastern Pearlshell	*Margaritifera margaritifera*
Eastern Elliptio	*Elliptio complanata*
Eastern Floater	*Pyganodon cataracta*
Alewife Floater	*Anodonta implicata*
Other	
Crayfish	*Orconectes, Cambarus*

(2005) marked and displaced brook trout downstream of a waterfall that was at least 1.17 m high (pool surface to waterfall crest) and tracked their upstream movement to assess whether the waterfall was a barrier. Six marked fish were found upstream of the waterfall the following fall. The waterfall was then modified by lowering the plunge pool depth and increasing the waterfall's vertical height to at least 1.38 m. They marked and relocated 626 fish downstream, and while the modifications blocked most fish, three were found upstream. Unusual conditions during high flows may have permitted these fish to negotiate the falls. Adams et al. (2000) documented large brook trout ascending a 1.5 m complex falls, and smaller brook trout ascending a 0.7 m nearly vertical falls.

Little is known about the jumping ability of non-salmonid species. Initial conceptual models developed by Coffman (2005) grouped stream fishes based on jumping and swimming ability, using published research, unpublished research, and expert opinion. The groups included (A) Salmonidae, (B) Cyprinidae and YOY Salmonidae, and (C) Cottidae and Percidae (except for walleye and perch). Initial models classified outlet drops of >60.96 cm, >22.86 cm, and >7.62 cm impassable for groups A-C, respectively. In field studies, initial models failed to accurately classify culverts for passage most of the time, meaning that species frequently moved through "impassable" culverts. Revised models set impassable thresholds for outlet drops at >60.96 cm, >20.32 cm, and >10.16 cm impassable for groups A-C, respectively. Field validation of the revised models was not completed.

Holthe et al. (2005) tested jumping ability of the European minnow (*Phoxinus phoxinus*), a species similar to our finescale or redbelly dace, at different water temperatures to find ways to exclude them from waters that supported brown trout populations. At cold temperatures (4.8-6.5°C), minnows were not able to jump even a 3 cm barrier—researchers could not induce them to jump. At warm temperatures (14-16.5°C), minnows could jump heights up to 27 cm. According to their analysis, there was only a 0.04% chance that minnows could pass waterfall barriers greater than 35 cm. Larger minnows could jump highest.

Utzinger et al. (1998) found that vertical drops of 18-20 cm were barriers for the European bullhead (*Cottus gobio*), which is a small benthic fish similar to the local slimy sculpin and mottled sculpin. The model developed by Coffman used 10.16 cm as an impassable outlet drop for Cottidae. Fish experts agree that benthic fish such as sculpins and darters are restricted by vertical barriers, but it is difficult to set a threshold because not enough research has been done, and even if it were, it is likely that variance would preclude the application of all but the most conservative thresholds. Other difficulties in using jumping ability to assess barriers are that some barriers can be behavioral (see section 3.5), the height of the jump changes with flow, and conditions for jumping are variable.

There is ample field evidence that species with poor jumping ability persist in relatively small stream reaches bounded by "impassable" barriers upstream and downstream. It is hard to imagine that these populations are not replenished by upstream migration, and that the only movement is immigration from upstream areas or emigration to downstream areas. Genetic studies might help determine how distinct "subpopulations" are on either side of a barrier (Morita and Yamamoto 2002).

Despite lack of research and tenuous application of existing data to real-life scenarios, a basic understanding of fish jumping ability may help guide management:

- Any outlet drop could be a barrier to some species some of the time
- Within a species and within groups of similar species, large fish can jump higher than small fish
- There is an inverse relationship between outlet drop and fish passage

3.3 VELOCITY AND EXHAUSTION BARRIER

For a species to get through a culvert, it must maintain forward momentum long enough to get to the other side. Species have different swimming modes, methods of propulsion, drag-reducing effects, and physiological traits that influence their swim speed and stamina (Beamish 1978).

Swim speed has been relatively well studied for many North American freshwater fish, particularly salmonids. This research has been thoroughly compiled and summarized by the FishXing group, an interdisciplinary team of scientists that have developed software to allow engineers, hydrologists, and fish biologists to evaluate and design culverts for fish passage. The software, available on the web (http://stream.fs.fed.us.fishxing/) is accompanied by extensive resources on the physical and biological foundations for fish crossing applications. It is beyond the scope of this document to recreate that effort. Unfortunately, FishXing has limited applicability in the Northeast. Only 14 of the species found in the Swim Speeds Table in the FishXing software occur in the Northeast, but with very few studies and little information that can help guide management, and 15 of the 25 most common fish in northeastern 0-4 order streams are not represented at all. Furthermore, FishXing is based on hydrologic criteria, whereas most culverts are on small ungauged streams without hydrologic data.

Most performance data come from studies of individual fish and results are hard to extrapolate to populations, species, life stages, or performance under different environmental conditions. Grouping species allows us to not get "bogged down" in the enormous complexity. Size has the strongest influence on swimming ability (Beamish 1978), so in the absence of better data, size can be a reasonably accurate predictor of a fish's ability to cross a velocity barrier and can be a useful criteria for grouping species. Factors that affect swimming performance are listed below (this is a greatly simplified list from the table provided in the FishXing software program that also includes specific examples and references):

- Species
- Length
- Time to exhaustion
- Weight
- Condition factor
- Stage of maturity
- Sex
- Disease
- River time (anadromous species)
- Strains/stock
- Hatchery vs. wild
- Feeding
- Nutrition
- Light
- Pipe fullness
- Oxygen
- Carbon dioxide
- Salinity
- Toxins
- Temperature
- Previous training
- Exhaustive exercise
- Stress
- Forced vs. volitional swimming

Coffman (2005) placed 14 stream fishes into three groups based on swimming ability: (A) Salmonidae, (B) Cyprinidae + YOY Salmonidae, and (C) Cottidae and Percidae (minus walleye and perch). These groups correspond to strong, medium, and weak, respectively. Field and laboratory studies have confirmed that darters, sculpins, and small-bodied insectivores (mainly the Cyprinidae) are weak swimmers with limited movement (Matthews 1985, Aadland 1993, Freeman et al. 1997, Warren and Pardew 1998, Toepfer et al. 1999, Adams et al. 2000, Roberts 2003, Schaefer et al. 2003, Knaepkens et al. 2006).

Swimming performance studies provide a basis for a range of applications including fishway design, road-stream crossing designs, and barrier assessments. These studies are also critical inputs for FishXing models. Most swimming performance studies are done in test chambers with respirometers and fall into two basic categories (Hammer 1995):

- **Fixed velocity tests:** these are endurance tests during which the velocity is raised to a prescribed level and the time to exhaustion is measured.
- **Increasing velocity tests:** these are critical velocity tests during which the velocity is raised incrementally and each increment is maintained for a specific period of time. Critical swimming speed (U_{crit}) 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" (Peake 2004).

Recent research has questioned the applicability of fish performance data derived from standard swimming tests conducted in confined laboratory conditions (Peake 2004, Peake and Farrell 2004, Castro-Santos 2004, Castro-Santos 2005). A more recent type of performance test is called the volitional swimming test, in which fish are required to swim a measured distance against a velocity challenge (Castro-Santos 2005). These tests allow fish more freedom to move naturally, choose different behaviors, and shift their swimming mode as needed. In other words, not all fish are adapted to swimming steadily at a fixed speed in a confined space, and judging their performance under such conditions may misrepresent their true abilities (Trump and Leggett 1980, Swanson et al. 1998, Peake 2004). Volitional swimming tests provide more realistic data on the ability of a species to ascend velocity barriers of different length.

Peake (2004) determined U_{crit} of 0.65-0.0.98 m/s for smallmouth bass in a respirometer, which translated into maximum allowable water velocities of 0.54-0.63 m/s for the fish to ascend a 50-m raceway. Yet in a volitional swim test, 82-95% of all individuals were able to make complete ascents of the raceway against water velocities of 0.40-1.2 m/s and the probability of fish making a successful ascent did not change with water velocity (i.e., the same proportion of fish ascended a 1.2 m/s velocity as 0.40 m/s velocity). Along with water velocity, neither fish length, water temperature, exposure time, nor time in captivity significantly affected the probability of successful ascent. Based on this research, Peake recommended that U_{crit} should not be used to set water velocity criteria for smallmouth bass. Peake's recommendation could also apply to a suite of species for which volitional swimming tests have not been conducted and whose swimming behavior is poorly understood.

Specific Velocity Threholds

Some examples specific velocity thresholds for different culvert lengths are as follows:

Jones et al. (1974): I was not able to find this important paper and only have the abstract. Here are relevant excerpts: "Critical velocities of 17 species of fish from the Mackenzie River had been determined from increasing velocity tests in both field and laboratory… From a graphical presentation of body length vs. maximum flow rate allowable in a 100 m culvert, it appears that culvert flow rates should be kept below 0.30-0.40 m/s to allow successful passage of the majority of mature individuals of migratory species."

Belford and Gould (1989): Studied ability of four trout species to swim through six culverts ranging from 45-93 m in length with varying slopes and water velocities. Using rainbow trout to represent all species, they indicated that "fish could swim distances of 10, 30, 50, 70, and 90 m with mean bottom velocities of up to 0.96, 0.80, 0.74, 0.70, and 0.67 m/s, respectively." To permit comparison with other studies, authors converted their bottom velocities to 0.6-depth velocities and this comparison is shown in the table below; this table is taken directly from Belford and Gould (1989); I was not able to track down four studies marked with an asterisk because they are outdated gray literature.

Maximum Passage Length (m)	Nonanadromous salmonids				Anadromous salmonids
	Belford and Gould (1989)	Saltzman and Koski (1971)*	Lauman (1976)*	Travis and Tilsworth (1986)*	Kay and Lewis (1970)*
10	1.32	1.22	1.22	1.38	2.51
30	1.12	1.22	1.22	0.9	2.29
50	1.04	0.61	0.61	0.79	2.16
70	0.99	0.61	0.46	0.55	2.02
90	0.95	0.61	0.46	0.55	1.89

Peake et al. (1997): Provided models to estimate swimming speed of fish for a given fork length, temperature, and time period. For different water velocities, one can determine the distance the fish can swim at a given swimming speed and time period. For example, a 7 cm brook trout could maintain a speed of 0.41 m/s for 5 minutes. To traverse a 30 m culvert in 5 minutes, water velocity could not exceed 0.31 m/s. In contrast, a 20 cm brook trout could swim over 200 m in 5 minutes against a water velocity of 0.311 m/s, and to traverse a 30 m culvert, water velocity could be 0.9 m/s. It is instructive to plug the equations into a spreadsheet and try different combinations of fish length, swimming time, and water velocity.

Adams et al. (2000): Studied swimming velocities and endurance for Topeka shiners (Notropis topeka), a small (<5.5 cm SL) stream-dwelling cyprinid. Developed a curvilinear regression model for distance vs maximum water velocity to predict ability of shiners to swim through culverts or other velocity barriers. Their curvilinear model was for smaller shiners [I did not attempt to generate an equivalent model for larger shiners]; authors felt this curve could be used as a conservatively low estimate for large individuals. At water velocities near 0.60 m/s, fish could only swim about 1 m before tiring. Fish could swim distances more than 10 m at velocities near 0.40 m/s. Authors felt that velocity barriers less than 0.35 m/s could be of indefinite length since fish could swim for a long time without fatigue at that velocity.

Oregon Department of Fish and Wildlife: Water velocity criteria for culvert design is based on a fish's swimming ability. For adult trout, average water velocity at high flow cannot exceed 1.2, 0.9, 0.6, and 0.3 m/s for culvert lengths of <30, 30-60, 60-90, and >90 m, respectively. For juvenile trout, maximum velocity cannot exceed 0.6 m/s for culverts less than 30 m, and for longer culverts, only the stream simulation method is acceptable.

Turbulence is an aspect of flow that is not often accounted for in swim tests but may strongly affect swimming performance. Turbulence is "the state of a flow characterized by the superposition of intense small-scale motions in all directions on a main large-scale flow" (Vogel 1994, cited in Enders et al. 2003). It is also referred to as chaotic flow, and is an antonym to laminar, or uniform, flow. Enders et al. (2003) found that swimming models that forced Atlantic salmon to swim against a flow of constant velocity, while minimizing flow heterogeneity, greatly underestimated the energetic costs of swimming in turbulent flow. Lupandin (2005) determined that turbulence disrupted the balance of swimming fish, and that the combined effects of expending energy to restore balance and the increased resistance (i.e., drag) of being off balance reduced the critical swimming velocity. These studies suggest that site-specific details (e.g., construction materials, crossing design, and water velocity) that affect turbulence under a range of conditions will strongly affect fish passage, and reduce the utility of swim performance tests conducted under controlled conditions.

Fish exhibit many non-swimming behaviors that help them ascend barriers. Several species (e.g., sturgeon, darters, and sculpins) exhibit station-holding in high-velocity environments by appressing themselves to the substrate and using fins and body shape to generate negative lift (Matthews 1985, Webb et al. 1996, Adams et al. 1997). This may allow them periods of rest between bursts of swimming, negating the need to be particularly strong swimmers or have great endurance. Matthews (1985) observed darters arching their bodies and lowering their heads at higher water velocities to reduce drag and maintain position. Adams et al. (2003) documented shiners using oral grasping in moderate water velocities to reduce downstream displacement; this behavior has been observed for other cyprinid species (Young and Cech 1996, Adams et al. 2000), and sea lampreys (personal observation).

Small fish exploit velocity refuges created by complex flow dynamics around objects and bed materials; this microscale flow variation is often not captured in routine barrier assessments; rather, it is inferred from the substrate conditions. Shallow laminar flow across a homogenous substrate (such as steel or concrete) will pose a greater challenge than deeper and more complex flows (Baker and Votapka 1990). Natural substrates can create heterogeneous flow—both surface and subsurface—that will allow passage for most species under a wide range of flow conditions (Warren and Pardew 1998, WDFW 2003). Artificial substrates such as baffles, weirs, and strategically placed stones can also create heterogeneous flow (WDFW 2003).

Broad Characterization of Swimming Ability

Weak Swimmers
- Small benthic species (e.g., sculpins, darters, burbot)
- Early life stages (age-0 and juvenile) of larger benthic and pelagic species

Weak-Marginal Swimmers
- Small pelagic species (e.g., sunfish, dace, shiners)
- Medium benthic species (e.g., creek chubsucker, bullhead)
- Juveniles of large benthic and pelagic species

Marginal-Strong Swimmers
- Large pelagic and benthic species (e.g., fallfish, creek chub, suckers, perch, bass, pickerel)

Strong Swimmers
- Large pelagic species (e.g., salmon, trout, shad, alewife)

3.4 DEPTH BARRIER

Characterization of swimming and endurance performance assumes an adequate water depth for swimming. Shallow water is a form of barrier related to culvert design, substrate, and environmental conditions (e.g., flow). Swimming ability is of little consequence if water depth is too shallow. Small fish with a higher W:H (width to height) ratio will be better suited for swimming in shallow water, whereas larger fish with a lower W:H ratio (such as centrarchids) may be impeded by shallow water. However, smaller fish are generally weaker swimmers, so any potential depth barrier should also consider flow velocity.

The American eel is one of the few fish species not limited by water depth because it can crawl across wetted surfaces and even up vertical walls (Haro et al. 2000); crayfish, amphibians, and reptiles are also not affected by shallow crossing depths. However, deep water can impede walking or crawling species, especially in undersized culverts where flood events can entirely fill a culvert.

3.5 BEHAVIORAL BARRIER

The behavioral aspects of stream crossings have been poorly studied, partly because field studies of animal behavior are difficult to conduct. These studies are often done with a small number of animals under controlled conditions, and investigators then try to infer behavior and intent from these observations and use other information (physical ability, environmental conditions, etc) to put results into context. In the case of stream crossing assessments, critical questions are:

1a. The species/individual wants to cross the road….2 [behavior]
1b. The species/individual does not want to cross the road….OK

2a. The species/individual is capable of crossing the road….OK [behavior and physical ability]
2b. The species is incapable of crossing the road….Engineering challenge!

If a species wants to cross a road but is incapable of doing so, then the challenge is to determine why. The reason could be behavioral, although most research has focused on physical ability because ability is easier to quantify than behavior. Engineers embrace swimming and jumping performance studies because these studies provide engineers with familiar quantitative parameters. But it does not matter how high a fish can jump or how strongly it can swim if a culvert is a behavioral deterrent.

Many groups (e.g., fish, amphibians, reptiles, mammals) will be deterred from entering culverts because dark tunnels are too foreign an environment, especially diurnal species that rely on light and visual orientation. Pavlov et al. (1972) found that pelagic (water column) species had a significantly higher critical swimming velocity in light than in dark environments, presumably because their upstream swimming behavior is triggered by optical reception. Benthic fish were not as strongly affected because they are more tactile than pelagic species. Painted turtles are a diurnal species that need light for navigation (DeRosa and Taylor 1978) and may avoid dark culverts. Use of culverts by other vertebrates is highly variable (Yanes et al. 1995).

Recognizing that some species avoid tunnels, ecologists—and a growing number of engineers—have advocated stream crossing designs that consider minimum openness ratios and widths to ensure that stream crossings are less tunnel-like and more stream-like. The “stream simulation design” developed by the WDFW (2003) assumes that if fish can migrate through a natural stream reach, then they can also migrate through a man-made channel that simulates a natural stream channel.

3.6 GROUPS AND PERFORMANCE THRESHOLDS

Despite a paucity of studies in the Northeast, it is possible to categorize northeastern stream fish based on athletic performance using FishXing, field and laboratory studies, and expert opinion. Coffman (2005) used this approach to develop predictive models for fish passage through culverts, and the three groups that he created based on jumping and swimming performance (see section 3.2 and 3.3) provide a starting point for grouping species in northeastern streams.

Table 2 lists 9 groups of common northeastern stream fish (39 species) based on taxonomic affinity and to a lesser extent athletic performance. Species and groups were then ranked according to their athletic performance (leaping ability and swimming ability) using expert opinion (Appendix 2) and published studies. Ranks were categorical (0-4) and the average of all responses (including my own which was guided by the literature review rather than expert opinion) was used to compare groups/species.

3.6.1 Leaping Ability

The question posed to experts, and what guided the literature review, was whether the species (adults and juveniles) were capable of ascending waterfalls of different heights. Categorical rankings were as follows:

0: Severely vertically challenged. 7 cm drop would be a barrier under most conditions
1: Vertically challenged. 15 cm drop would be a barrier under most conditions
2: Moderate jumping ability. Can ascend drops of up to 30 cm
3: Good leaping ability. Can ascend drops of up to 60 cm
4: Excellent leaping ability; can ascend drops of greater than 100 cm under ideal conditions

Using expert opinion and the few published studies that provide actual leaping data, Figure 2 illustrates general height thresholds for species groups and life stages. Thresholds are simple ways to represent complex problems and should be used cautiously.

3.6.2 Swimming Ability

The question posed to experts, and what guided the literature review, was how fast can the species or group swim (maximum swimming speed). Categorical rankings were as follows:

0: Extremely slow
1: Slow
2: Moderate
3: Fast
4: Extremely fast

Initially, experts were asked to rank species by endurance, or the time (or distance) that species could maintain maximum speeds. I included this category because swimming speed does not indicate whether a fish could cross a velocity barrier because it does not account for distance. Certainly water flowing at 0.5 m/s through a 25 m culvert is a different challenge than the same water velocity through a 100 m culvert. Ted Castro-Santos at the Conte Lab pointed out that my questions regarding endurance were misguided: fatigue time is a function of swim speed, and distance is a function of flow velocity. The complexity, although interesting from a research perspective, is more than I felt comfortable tackling with this simple ranking process. I decided to eliminate this variable: I think it is adequately accounted for by the swim speed rankings and the grouping process that considered body size and swimming ability.

Figure 3 illustrates general velocity thresholds for species groups and life stages based on expert opinion and published literature. This is represented as the highest culvert water velocity that could allow fish to swim through a 30-m culvert. As was true for leaping ability, Figure 3 illustrates general velocity thresholds for species groups and life stages and is by no means definitive.

Coffman (2005) is the first good attempt to develop predictive models for fish movement through culverts in the eastern US. Although his models do specify thresholds, he only monitored fish movement for 30 days during the summer and fall of 2004, meaning that streams did not undergo a full range of flow conditions, nor did species exhibit a full range of behaviors. Therefore, it is unlikely that the specific models developed by Coffman (2005) can be applied elsewhere and at different seasons, but the conceptual basis of his work is strong.

Table 2. Northeastern stream fish grouped by taxonomic affinity and athletic performance. Species marked with an asterisk (*) collectively comprise the majority of fish biomass in most 0-4 order streams.

Group	Species
Group A Salmonidae	Brook Trout* Rainbow Trout* Atlantic Salmon* Brown Trout*
Group B Large Cyprinidae + Catostomidae	White Sucker* Creek Chub* Fallfish* Longnose Sucker* Lake Chub Creek Chubsucker
Group C Small Cyprinidae	Blacknose Dace* Longnose Dace* Common Shiner* Spottail Shiner Redbelly Dace Finescale Dace Silvery Minnow Bridle Shiner Golden Shiner Pearl Dace
Group D Benthic Non-Minnows	Slimy Sculpin* Tesselated Darter* Burbot
Group E Bass, Pickerel, and Perch	Chain Pickerel Yellow Perch Largemouth Bass Smallmouth Bass Rock Bass
Group F Sunfish	Bluegill Pumpkinseed Sunfish Banded Sunfish Redbreasted Sunfish
Group G Catfishes	Brown Bullhead Yellow Bullhead
Group H Eels and Lampreys	American eel Sea Lamprey Brook Lamprey
Group I Alosidae	River Herring American shad

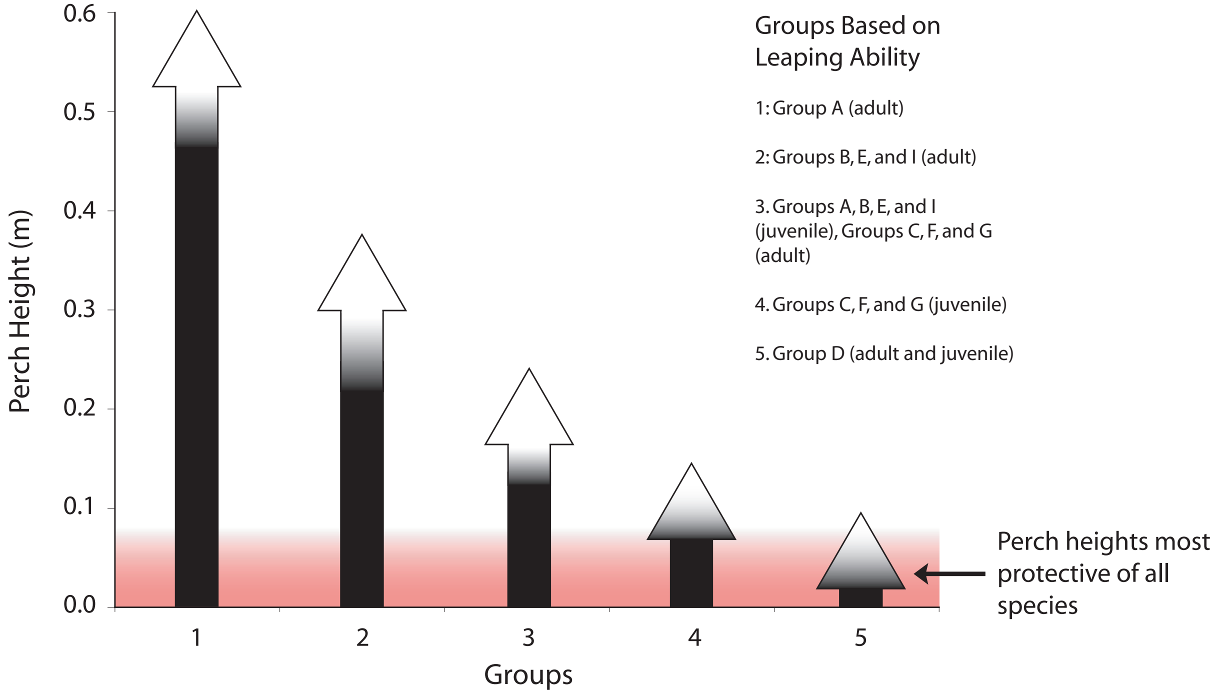

Figure 2. Perch height thresholds for species groups. The gradient from black to white indicates uncertainty and variability within the groups. The perch height protective of most species is indicated in red. Table 2 lists species groups.

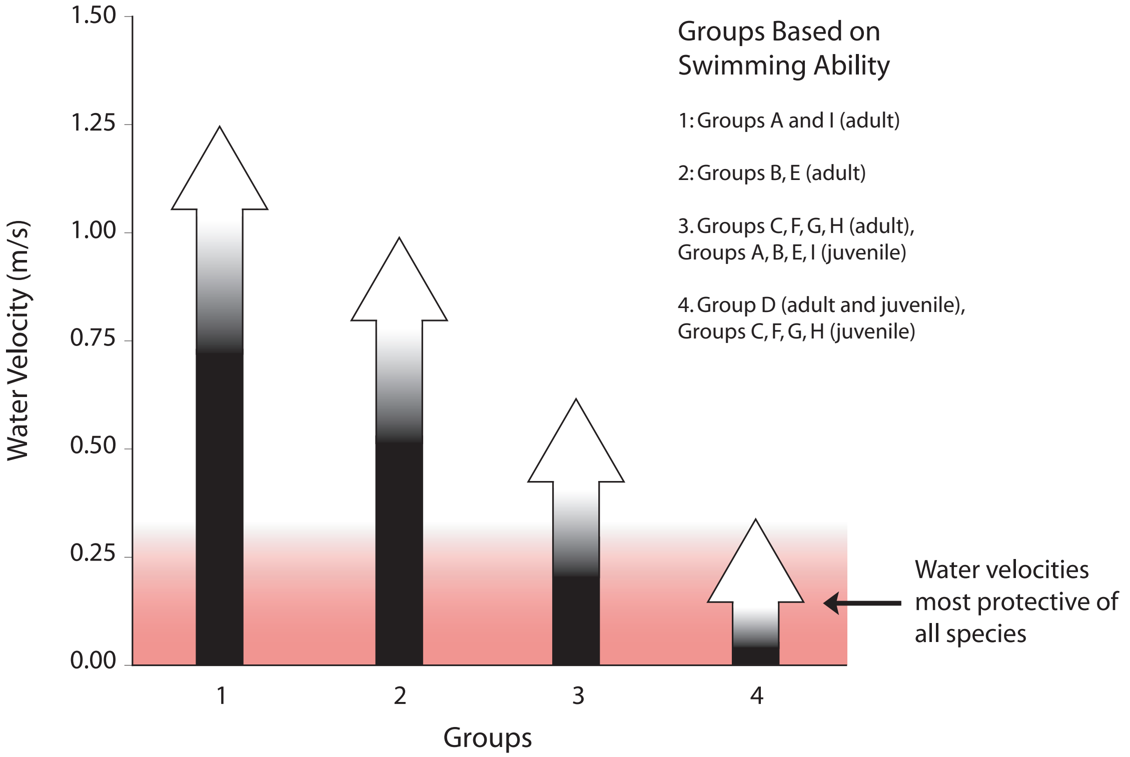

Figure 3. Water velocity thresholds for species groups to swim through a 30-m smooth culvert. The gradient from black to white indicates uncertainty and variability within the groups. The water velocity protective of most species is indicated in red. Table 2 lists species groups.

3.7 COMPLEXITY OF FISH MOVEMENT AND BARRIERS

Although several attributes of a stream crossing can impede animal movement, the interaction of these features—particularly under different environmental conditions—reflects the true nature of a barrier. Fish are often presented with jumping, swimming, endurance, and behavioral challenges at each crossing.

It is important to be familiar with local species assemblages, periods during which species need to move, and how important movement is for each species. All species move, but the distances they move and the consequences of restricted movement vary greatly because of life histories and habitat (Railsback et al. 1999, Albanese 2001, Albanese et al. 2004). Integrating fish movement and habitat into stream crossing assessments is described more fully in Chapter 4. Appendix 1 compiles some movement and ecology data for common stream fishes of the Northeast.

Stream crossings that delay movement also have population-level consequences, especially when there are multiple crossings. Species that congregate downstream of crossings are vulnerable to overcrowding, predation, and fluctuating environmental conditions (e.g., temperature and flow) that can further hinder their ability to move upstream. Many terrestrial and semi-terrestrial species prefer to move along streambanks and stream corridors; restrictive crossings may force them to cross roads. Each crossing can be a bottleneck (if not an outright barrier), and the cumulative effect of all crossings can be to effectively block all species from moving through a watershed.

Terms such as “barrier” or “threshold” must be qualified by species, time of year, and other contextual parameters. These qualifications collectively determine the ecological significance of a barrier and must be considered if a project has ecosystem-based goals. Until research provides better information, the scientific basis for “passage thresholds” based on athletic performance is too tenuous for many applied fields, including culvert assessments.

3.8 CONSERVATIVE APPROACH

Given the enormous complexity related to barriers and thresholds, and the paucity of scientific data, managers must evaluate stream crossings conservatively. In other words, either define barriers based on athletic performance of the “weakest” species during the most challenging conditions, or assume that a stream crossing with design parameters outside the range of natural variability is a barrier. A conservative approach negates the need for exhaustive scientific inquiry on athleticism of all species, and should allow movement of the greatest number of species under most conditions.

Coffman (2005) provided a general recommendation that has much broader application than the specific models that he developed: “Generally, culverts providing the greatest advantage for fish moving upstream were those with little to no outlet drop (<10 cm), gentle slopes (<2.0%), and low slope x length (< 25) values.” Fisheries professionals would have likely reached this same conclusion using best professional judgment. A growing number of studies advocate conservative thresholds:

- Research on stream crossings and fish movement by the Etowah HCP (2005) concluded that culverts should be designed so that average water velocities at low flows do not exceed 0.3 m/s, and under no circumstances should non-embedded or perched culverts (box culverts or pipe culverts) be used.
- Several other studies suggest that water velocities should not exceed 0.3-0.4 m/s in culverts to permit passage of the greatest number of species (Jones et al. 1974, Peake et al. 1997, Warren and Pardew 1998, Coffman 2005). If high velocities cannot be avoided, then natural substrates or baffles should be used to create velocity refuges.
- Massachusetts stream crossing standards, which are approved by the US Army Corps of Engineers, call for the following: (1) all culverts are to be embedded, (2) all crossings are to be at least 1.2x the bankfull width of the stream, (3) natural substrate must be used, (4) water depth and velocity within the crossing must match conditions upstream and downstream, and (5) crossings must have a minimum openness ratio (i.e., they should be wide and high relative to their length). Open arches or bridges are preferred over culverts.

Crossings should be essentially “invisible” to fish and wildlife—they should maintain appropriate flow and substrate throughout a crossing and not constrict a stream. The “stream simulation design” accomplishes this, and is currently most practical way to maintain viable populations of organisms that make up aquatic communities and maintain the fundamental integrity of river and stream ecosystems (WDFW 2003).

CHAPTER 4

Ecological Basis of Stream Crossing Assessments

4.1 OVERVIEW

In any watershed, a large proportion of stream crossings are partial barriers (i.e., they restrict *some* species *some* of the time), and lesser proportions are complete barriers or are not barriers at all. The complexity of ecological interactions makes it difficult to discriminate between partial barriers using physical measurements alone. In other words, culverts with similar physical dimensions and perch height can have profoundly different effects on stream continuity and species assemblages.

Recent development of stream crossing standards set a precedent for a hierarchy of stream habitats in terms of the importance of barriers and continuity, from small ephemeral streams (that receive almost no protection) to large fish-bearing streams with high conservation value (that receive greatest protection). Since this hierarchy is based on somewhat subjective parameters (e.g., size, permanence, and conservation value), it should be explicitly justified with the best available information, and should be suited to specific conservation targets and watersheds.

Rabeni and Sowa (1996) stated, "Successful habitat conservation or restoration must be biologically based, which requires an understanding on habitat variables most influencing fish, the relative influence of each habitat variable, and the spatial scale over which each operates." An ecologically based assessment helps distinguish those barriers that have the greatest ecosystem effects, and can provide guidance on where highest quality (i.e., least restrictive) stream crossings should be located. The strengths of an ecologically based assessment are that it focuses on stream reaches and riparian areas upstream and downstream of each crossing and considers species assemblages, habitat, landscape or regional-scale considerations, and specific conservation targets. Some critical questions that an ecologically based assessment can address are:

- What species are likely to move, and when?
- How important is movement for populations and communities?
- What ecological parameters contribute to the potential for stream crossings to disrupt continuity, and how can these parameters be used to prioritize streams or specific stream reaches for protection and restoration?

The scientific basis for ecologically based assessment exists but has not been synthesized and is incomplete. The conceptual basis presented in this chapter draws on research on basic lotic ecology, stream and riparian habitat, aquatic fragmentation, aquatic-terrestrial connectivity, habitat suitability models for species and species groups, life histories of aquatic and riparian species, population (and metapopulation) ecology, and community ecology. Application of landscape ecology principles to stream networks is a promising direction for understanding stream continuity and assessing barriers. Excellent starting points are papers by Schlosser (1991), Ward (1998), Jackson et al. (2001), Fausch et al. (2002), and Wiens (2002).

Since most stream barrier assessment projects have general ecological goals (e.g., to restore continuity), rather than single-species goals (e.g., to restore brook trout), the prioritization process should explicitly consider ecological parameters. In general, conservation targets should dictate the scope of an ecological assessment to ensure that objectives, actions, and outcomes are congruent.

4.2 SPECIES ASSEMBLAGES

To assess the degree to which a stream crossing affects species or disrupts stream continuity, it is essential to know what species inhabit a stream or stream corridor. Environmental managers often have limited knowledge of species assemblages and instead focus on common game species, such as brook trout, which may not be suitable surrogates for the entire community. Investigators should establish species lists of fish, mobile invertebrates (i.e., crayfish), salamanders, frogs, and turtles. These lists need not be compiled through intensive fieldwork at each location, but rather from published studies on species assemblages and species-habitat relationships in comparable watersheds or ecoregions. Species likely to occur in small rivers and streams in southern New England are listed in Table 1 (page 10), Table 3 shows the range of stream sizes that these species are likely to inhabit, and Table 4 lists some attributes for these species.

Good discussion of stream fish assemblages as they relate to ecoregions or other geographic factors can be found in Omernik (1987), Larsen et al. (1988), Lyons (1989), McCormick et al. (2000), Hawkins et al. (2000), Cyterski and Barber (2006). Sources that were most useful in generating species lists for 0-5 order streams in the Northeast (Table 1) include Peterson and Gale (1991), Fairchild et al. (1998), McCormick et al. (2000), Werner (2004), Cyterski and Barber (2006), as well as data provided by the New Hampshire Department of Environmental Protection's Biomonitoring section (www.des.state.nh.us/wmb/biomonitoring/fish_assess.htm) and personal communication with regional scientists.

A complete species list, combined with life history data for each species, can be a powerful way to demonstrate the potential effect of a barrier. Categorizing species according to life history, ecology, or conservation value is a proven way of extracting useful information from species lists. These categories often correspond with conservation targets, such as migratory species, rare and endangered species, and coldwater indicator species. Some categories can indicate degraded assemblages that restoration actions should seek to avoid, such as non-native species (although non-native trout are often protected), warmwater lentic species, or ecologically destructive species. Information on life history and other attributes of northeastern species and groups of species is provided in Table 4, Appendix 1, and Chapter 5.

In terms of prioritizing stream crossings for restoration, it is tempting to use species richness as a criterion. Upgrading or restoring stream crossings that affect the greatest number of species is a logical way to promote biological diversity in a stream or watershed. Angermeier and Winston (1997) cautioned that species richness represents an arbitrary proportion of all biological diversity and that the relationship between species richness and conservation value is variable. Stream reaches with identical species lists could have dramatically different contributions to long-term biological conservation because species lists do not account for population viability (this concept can also be applied to habitats). They advocate identifying source populations (i.e., larger and more viable populations) of species with a high conservation value, and they developed an index called the ICD (Index of Centers of Diversity) to help distinguish areas with source populations.

Table 3. Typical stream sizes for northeastern stream fish and salamanders. Black = most likely. Gray = seasonal or unlikely.

Species	Stream Order							
	0	1	2	3	4	5	6	7
Spring Salamander	■	■	▒					
Two-Lined Salamander	■	■	■	▒				
Northern Dusky Salamander	■	■	■	▒				
Brook Trout	▒	■	■	■	▒			
Slimy Sculpin	▒	■	■	■	▒			
Brook Lamprey		▒	■	■	▒			
Blacknose Dace		▒	■	■	■	▒		
Brown Trout		▒	■	■	■	▒	▒	
Atlantic Salmon		▒	■	■	■	▒	▒	
Longnose Dace		▒	■	■	■	■	▒	
Creek Chub		▒	■	■	■	■	▒	
Longnose Sucker		▒	■	■	■	■	▒	
Rainbow Trout		▒	■	■	■	■	▒	
Tesselated Darter		▒	■	■	■	■	■	■
White Sucker		▒	■	■	■	■	■	■
Creek Chubsucker		▒	■	■	■	■	■	■
Fallfish		▒	▒	■	■	■	■	■
Common Shiner			▒	■	■	■	■	■
Lake Chub			▒	■	■	■	■	■
Burbot			▒	■	■	■	■	■
Redbelly Dace			▒	■	■	■	■	■
Finescale Dace			▒	■	■	■	■	■
Bridle Shiner			▒	■	■	■	■	■
Golden Shiner			▒	■	■	■	■	■
Pumpkinseed Sunfish			▒	■	■	■	■	■
Redbreasted Sunfish			▒	■	■	■	■	■
Bluegill			▒	■	■	■	■	■
Banded Sunfish			▒	■	■	■	■	■
American Eel			▒	■	■	■	■	■
Brown Bullhead			▒	▒	■	■	■	■
Sea Lamprey			▒	▒	■	■	■	■
Smallmouth Bass				▒	■	■	■	■
Spottail Shiner				▒	■	■	■	■
Rock Bass				▒	■	■	■	■
Chain Pickerel				▒	■	■	■	■
Yellow Bullhead				▒	■	■	■	■
Yellow Perch				▒	▒	■	■	■
Largemouth Bass				▒	▒	■	■	■
Alewife				▒	▒	■	■	■
Silvery Minnow					▒	▒	■	■
American Shad						▒	■	■

Table 4. Traits of northeastern stream fishes (spawning periods are also illustrated in Table 5).

Species	Origin	Typical Size[1]	Habitat	Thermal Class[2]	Rare[3]	Spawning Period	Spawning Movement[4]	Non-Spawning Movement[5]
Salmonidae								
Rainbow Trout	Introduced	10	Stream	Cold		Mar-May	Meso-River	Micro-Meso
Atlantic Salmon	Native	8	Stream	Cold	Yes	Oct-Dec	Watershed	Meso-River
Brown Trout	Introduced	10	Stream	Cold		Oct-Nov	Meso-River	Micro-Meso
Brook Trout	Native	8	Small Stream	Cold		Sep-Dec	Meso-River	Micro-Meso
Cyprinidae								
Lake Chub	Native	8	Stream	Cold	Yes	Apr-Jun	Meso	Micro-Meso
Silvery Minnow	Native	3.5	Generalist	Cool	Yes	Apr-Jun	Meso	Meso
Common Shiner	Native	8	Stream	Warm		May-Jun	Meso	Micro-Meso
Pearl Dace	Native	4	Generalist	Cold	Yes	May-Jun	Micro-Meso	Micro-Meso
Golden Shiner	Native	8	Generalist	Warm		May-Aug	Micro-Meso	Micro-Meso
Bridle Shiner	Native	2	Generalist	Cool	Yes	May-Jul	Meso	Micro-Meso
Spottail Shiner	Native	4	Generalist	Cool		Jun-Jul	Meso	Micro-Meso
Redbelly Dace	Native	2.5	Generalist	Cool	Yes	May-Aug	Micro-Meso	Micro
Finescale Dace	Native	3.5	Generalist	Cool		Apr-Jun	Micro-Meso	Micro
Blacknose Dace	Native	3.5	Small Stream	Cold		Apr-Jun	Micro-Meso	Micro
Longnose Dace	Native	4.5	Small Stream	Cold		Apr-Jun	Micro-Meso	Micro
Creek Chub	Native	8	Stream	Cool		Apr-Jun	Meso	Micro-Meso
Fallfish	Native	10	Stream	Cool		Apr-Jun	Meso	Micro-Meso
Catostomidae								
White Sucker	Native	12	Stream	Cool		Apr-May	Meso-River	Meso
Longnose Sucker	Native	12	Stream	Cool	Yes	May-Jun	Meso-River	Meso
Creek Chubsucker	Native	6	Stream	Cool		Apr-May	Meso-River	Meso
Centrarchidae								
Rock Bass	Introduced	8	Generalist	Warm		May-Jul	Meso	Micro-Meso
Banded Sunfish	Native	4	Generalist	Warm	Yes	May-Jul	Micro-Meso	Micro
Redbreasted Sunfish	Native	7	Generalist	Warm		May-Jul	Micro-Meso	Micro
Pumpkinseed Sunfish	Native	8	Generalist	Warm		May-Jul	Micro-Meso	Micro
Bluegill	Introduced	8	Generalist	Warm		May-Jul	Micro-Meso	Micro
Smallmouth Bass	Introduced	10	Generalist	Warm		May-Jun	Meso	Micro-Meso
Largemouth Bass	Introduced	12	Generalist	Warm		May-Jul	Micro-Meso	Micro-Meso
Percidae								
Tessellated Darter	Native	2.5	Stream	Cool		Apr-May	Micro	Micro
Swamp Darter	Native	1.25	Generalist	Warm		Apr-May	Micro	Micro
Yellow Perch	Native	10	Generalist	Warm		Apr-May	Meso	Meso
Anguillidae								
American Eel	Native	14	Generalist	Warm		NA	Watershed	Watershed
Ictaluridae								
Brown Bullhead	Native	10	Generalist	Warm		May-Jul	Meso	Micro-Meso
Yellow Bullhead	Introduced	8	Generalist	Warm		May-Jun	Meso	Micro-Meso
Esocidae								
Chain Pickerel	Native	12	Generalist	Warm		Mar-Apr	Meso	Micro-Meso
Cottidae								
Slimy Sculpin	Native	4	Small Stream	Cold		Apr-May	Micro	Micro
Lotidae								
Burbot	Native	6	Stream	Cool	Yes	Jan-Mar	Micro-Meso	Micro
Umbridae								
Central Mudminnow	Introduced	4	Generalist	Warm		Mar-Apr	Micro-Meso	Micro
Clupeidae								
River Herring	Native	12	Stream	Cool		Apr-Jun	Watershed	Watershed
Petromyzontidae								
Sea Lamprey	Native	20	Stream	Cool		May-Jun	Watershed	Watershed
Brook Lamprey	Native	6	Small Stream	Cold	Yes	Mar-Apr	Meso	Micro

Footnotes: 1) Typical size of adults or life stages commonly found in streams and small rivers (inches), **2)** In the context of streams and small rivers in New England, and recognizing that some species can tolerate a broader range, **3)** State-listed in one or more states in New England, **4)** Spatial scale of spawning movement, micro = <100m, meso = 100-1000m, river = 1000-10000m, watershed = diadromous, **5)** Spatial scale of movement not during the spawning season for spawning purposes

4.3 SPECIES MOVEMENT

With regard to stream crossings, there are three important aspects of species movement: (1) ability, (2) likelihood, and (3) timing. The ability of a species to cross barriers is covered in Chapter 3 of this document and is the basis for barrier-based stream crossing assessments. The problems with relying on species ability (besides a lack of performance studies for most species) are that not all species need to move great distances and the effects of restricted movement vary. Table 4 lists the spatial scale of movement for common stream fishes of the Northeast, based on expert opinion and literature review.

All species move to meet their resource needs, but the temporal and spatial scale of movement is highly variable (Schlosser and Angermeier 1995, Northcote 1997, Fausch et al. 2002, Albanese et al. 2004). Small-scale movement allows individuals to exploit better feeding opportunities and optimize conditions for growth and survival, whereas larger scale movement is tied to reproduction and dispersal. The importance of movement is well established for diadromous species such as the Salmonidae (Northcote 1997), but there is growing appreciation of movement in species that were traditionally considered relatively sedentary on reach or river scales (Gowan et al. 1994, Freeman 1995, Smithson and Johnston 1999, Johnston 2000, Larson et al. 2002, Fausch et al. 2002). No matter the spatial scale, movement is essential for the survival and persistence of individuals, populations, and metapopulations.

4.3.1 Reasons for Movement

Breeding: Most species increase movement during breeding periods to reach specific breeding areas, find mates, or return to non-breeding areas. Breeding movement is most pronounced for diadromous species, but even non-migratory species such as Catostomidae and Cyprinidae have been shown to move on a reach or river scale to spawn (Miller 1964, Curry and Spacie 1984). Table 5 shows breeding/spawning periods of northeastern stream fishes and this should correspond with periods of greatest movement for most species.

Thermal Refuge: Many coldwater species must seek thermal refuge during the year, such as areas of groundwater upwelling, small tributaries, upstream reaches with heavier forest canopy, or riffle habitats where oxygenated waters can offset some effects of warmer temperatures (Magnuson et al. 1979, Matthews et al. 1994, Peterson and Rabeni 1996). Leopard darters (*Percina pantherina*), generally considered a benthic species with extremely limited mobility, sought refuge in deep cool water during late summer, suggesting that even small-scale movement is necessary for persistence (Schaefer et al. 2003).

Drought Refuge: Species must have access to deep and stable areas of stream reaches to persist during droughts (Heggenes et al. 1991, Labbe and Fausch 2000, Magoulick 2000). Expansive reaches of shallow riffles can become largely dewatered during extreme droughts and recolonization rates will be higher if there are nearby refuges (Lonzarich et al. 1988). Albanese et al. (2004) predicted that probability of emigration would be negatively correlated with stream depth because shallow areas are more likely to become unsuitable habitat during seasonal low flows.

Predation: Predation risk is thought to influence movement (Power et al. 1985, Gorman 1988, Schlosser and Angermeier 1990, Gilliam and Fraser 2001), although this phenomenon is most often inferred from species distribution and habitat segregation rather than direct observations of prey fleeing predators. Areas that provide the most "cover" (i.e., complex habitat with hiding places) have been shown to harbor higher densities of prey species (Gorman 1988). Roberts (2003) found some evidence that addition of stream cover allowed greater movement by darters.

Habitat Segregation: Life stages of species utilize different habitats (Moyle and Vondracek 1985, Freeman and Stouder 1989, Johnson et al. 1992, Aadland 1993) or different areas of the same habitats (Mullen and Burton 1995). In streams, large fish generally occupy pools and stable areas and small fish occupy riffles and temporally dynamic areas (Schlosser 1982), presumably because small fish cannot compete with large fish for space or because riffles are a refuge from predators (Schlosser 1987). Larger species and individuals generally have larger home ranges.

Feeding: All species move to exploit feeding opportunities. Prey availability is spatially and temporally variable, and some species will travel long distances to maximize foraging. Some examples are species that follow other migrating species to feed (e.g., striped bass following alewife upriver to eat adult fish, or salmonids following spawning suckers to eat eggs), species that move between pools to

Table 5. Visual representation of spawning periods for common stream fish in the Northeast.

		Month											
	Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Salmonidae	Rainbow Trout			■	■	■							
	Atlantic Salmon										■	■	■
	Brown Trout										■	■	
	Brook Trout									■	■	■	■
Cyprinidae	Lake Chub				■	■	■						
	Silvery Minnow				■	■	■						
	Common Shiner					■	■						
	Pearl Dace					■	■						
	Golden Shiner					■	■						
	Bridle Shiner					■	■	■					
	Spottail Shiner						■	■					
	Redbelly Dace					■	■	■	■				
	Finescale Dace				■	■	■						
	Blacknose Dace				■	■	■						
	Longnose Dace				■	■	■						
	Creek Chub				■	■	■						
	Fallfish				■	■	■						
Catostomidae	White Sucker				■	■							
	Longnose Sucker					■	■						
	Creek Chubsucker				■	■							
Centrarchidae	Rock Bass					■	■	■					
	Banded Sunfish					■	■	■					
	Redbreasted Sunfish					■	■	■					
	Pumpkinseed Sunfish					■	■	■					
	Bluegill					■	■	■					
	Smallmouth Bass					■	■						
	Largemouth Bass					■	■	■					
Percidae	Tessellated Darter				■	■							
	Swamp Darter				■	■							
	Yellow Perch				■	■							
Other	American Eel												
	Brown Bullhead					■	■	■					
	Yellow Bullhead					■	■						
	Chain Pickerel			■	■								
	Slimy Sculpin				■	■							
	Burbot	■	■	■									
	Central Mudminnow			■	■								
	Alosa sp.				■	■	■						
	Sea Lamprey					■	■						
	American Brook Lamprey			■	■								

riffles when benthic insect densities are highest (Schlosser 1982), and species that move laterally into floodplains to consume terrestrial prey (Kwak 1988, Junk et al. 1989).

Overwintering: Stream fish often have overwintering habitat requirements that cause them to move in late fall and again in early spring. Species often emigrate from shallow unstable environments into deeper stable environments, such as from riffles to pools or to instream cover (Cunjak and Power 1986a, 1986b; Whalen et al. 1999), from small streams to larger streams (Miller 1964, Gorman 1986), or from streams into accessible ponds (Schlosser 1998). Given the physiological costs of enduring harsh winters, species prevented from seeking overwintering habitat are less likely to survive and unfavorable winter habitats can be considered a population sink (Schlosser 1995, 1998; Cunjak et al. 1998).

Random: Random movement (or what might seem like random movement to humans who cannot determine intent) has long been recognized as a vital part of the colonization and persistence of aquatic organisms but has been difficult to quantify with fish because of inherent difficulties of mark-recapture studies (specifically, recapturing marked animals) (Gowan et al. 1994). It is important to keep in mind that our understanding of the spatial scale of species movement is often based on limited data collected during short observation periods. We should expect that natural random movement can be far greater than scientists have been able to measure, especially over longer time periods.

4.3.2 Effects of Flow and Temperature on Movement

Flow is a strong cue for movement for most species. Possible reasons for movement at high flows include accessing spawning or foraging habitats, accessing inundated reaches of intermittent habitats, escaping habitats that had become disconnected by low flows, circumventing natural barriers, or seeking a flow refuge (Albanese et al. 2004). Several studies have shown that movement of stream fish is greatly elevated during high flow periods (e.g., Ross and Baker 1983, Schlosser 1995, Gowan and Fausch 1996, Albanese 2004). Albanese (2004) found that 30% of the marked fallfish that were recaptured during a 87-day trapping period moved on a single day when flow was elevated.

The importance of flow as a trigger for movement has important implications for understanding effects of barriers. Barriers that either store or impede flows can dampen discharge peaks and weaken the trigger for species movement. The colonization and persistence of stream fish assemblages will depend on maintenance or restoration of natural flow regimes (Poff et al. 1997).

Temperature is another trigger for movement and swimming performance in general. All fish endure periods when water temperatures are outside their optimum range, and the typical response is that they become less active or seek more favorable conditions. Holthe et al. (1995) showed that minnows in the genus *Phoxinus* could not be induced to jump at cold temperatures but could jump upwards of 30 cm when temperatures were as little as 8°C warmer. Myrick and Cech (2000) determined experimentally that swimming performance (critical swimming velocity) of four stream fishes was lowest at cold (10°C) temperatures. Hall (1972) found that most stream fish stopped moving when water temperatures dropped below 7°C. Albanese (2001) found that three stream fishes—fallfish, bullhead, and sculpin—did not begin moving until stream temperatures surpassed 13°C.

Except perhaps for the most cold-adapted species, most stream fish do not move during the winter. The movement window for most stream fish in the Northeast is late March to December, depending on how quickly streams warm in the spring or cool in the fall. Within the movement window, most resident species move during periods of high flow, particularly during breeding periods or when they are ready to disperse. This basic knowledge can be important for management: potential stream barriers should be assessed at a time that is relevant for the species that are likely to cross.

4.4 PREDICTING MOVEMENT FROM HABITAT

Species move for many reasons, and the spatial extent and timing of movement is far too variable for managers to make decisions that account for all of the complexity. General rules for conservation are that continuous reaches with high habitat complexity should meet the needs of most resident species, and that reaches with homogenous habitat and less stability will have less diverse and more dynamic fish communities (Gorman and Karr 1978, Gorman 1986, Schlosser and Angermeier 1995).

In simplest terms, if a continuous stream reach has everything a species could want, then the likelihood that individuals will emigrate should be low and the importance of restrictive stream crossings on either end of the reach will also be low. Likewise, if a continuous stream reach lacks important habitat features that a species needs, individuals will likely use the reach some of the time and will need to emigrate into neighboring reaches. In this case, there should be passable road-stream crossings on either end of the reach. These simple relationships apply mainly to resident species that move at small to intermediate scales. Larger-scale movement (i.e., diadromous species such as salmon, alewife, and eels) requires unrestricted passage through watersheds at least as far upstream as optimum breeding or rearing habitat exists.

By knowing the life history and habitat of each species that potentially exists in a stream reach, it is possible to characterize habitat to determine which species are most likely to emigrate, and when movement is likely to occur. Unfortunately, this type of research has not been conducted for most species. Fausch et al. (2002) stress a lack of understanding about population and community ecology at intermediate spatial (1-100 km) and temporal (5-50 years) scales—scales that are critical for management.

CHAPTER 5

Restoring Continuity in the Ashuelot River Watershed

The first phase of the Ashuelot River Continuity Project is an inventory of all road-stream crossings in the watershed, which may include more than 1000 sites. The survey is largely based on physical measurements described in Chapter 2, with emphasis on the following: (1) outlet and inlet perch, (2) culvert dimensions (length, width, and height), (3) culvert slope, (4) bed materials, (5) bank and instream habitat parameters near the crossing. The assessment procedure is based on projects completed in Massachusetts (Massachusetts River and Stream Continuity) and Vermont (Vermont Agency of Natural Resources 2005).

The inventory will result in a database of all road-stream crossings that will serve as a tool to screen and prioritize the crossings that should be upgraded or replaced. Because the culvert assessment procedures only call for physical measurements, subsequent analysis and prioritization to meet biological or ecological goals must rely on our understanding of how the measured parameters relate to population, community, or ecosystem parameters.

It is important to consider how physically comparable road-stream crossings might have different effects on natural stream flow, passage for aquatic and riparian species, and ecosystem processes and functions. For reasons described in Chapter 4, the biological and ecological context of a road-stream crossing should, in many cases, weigh more heavily than specific physical parameters. I suggest that road-stream crossings be assessed according to landscape/watershed, habitat, and species variables. Specific variables, and the weight given to each, will depend on conservation strategies and targets for a specific watershed. Collectively, the physical characterization and ecological characterization of road-stream crossings will enable managers to focus on restoring the most egregious barriers.

5.1 CONSERVATION STRATEGIES AND TARGETS

Roni et al. (2002 present a hierarchical strategy for setting watershed restoration priorities. A watershed assessment is a critical step that should guide subsequent restoration. The road-stream crossing inventory currently being conducted in the Ashuelot River watershed is an important part of the initial assessment of watershed connectivity. Ultimately, restoration should first focus on reconnecting high quality habitats that are fragmented by barriers. The challenge is to determine what constitutes a "high quality" habitat, what species are likely to be affected, and to what degree habitat was fragmented (and species affected) in the first place. A large part of this challenge is defining conservation strategies and targets, and clearly demonstrating the biological and ecological basis for proposed action.

The need for a biologically and ecologically based assessment of stream continuity is implicit in a key conservation strategy stated in Zankel (2004) for the Ashuelot River watershed:

> *"Maintain or restore important landscape connections and corridors that result in a functional network of habitat conservation areas for wildlife management, and which prevent long-term fragmentation into disjunct conservation islands."*

A second strategy that explicitly mentions road-stream crossings in the Ashuelot River watershed is as follows:

> *"Document and evaluate the extent and impacts of aquatic habitat fragmentation in the watershed (e.g., dams and culverts) and develop recommendations and priorities for restoration actions to reduce the impacts of aquatic barriers."*

Both strategies are biologically and ecologically based, and both explicitly mention restoration. Clearly, the Ashuelot River Continuity Project is intended to provide the basis for restoration actions. To be effective, stated conservation targets should guide the entire process. A conservation target could be a species, species group, habitat, natural community, or even an ecological process. Defining the conservation target is a difficult decision that will greatly influence how we measure and assess crossings, prioritize crossings for potential restoration, allocate time and money for specific crossings, demonstrate the effectiveness of restoration, and apply "lessons learned" to other projects.

Documenting how well projects meet their intended goals is a critical component of good adaptive management. Ef-

Table 6. Stream reaches that are conservation targets in the Ashuelot River watershed. From Zankel (2004).

Stream Reach	Type	Explanatory Notes
Ashuelot River mainstem, from mouth to Marlow-Washington town line	Large river (Size 3), low gradient	The unifying ecological feature that ties together the watershed. Designated river though the NH Rivers Management and Protection Program. Supports globally imperiled Dwarf Wedgemussel and exemplary floodplain forest communities. Identified as important for anadromous fish restoration by U.S. Fish & Wildlife Service. Stocking site for river herring and American shad (Sawyer's Crossing Bridge). Provides shad spawning and nursery habitat below Surry Dam. Active river restoration efforts underway including dam removal. Selected as a TNC Portfolio stream through Aquatic Ecoregional Planning.
Ashuelot River mainstem, upstream of Marlow-Washington town line	Large tributary (mostly Size 2)	Forms the headwaters of the Ashuelot River system. The 5-mile stretch from Butterfield to Ashuelot Pond is designated as “Natural” through the Rivers Management and Protection Program; other reaches are designated as “Rural” or“Community”. The corridor and watershed are largely forested, and water quality is very good. Important potential habitat for juvenile salmon restoration. Selected as a TNC Portfolio stream through Aquatic Ecoregional Planning.
South Branch	Large tributary (Size 2 and 3).Lower 5 miles is low-gradient, upper section is moderate-gradient.	Supports globally imperiled Dwarf Wedgemussel and exemplary floodplain forest and riparian wetland communities. Maintains stable water temperature and adequate flow throughout the year to support native fish communities. Undammed upstream to East Swanzey. Good spawning habitat for blueback herring. Salmon stocking site. Important for anadromous fish restoration. Brook trout index site. Reach between Iron Bridge in East Swanzey to Farrar Pond dam in Troy is managed as a Quality Trout Fishery by NH Fish and Game Department. Selected as a TNC Portfolio stream through Aquatic Ecoregional Planning.
Minnewawa Brook	Large tributary (Size 2), low-gradient to center Marlborough, moderate gradient above	One of, if not the, most productive salmon stocking stream in southwestern New Hampshire. Upper reaches are coldwater and support wild brook trout, and are not stocked. Impacted by development and multiple dams in Marlborough.
Rice and Falls Brooks	Small tributaries (Size 1), high and moderate gradients	Good water quality. Support wild brook trout and slimy sculpin. Both are designated by NH Fish and Game as Wild Trout Waters.
Shaker Brook	Small tributary (Size 1), moderate gradient	High quality coldwater stream. Watershed mostly forested and in good condition. Supports wild brook trout. Links South Branch to Monadnock focus area.
Roaring Brook	Medium tributary (Size 2), low-moderate gradient	Supports coldwater fish assemblage, including wild brook trout and cusk. High quality tributary. No dams, thus free-flowing connectivity with lower Ashuelot mainstem. Potentially significant for anadromous fish restoration. Salmon stocking site. Links mainstem to Sprague Brook focus area.
Hog Tongue Brook	Small tributary (Size 1), high gradient	High quality tributary near the mouth of the Ashuelot. No dams, thus free-flowing connectivity with lower Ashuelot mainstem. Drains from Pisgah State Park, and links mainstem to Pisgah focus area.
Beaver Brook	Medium tributary (mostly Size 2, some Size 1), low gradient	Flows through three-mile swamp, which supports abundant wildlife. Supports wild brook trout. Affected by runoff from Route 10 and development in downtown Keene.
Hurricane and White Brooks	Small tributary (mostly Size 1), mostly high gradient	Supports wild brook trout. Drain into the Ash Swamp Brook focus area, and then into mainstem. No dams, thus free-flowing connectivity with central Ashuelot mainstem.
Thompson Brook	Small tributary (Size 1), high gradient	Coldwater tributary, with intact riparian vegetation. Wild brook trout index site. Salmon stocking site.
Spaulding Brook	Small tributary (Size 1), high gradient	High quality, coldwater tributary stream. Mostly forested watershed.
Hayward Brook	Small tributary (Size 1)	Outstanding riparian and riverine wetland complex. Mostly forested watershed. Overlaps with Grassy Brook focus area.
Grassy Brook/Whittemore Brook	Small tributary (Size 1)	Outstanding riparian and riverine wetland complex. Mostly forested watershed. Overlaps with Grassy Brook focus area.
Wheeler Brook		Outstanding riparian and riverine wetland complex. Mostly forested watershed. Overlaps with California Brook focus area.
Sprague Brook	Small tributary (Size 1)	Outstanding riparian and riverine wetland complex. Mostly forested watershed. Overlaps with Sprague Brook focus area.
Broad Brook	Small tributary (Size 1)	Identified in the U.S. Fish and Wildlife Service Conte Refuge EIS as an aquatic conservation priority.
Tufts Brook	Small tributary (Size 1)	Identified in the U.S. Fish and Wildlife Service Conte Refuge EIS as an aquatic conservation priority.
Kilburn Brook	Small tributary (Size 1)	Identified in the U.S. Fish and Wildlife Service Conte Refuge EIS as an aquatic conservation priority.

ficient performance measures may include the number of culverts replaced or the number of river miles reconnected. But these performance measures may not relate to larger goals such as “*restore important landscape connections and corridors that result in a functional network of habitat conservation areas*” or “*protect and restore endangered species habitat.*” Biological or ecological performance measures are more powerful ways to demonstrate the success of restoration. It is also important to demonstrate to stakeholders how specific projects fit into a larger context of watershed restoration (Roni et al. 2002).

5.1.1 Landscape

The three landscape-scale conservation targets listed in Zankel (2004) that are affected by road-stream crossings include the following:

- Ashuelot River mainstem
- Major tributaries
- Small tributaries and headwater streams

Of the three, road-stream crossings are likely to have the greatest effect on small tributaries and headwater streams because culverts are most commonly installed in smaller streams. Bridges, which have far fewer ecological effects, are more commonly used in larger rivers. By narrowing the focus of a road-stream crossing assessment to smaller streams, we also narrow the list of species and habitats that road-stream crossings are likely to affect.

Specific stream reaches are conservation targets because of the habitat they offer and species they support. Streams should also be viewed as natural "roads" (i.e., migration corridors) for a variety of aquatic and riparian species. The Ashuelot River Watershed Conservation Plan focuses heavily on connectivity of large parcels of undeveloped and protected land such as state parks and forests, conservation easements, and roadless areas. Examples include Pisgah State Forest, Surry Mountain, the Andorra Highlands, and Mt. Monadnock. It is important to maintain stream and riparian connectivity into and within these lands, since these lands (and waters) will become increasingly important for maintaining the region's biodiversity as development pressure intensifies. One example is Broad Brook that connects the mainstem Ashuelot River to Pisgah State Forest.

Table 6 lists the stream reaches in the Ashuelot watershed that TNC has identified as important. Removing barriers to provide access to and within these habitats is important, whereas restoring connectivity between an urban stream reach and an agricultural stream reach might not be as important.

5.1.2 Habitat

A critical component of integrating habitat considerations into stream barrier assessments is to characterize habitat and consider the life history and habitat requirements of target species. The key would be to look at habitat availability, habitat quality, and presence of target habitats on either side of a road-stream crossing. Managers could focus on road-stream crossings that are barriers, and look for obvious mismatches in habitat availability/quality on either side of the barrier. These road-stream crossings are more likely to fragment streams. The following are examples of important habitat features:

- Connectivity with other habitats, such as small tributaries, wetlands, floodplains, and ponds
- Critical feeding areas, such as riffles, pools, adjacent wetlands, and adjacent fields and thickets (for wood turtles)
- Spawning areas, such as gravel substrates with groundwater upwelling or floodplain vernal pools
- Overwintering areas, such as deep pools or natural ponds
- Thermal refuge
- Connectivity between degraded areas and high-quality habitats
- Habitat likely to support source populations of target species
- Rearing habitat

Unique habitats and natural communities should also be considered, such as natural waterfalls or springs. In addition specific habitat considerations, the distance between stream crossings can be a useful criterion for assessing the fragmenting effect of barriers. How many miles of stream habitat would be reconnected if a restrictive stream crossing were removed? Longer distances will usually encompass greater habitat complexity and are more likely to function as complete ecological units. Thus, using continuous river miles as a criterion for prioritizing which barriers to remove or restore can be suitable approach if other information is lacking. However, this may not account for rare or endangered species, unique habitats, source populations, and other features with high conservation value.

5.1.3 Species

It may be necessary to compile a species list for reaches upstream and downstream of each crossing and examine the life history, ecology, and conservation value of each species. Table 7 lists potential target species for assessing and restoring continuity in the Ashuelot River watershed. The traits that make these species conservation targets might include:

- Rarity
- Indicator species for target habitats
- Indicator species for watershed connectivity
- Susceptibility to barriers
- Ecosystem role

Fish: More than 40 species of fish exist in the Ashuelot River watershed, though fewer than 20 species exist in the small streams that are most affected by road-stream crossings, and fewer than 10 species in most individual

Table 7. Species that are potential conservation targets in the Ashuelot River watershed.

Species	Justification
Brook Trout	Coldwater species restricted to headwater streams. Dominant vertebrate in many 0-2 order streams. Sensitive to disturbance and fragmentation, especially changes in flow regime, thermal regime, and non-native species. Target of habitat protection and restoration programs throughout the Northeast. Host for eastern pearlshells. Recreationally valuable.
Atlantic Salmon	Coldwater species whose juveniles are restricted to small streams. Sensitive to disturbance and fragmentation, especially changes in flow regime, thermal regime, and non-native species. Diadromous species that needs downstream passage to Ashuelot mainstem and the Connecticut River; upstream passage for adults should be a long-term goal but is contingent on successful restoration of Connecticut River spawning stocks. For now, Ashuelot populations exist because of stocking. Target of habitat protection and restoration programs throughout the Northeast. Juveniles are hosts for eastern pearlshell, dwarf wedgemussel, and creeper. Recreationally valuable.
Fallfish	One of the more common and widespread species in small to large northeastern rivers, often comprising a significant proportion of total biomass. One of the largest native resident predators in small rivers. Mound-building behavior influences instream habitat for other species and makes spawning easy to observe and measure. Overwinter in larger streams and deeper portions of small streams and may migrate into smaller streams for spawning and feeding. River continuity is probably as important for fallfish as it is for brook trout, but fallfish are less athletic and might be more susceptible to barriers. Host for triangle floater and creeper, and possibly other mussels.
White Sucker	One of the more common and widespread species in small to large northeastern rivers, often comprising a significant proportion of total biomass. One of the largest native species in small rivers. One of the few large benthivores in local rivers and probably has an important role in the abundance and distribution of benthic macroinvertebrates and ecosystem processes. Overwinter in larger streams and deeper portions of small streams and may migrate into smaller streams for spawning and feeding. Spawning migrations can be at the scale of reaches and rivers (1000-10000 meters). River continuity is probably as important for white suckers as it is for brook trout, but suckers are less athletic and might be more susceptible to barriers. Host for triangle floater, possibly other mussels.
Blacknose Dace	The second most common and widespread species in small streams in the Northeast behind brook trout. Important forage for large fish, and as a numerically dominant insectivore, likely has an important role in nutrient cycling and stream productivity. Mainly resident, with micro-scale to possibly reach-scale movement, but susceptible to downstream displacement during floods. Limited mobility and poor jumping and swimming ability makes this species slow to recolonize areas after being displaced. Highly susceptible to introduced predators, habitat degradation, and changes in thermal regime. Host for triangle floater, brook floater, creeper, and possibly other mussels.
Longnose Dace	See blacknose dace.
Tessellated Darter	Common in small to large rivers throughout the Connecticut River Valley, often numerically dominant in 3-5 order streams. Small-bodied benthic species that provides forage for larger species. Typically displays only micro-scale movement but individual movement of more than 500m has been reported in the literature. Morphology and benthic existence probably makes them less vulnerable to downstream displacement during floods than other water column species, but darters have extremely poor jumping and swimming abilities (especially with regard to instream barriers) and are likely slow to recolonize areas after being displaced. Primary host for the federally endangered dwarf wedgemussel, boosting the conservation value of this species.
Slimy Sculpin	Somewhat common in small coldwater streams, often sharing habitat with only brook trout and two-lined salamanders in headwater reaches. Sculpins are morphologically, behaviorally, and ecologically similar to tessellated darters but are more small-stream and coldwater specialists. Typically displays only micro-scale movement but individual movement of more than 200 m has been reported in the literature. Like darters, sculpins are slow to recolonize after being displaced because of their sedentary nature and poor jumping and swimming ability. Host for at least 4 important mussels: triangle floater, brook floater, dwarf wedgemussel, and creeper.
Dwarf Wedgemussel	Federally endangered freshwater mussel whose stronghold is the upper Connecticut River and a few of its principal tributaries. The Ashuelot River supports one of the largest known populations, particularly the reach between West Swanzey and Surry, as well as lower portions of the South Branch. Because of its habitat in the Ashuelot River (larger, low-gradient systems), it is unlikely to be as strongly affected by culverts as other small-stream species. Nevertheless, maintenance of stream continuity for native fish assemblages and maintenance of water quality and habitat quality are imperative for dwarf wedgemussels.
Mussel Assemblages	Eight species of freshwater mussels occur in the Ashuelot River watershed, occupying most of the large permanent waterbodies. Freshwater mussel assemblages should be conservation targets because mussels are long-lived (some more than 75 years), relatively sedentary, sensitive to water quality and habitat disturbance, and reliant on fish to reproduce and disperse. Mussels are excellent monitors of ecosystem health.
Spring Salamander Two-lined salamander	Confined to permanent or ephemeral headwater streams, particularly high-gradient reaches with coarse substrate and bedrock exposure, especially where fish are not present. Two-lined salamanders are more tolerant of fish presence than spring salamanders, often being co-dominant with brook trout in high-gradient coldwater streams. Culverts could be physical or behavioral challenges. Both species are sensitive to sedimentation, which is often associated with poorly sited and poorly designed road-stream crossings. The main reason that these species should be considered conservation targets is because of their reliance on tiny headwater streams that often receive the least protection, and their sensitivity to disturbance.
Wood Turtle	Found throughout the Ashuelot River watershed. Associated with streams and rivers but use upland areas within 300 m of the stream. Daily and seasonal migration between streams and upland foraging and breeding areas are essential for wood turtle populations. The greatest effects of road-stream crossings are culverts that are physical or behavioral barriers to wood turtle movement, fragmentation of migration routes, and potential vehicle mortality (especially if turtles are forced to cross roads rather than walk/swim along streams).

Table 8. Habitat and host fish of freshwater mussels that occur in the Ashuelot River watershed.

Species	General Habitat	Ashuelot Watershed	Host Species
Eastern Pearlshell *Margaritifera margaritifera*	Small rivers and streams	Small trout streams; uncommon	Atlantic salmon, brook trout, brown trout
Triangle Floater *Alasmidonta undulata*	Small streams to large rivers	Ashuelot mainstem and South Branch; common	Common shiner, blacknose dace, longnose dace, pumpkinseed sunfish, fallfish, slimy sculpin, white sucker
Brook Floater *Alasmidonta varicosa*	Small rivers and streams	Not in Ashuelot; present in Sugar River (NH) and West River (VT)	Longnose dace, blacknose dace, golden shiner, pumpkinseed sunfish, slimy sculpin, yellow perch
Dwarf Wedgemussel *Alasmidonta heterodon*	Small to large rivers	Ashuelot mainstem (West Swanzey to Surry Dam) and South Branch; rare	Tesselated darter, slimy sculpin, Atlantic salmon
Creeper *Strophitus undulatus*	Small streams to large rivers	Ashuelot mainstem and South Branch; fairly common	Creek chub, longnose dace, fallfish, golden shiner, common shiner, yellow perch, slimy sculpin, Atlantic salmon, largemouth bass
Eastern Floater *Pyganodon cataracta*	Small streams to large rivers and lakes	Ashuelot mainstem, South Branch, and ponds; fairly common	Generalist: Warmwater species
Alewife Floater *Anodonta implicata*	Small to large rivers and lakes	Introduced to mainstem Ashuelot; uncommon	American shad, alewife, blueback herring
Eastern Elliptio *Elliptio complanata*	Small streams to large rivers and lakes	Most permanent waterbodies; abundant	Generalist
Eastern Lampmussel *Lampsilis radiata*	Small to large rivers and lakes	Ashuelot mainstem and South Branch; common	Generalist: Warmwater species

streams. Thus, species that are clearly conservation targets for the watershed as a whole—such as American shad—might not factor into a road-stream crossings assessment because American shad do not enter 0-4 order streams. In terms of barrier assessments and connectivity, the focus should be on native fish species that are challenged by barriers and whose populations are vulnerable to migration barriers. The best candidates are brook trout, Atlantic salmon, white sucker, fallfish, blacknose dace, longnose dace, slimy sculpin, and tessellated darter. Table 7 provides justification for these species to be considered conservation targets.

Invertebrates: The dwarf wedgemussel is clearly a watershed-wide conservation target, being the only federally endangered aquatic species in the watershed. But the species is naturally confined to large, low-gradient portions of the mainstem Ashuelot River and the south branch of the Ashuelot River (Nedeau 2003). The primary host fish for the dwarf wedgemussel, the tessellated darter, occupies a greater range of habitats, including small streams. Thus, culvert removal is likely to have only a slight indirect positive effect on dwarf wedgemussels by promoting the long-term persistence of tessellated darter populations in small headwater refugia.

Seven other freshwater mussel species occur in the Ashuelot River watershed, one of which—the alewife floater—was accidentally introduced as part of New Hampshire Fish and Game's shad stocking program (Nedeau 2004). Though none of the species are state-listed in New Hampshire, several species are state-listed elsewhere in New England, making the Ashuelot's populations regionally important. These species include the triangle floater, creeper, and eastern pearlshell. The eastern lampmussel is common in the upper Connecticut River but is conspicuously scarce or absent in the Massachusetts portion of the river (personal observation). The Ashuelot River supports large populations of eastern lampmussels and could provide a source of colonizers for the lower Connecticut River.

Regardless of rarity, freshwater mussels play an important role in nutrient cycling and ecosystem function and thus should be a conservation target in streams that can support mussels. Given the unique relationship between freshwater mussels and fish, any projects that seek to restore native fish assemblages should also benefit mussels. Table 8 lists habitats and likely host fish for freshwater mussels that occur in (or near) the Ashuelot River watershed.

Other Species: Stream salamanders (particularly spring salamanders and two-lined salamanders) should be conservation targets in 0-1 order, high-gradient headwater streams. Few studies have documented the effect of barriers on these species, or their ability to ascend barriers, but Lowe (2003, 2005) documented the importance of reach-scale movement for the spring salamander in New Hampshire. It seems logical that perched crossings and pipe culverts would inhibit movement of these species. Sedimentation is considered a threat to spring salamander populations (Lowe et al. 2004) by increasing embeddedness. Poorly sited or undersized stream crossings that cause bank erosion, or are susceptible to flood-related damage, may threaten salamander populations. Wood turtles, found throughout the Ashuelot River watershed, also rely on streams and rivers and migrate along watercourses and into riparian areas. Wood turtles are a species of conservation concern throughout the Northeast.

5.2 COMPREHENSIVE ECOLOGICAL ASSESSMENT

A comprehensive assessment should consider three levels of conservation targets: landscape, habitat, and species. For example, the more than 1000 road-stream crossings in the Ashuelot River watershed could be evaluated in the context of these three categories. The exercise could be as simple as having a list of parameters and a system to score and rank stream crossings according to their ecological impact. Specific restoration objectives would dictate the list of parameters and the scoring process, perhaps weighing certain parameters more heavily than others (e.g., endangered species habitat vs. distance to conservation lands). Table 9 provides a list of potential variables for use in the Ashuelot River watershed.

There are two obvious benefits of this exercise: to focus only on the conservation targets that are most affected by road-stream crossings, and to narrow the list of all road-stream crossings to a short list: the worst of the worst. Since restoration dollars are limited, and a single culvert upgrade or replacement can cost tens of thousands of dollars, this exercise is extremely valuable.

A parallel effort could rank road-stream crossings according to engineering specifications and physical measurements, and provide a “worst of the worst” list comprised of crossings that are severely perched, grossly undersized, or fail during floods. Upgrading or replacing these structures might meet economic objectives and restore physical habitat, but may do little to further the ecological goals that the Ashuelot River Continuity Project is based on. It would be instructive to compare scores/ranks derived from ecological vs. physical ranking processes to see how congruent they are. A reasonable compromise between physical measurements and ecological concerns would be to target those stream crossings that rank high in both categories.

The field of barrier assessments and watershed continuity is replete with analogies to humankind’s transportation infrastructure, and here is one to close on: a tree that falls across a dead-end road causes fewer problems than a tree that falls across a busy highway. Determine where a road originates, where it leads, and who is driving on it before deciding what downed trees to remove first.

Table 9. Landscape/watershed, habitat, and species variables that might be used to assess the ecological effects of road-stream crossings.

Variable	Note
Landscape/Watershed	
Elevation	
Stream Order	Using Strahler method of stream order classification
Link Number	Number of 1st order source streams upstream from the site
C-Link	Number of confluences downstream along a direct path to the mainstem
D-Link	Magnitude of the link number of the channel below the next downstream confluence
Upstream Watershed Area	
Distance to Ashuelot Mainstem	
Distance from Headwater Source	Distance (by stream) to furthest point in the upstream stream network
Fragmentation Index	Number barriers along distance to mainstem + distance from source
Unimpeded Reach Length	Distance to next upstream barrier + distance to next downstream barrier
Distance to Target Lands	Distance (by stream) to protected lands and other important habitat areas
Target Corridor	Is the road-stream crossing in a target stream corridor?
Human Development in Watershed	Some sort of index of development, such as roads or buildings per square mile
Percent Agriculture in Watershed	
Percent Forest in Watershed	
Percent Wetlands in Watershed	
Habitat	
Natural waterfalls	Presence, distance to, and number of other barriers in between
Springs and Seeps	Presence, distance to, and number of other barriers in between
Riparian Wetlands	Presence, distance to, and number of other barriers in between
Floodplain Forests	Presence, distance to, and number of other barriers in between
Coldwater Habitats	Presence, distance to, and number of other barriers in between
Natural Ponds	Presence, distance to, and number of other barriers in between
Deep Pools	Presence, distance to, and number of other barriers in between
Upstream Mesohabitat Diversity	Pools, riffles, runs
Downstream Mesohabitat Diversity	Pools, riffles, runs
Bank Condition	Some sort of measure/index of bank condition (stability)
Riparian Condition	Some sort of measure/index of riparian condition
Substrate	Dominant substrate upstream and downstream (e.g., sand, gravel, boulder)
Species	
Brook trout	Presence, abundance, habitat suitability
Atlantic salmon	Presence, abundance, habitat suitability
Fallfish	Presence, abundance, habitat suitability
White sucker	Presence, abundance, habitat suitability
Blacknose dace	Presence, abundance, habitat suitability
Longnose dace	Presence, abundance, habitat suitability
Tessellated Darter	Presence, abundance, habitat suitability
Slimy Sculpin	Presence, abundance, habitat suitability
Dwarf Wedgemussel	Presence, abundance, habitat suitability
Mussel Assemblages	Presence, abundance, habitat suitability
Spring Salamander	Presence, abundance, habitat suitability
Two-lined Salamander	Presence, abundance, habitat suitability
Wood Turtle	Presence, abundance, habitat suitability
Invasive Species	Presence, abundance, habitat suitability
Unique Assemblages	Such as headwater, coldwater, springs, etc.

APPENDIX 1

Movement and Ecology Information

The following is an informal synopsis of pertinent movement and ecology data for some common stream fish of the Northeast. The literature review was not exhaustive, but nevertheless provided enough information to broadly characterize species and species groups (along with expert opinion provided by regional scientists). Additional information was found in Werner (2004) but is not included here. Collectively, these sources provided information to group species, develop performance thresholds, characterize key species traits, and understand ecological effects of barriers.

Trout and Salmon (Family Salmonidae)

Schmetterling and Adams (2004)
Brook trout displayed average movement of 34m (range: 18-1248) during 24-July to 16-August in a small stream in Montana.

Adams et al. (2000)
Brook trout exhibited considerably more upstream movement in high-gradient streams than expected, including 1.2m high falls. Upstream movement through steep channels was dominated by larger trout, whereas immigration into high-gradient reaches by small fish was uncommon.

Gowan and Fausch (1996)
Used mark-recapture techniques to determine movement of brook trout in high elevation mountain streams. Fish moved upstream more during the summer, and moved equally upstream and downstream between summers. Two main triggers for movement included elevated flow and onset of the reproductive season, but a large proportion of fish also exhibited large-scale movement during the summer. Surprisingly large number of individuals moved more than 2000 m. and greatest recorded movement was 3380 m. Authors point out that traditional methods of studying movement are biased and that movement is greater than previously thought.

Gowan and Fausch (2002)
Brook trout moved during the summer to monitor habitat conditions at a large spatial scale (100s of meters) and to maximize foraging locations.

Belford and Gould (1989)
Studied ability of four trout species to swim through six culverts ranging from 4593 m in length with varying slopes and water velocities. Using rainbow trout to represent all species, they indicated that "fish could swim distances of 10, 30, 50, 70, and 90 m with mean bottom velocities of up to 0.96, 0.80, 0.74, 0.70, and 0.67 m/s, respectively."

Kondratieff and Myrick (2006)
Quote: "10–15-cm brook trout could jump a 63.5-cm-high waterfall, equivalent to 4.7 times their body length, from a 50-cm-deep plunge pool, which was 3.7 times their body length. Larger size-classes were capable of jumping 73.5-cm waterfalls, or 2.9–4.0 times their body length, provided the plunge pools were at least 40 cm deep (1.6 times their body lengths). Shallow plunge pools (10 cm) prevented brook trout from all size-classes from jumping waterfalls 43.5 cm or more in height. Small fish were capable of jumping a greater number of body lengths over vertical obstacles than large fish. The data analyses identified vertical height, plunge pool depth, fish total length, and fish condition as factors important in predicting brook trout jumping performance."

Brandt et al. (2005)
Measured jumping performance of age-0 brook trout as a function of waterfall height, plunge pool depth, waterfall width, and light intensity. Fish were 44-104 mm long. Generally, fewer than 20% of the fish ascended waterfalls greater than 18 cm no matter the plunge pool depth. Brook trout had less success ascending narrow waterfalls. Light intensity had little success on jumping performance. Concluded that "narrow waterfalls with heights more than three body lengths and shallow plunge pools will probably restrict the movement of age-0 brook trout."

Erman and Hawthorne (1976)
Documented importance of intermittent streams for spawning rainbow trout. 39-47% of adult rainbow trout from a permanent stream (California) migrated into an intermittent stream and only 10-15% of the spawning run moved into permamently flowing tributaries. Early peak discharge and absence of competition from brook trout (that, being fall spawners, cannot spawn in the stream because it is dry during their spawning period) likely made the intermittent stream favorable for rainbow trout. The stream usually runs dry by late July to September, and it is interesting that this relatively short hydroperiod can support trout reproduction in most years.

Peake et al. (1997)
Provided models to estimate swimming speed of fish for a given fork length, temperature, and time period. For different water velocities, one can determine the distance the fish can swim at a given swimming speed and time period. For example, a 7 cm brook trout could maintain a speed of 0.41 m/s for 5 minutes. To traverse a 30 m culvert in 5 minutes, water velocity could not exceed 0.31 m/s. In contrast, a 20 cm brook trout could swim over 200 m in 5 minutes against a water velocity of 0.311 m/s, and to traverse a 30 m culvert, water velocity could be 0.9 m/s. It is instructive to plug the equations into a spreadsheet and try different combinations of fish length, swimming time, and water velocity.

Minnows (Family Cyprinidae)

Hill and Grossman (1987)
Determined that the home range of blacknose dace was 12.9 m and the highest recorded movement was 40 m.

Mullen and Burton (1995)
Studied habitat use of adult and juvenile longnose dace in a Michigan stream to look for size-related habitat segregation. They were segregated by water velocity and substrate type – adults used areas of faster current and boulder substrate more than juveniles, although both adults and juveniles preferred similar habitat types within the riffle at large. But adults were more selective than juveniles.

Ross and Reed (1978)
Fallfish built nests and spawned from April to June, when water temps were above 15C. Fish spawned in riffle/run habitats with gravel substrates, in water at least 0.5m deep. Presumably fish congregated in these areas prior to spawning, though the study did not examine spawning movement.

Holthe et al (1995)
Tested jumping ability of the European minnow (Phoxinus) at different water temperatures to find ways to exclude them from brown trout waters. At cold temperatures (4.8-6.5C), no minnows were able to jump even a 3cm barrier. They could not induce them to jump. At warm temperatures (14-16.5C), minnows could jump up to 27cm. According to their analysis, there was only a 0.04% chance that minnows could pass waterfall barriers greater than 35cm. Larger minnows could jump highest.

Adams et al. (2000)
Studied swimming endurance and behavior of Topeka shiners (Notropis topeka) in the laboratory. Shiners could exhibited sustained swimming at water velocities of 30-40 cm/s. At water velocities from 40-75 cm/s. they exhibited prolonged and burst swimming and could swim for 10 min to less than six seconds before tiring. Swim speed and endurance increased with fish size. Authors felt that culvert water velocities less than 35 cm/s could be an indefinite length because fish could swim at this velocity without tiring, but culvert velocities near 60 cm/s would have to be very short (less than 2-3 meters) or need to have velocity refuges to be passable.

Miller (1964)
Cyprinids moved out of small and headwater streams as winter approached and overwintered in larger rivers. Fish that remain tend to be smaller adults or juveniles. Those remaining in smaller systems sought out backwaters, deeper pools, or other places with shelter from the currents. The proportion of resident vs migrant minnows depended in part on the severity of the winter. More fish stayed during mild winters and there was a corresponding weak spring migration. During harsh or wet winters, more fish moved downstream and there was a stronger spring migration back to spawning areas. This paper covered spawning behavior of several stream cyprinids in New York.

Sculpins (Family Cottidae)

McCleave (1964)
Home range of mottled sculpin estimated to be less than 150 ft in a small Montana stream from 4-August to 10-March. Upstream movement was almost 24% greater than downstream movement, movement was somewhat arbitrary (no mass movement), and homing was not exhibited. Greatest distances moved were 590 ft upstream and 502 ft downstream.

Greenberg and Holtzman (1987)
Maximum home range of banded sculpin estimated at 47 m^2.

Hill and Grossman (1987)
Home range of mottled sculpin estimated at 12.9m. The greatest recorded movement was 54.8 m.

Brown and Downhower (1982)
Mottled sculpin moved less than 15m and suggest that in June and July, movement is short and haphazard.

Schmetterling and Adams (2004)
Slimy sculpin moved an average of 18m (range: 16-209) in a small Montana stream during late summer. Estimated that 14% of the population was active, mostly during night or twilight and more often downstream than upstream.

Bass and Sunfish (Family Centrarchidae)

Gerking (1953)
Longear sunfish exhibited home range in a small bedrock stream generally less than 200 ft, fish stayed in pools and rarely crossed long riffle sections. Most spawned May to June (Indiana). Rock bass generally moved less than 200 ft, fish stayed in pools and rarely crossed long riffle sections, and spawned in early spring. Home range of smallmouth bass generally about twice that of sunfish and rock bass. Larger fish roamed more often. Spawning period: May to July

Lukas and Orth (1993)
Stream-spawning redbreast sunfish began spawning in late May when water temperatures exceeded 20 C. Fish generally spawned in pools in depths greater than 0.5m (mean: 1.08 m) and water velocities <0.15 m/s (mean: 0.04 m/s).

Peake (2004)
Determined U_{crit} of 65-98 cm/s for smallmouth bass in a respirometer, which translated into maximum allowable water velocities of 54-63 cm/s for the fish to ascend a 50-m raceway. Yet in a volitional swim test, 82-95% of all individuals were able to make complete ascents of the raceway against water velocities of 40-120 cm/s. Neither water velocity, fish length, water temperature, exposure time, nor time in captivity significantly affected the probability of successful ascent. Based on this research, Peake recommended that U_{crit} should not be used to set water velocity criteria for smallmouth bass.

Bunt et al. (1999)
Compared two Denil fishways with different velocities/slopes for attraction and passage efficiency of smallmouth bass (and suckers). Attraction and passage efficiency through the low velocity fishway was 82% and 36%, respectively. Attraction and passage efficiency through the high velocity fishway was 55% and 33%, respectively. Maximum water velocity used by bass was 0.99 m/s, very comparable to white suckers. Sample sizes were quite low, so results were not statistically robust. I was most impressed that suckers and bass had similar passage efficiency.

Perch and Darters (Family Percidae)

Matthews (1985)
Determined that Etheostoma flabellare could hold position at 24 cm/sec, juveniles 16.2 cm/sec. This was holding position only, not swimming. Defined critical current speed as the maximum velocity at which benthic fish can remain stationary without active swimming.

Toepfer et al. (1999)
From review: Percina pantherina spawn in areas with current velocities as high as 50 cm/sec, in swifter currents they can move short distances along the substrate but are generally washed downstream. From experiment: Fish more active at higher velocities 25-42cm/sec, though burst distance and total distance was lower at 42 and 60 cm/s than at 25 cm/s. Maximum burst distance at 25 cm/sec was 90cm, though successive bursts were shorter.

Suckers (Family Catostomidae)

Curry and Spacie (1984)
[Illinois] White suckers spawn in shallow riffles in upper reaches of tributaries, over gravel substrate. Spawning occurred when water temps stayed at or above 10C. Both white suckers and creek chubsuckers were more characteristic of headwater streams. Creek chubsuckers spawned in same areas as white suckers, but a bit later in the season and in deeper water with slower water velocity.

Page and Johnston (1990)
Provide good general description of sucker reproduction. Most stream-spawning suckers swim upstream to spawn, usually in the spring over rubble and gravel substrates in shallow fast-moving water. Suckers often have distinct spawning areas – males aggregate first and females come later. Distinct spawning habitat preference does have implications for stream-crossing assessments, particularly if spawning areas are isolated and potentially blocked by impassable barriers.

Bunt et al. (1999)
Compared two Denil fishways with different velocities/slopes for attraction and passage efficiency of white suckers (and smallmouth bass). Attraction and passage efficiency through the low velocity fishway was 50% and 55%, respectively. Attraction and passage efficiency through the high velocity fishway was 59% and 38%, respectively. Maximum water velocity used by bass was 0.96 m/s, very comparable to bass. Sample sizes were quite low, so results were not statistically robust. I was most impressed that suckers and bass had similar passage efficiency.

Crayfish

Hazlett et al. (1974)
Used mark-recapture techniques to monitor movement of Orconectes virilis. Home range ranged from 0-308m, and average movement between captures was 33m. Larger females moved more than smaller ones, and data suggested that while most crayfish do not move, the ones that do actually move may move quite far. One male moved 292m upstream in just two days.

APPENDIX 2

Expert Opinion

Because there is little published information on the athleticism or ecology of northeastern stream fauna, I attempted to get expert opinion from regional fish biologists. Using an Excel-based survey, I asked biologists to provide numeric categorical scores for the spatial extent and seasonality of movement, jumping ability, swimming ability, and depth limitation. Scores were provided for all species (adults and juveniles) and for species groups. I received only a small number of completed surveys and the table on the facing page provides average values.

I found it difficult to get experts to offer their opinions. It

Likelihood of Movement

Spatially: To what extent would you expect them to move within a river or watershed?

Micro	Small-scale movement within microhabitats, generally less than 50m
Meso	Movement among mesohabitats, perhaps 50 to 1000m
River	Movement among mesohabitats and reaches along a river, perhaps 1000 to over 10000m
Watershed	Long-distance migration throughout watersheds, from large rivers into small tributaries and back

Seasonally: When are these species or groups most likely to move? (for spawning, feeding, migration, and other habitat needs)

Spring	April to June
Summer	July to September
Fall	October to December
Winter	January to March

Ranks (likelihood)

0	None
1	Low
2	Moderate
3	Moderate/high
4	High

Confidence: Please rank, from 1-10, how confident you are in the rankings you provided for each species or group of species.

Jumping Ability

Is the species or group capable of ascending waterfalls, and to what extent?

Ranks

0	Severely vertically challenged. 7 cm drop would be a barrier under most conditions
1	Vertically challenged. 15 cm drop would be a barrier under most conditions
2	Moderate jumping ability. Can ascend drops of up to 30 cm
3	Good leaping ability. Can ascend drops of up to 60 cm
4	Exclent leaping ability; can ascend drops of greater than 100 cm under ideal conditions

Swimming Speed

How fast can the species or group swim? (maximum swimming speed)

Ranks

0	Extremely slow
1	Slow
2	Moderate
3	Fast
4	Extremely fast

Depth Limitation

To what extent is the species jumping or swimming ability limited by water depth, due to factors such as body shape or how they propel themselves through the water?

Ranks

0	Severe
1	Strong
2	Moderate
3	Slight
4	None

Confidence: Please rank, from 1-10, how confident you are in the rankings you provided for each species or group of species.

Appendix Table 1. Average ranks (expert opinion) for movement and athleticism of of 9 groups of stream fish which were grouped according to taxonomic affinity and biology. More information on groups, movement, and athleticism is presented in Chapter 3 and Chapter 4.

		Likelihood of Movement										
Group	Stage	Micro	Meso	River	Watershed	Spring	Summer	Fall	Winter	Jumping Ability	Swimming Speed	Depth Limitation
Trout and Salmon	Adults	4.00	3.83	3.35	3.02	2.77	2.17	3.71	1.52	3.38	3.56	1.75
	Juveniles	4.00	3.19	1.77	0.88	1.96	1.69	2.63	1.25	2.23	2.65	1.50
Large Minnows and Suckers	Adults	4.00	3.94	3.28	1.56	3.56	2.17	2.17	1.06	2.03	2.83	2.44
	Juveniles	3.89	2.72	1.28	0.39	1.39	1.78	1.89	1.06	1.17	1.64	3.50
Small Minnows	Adults	4.00	2.44	0.96	0.41	2.00	1.89	1.67	1.00	1.19	1.78	3.04
	Juveniles	4.00	1.41	0.67	0.33	1.78	1.59	1.74	0.96	0.74	1.11	4.00
Benthic Non-Minnows	Adults	3.67	1.92	0.83	0.67	1.92	1.58	1.67	1.50	0.42	1.00	3.58
	Juveniles	3.67	1.33	0.67	0.67	1.50	1.50	1.67	1.42	0.33	0.50	4.00
Bass, Pickerel, and Perch	Adults	4.00	3.47	2.33	1.07	3.60	2.40	2.67	0.87	2.20	3.37	1.73
	Juveniles	4.00	2.87	1.33	0.40	1.80	1.93	2.00	1.13	1.20	1.73	3.07
Sunfishes	Adults	4.00	3.00	2.00	0.67	3.00	2.67	2.00	0.67	1.00	2.00	1.00
	Juveniles	4.00	2.00	1.00	0.33	1.67	1.67	1.33	1.00	0.67	1.00	3.00
Catfishes	Adults	4.00	3.33	2.17	0.67	3.00	2.00	2.00	1.00	1.00	1.33	3.00
	Juveniles	4.00	2.33	1.00	0.33	1.67	1.67	1.67	0.67	0.67	0.67	4.00
Eels and Lampreys	Adults	4.00	4.00	4.00	4.00	3.00	2.67	3.67	1.00	1.33	2.00	4.00
	Juveniles	3.67	3.67	3.67	3.67	3.67	1.67	1.33	0.67	0.33	0.83	4.00
Alewife	Adults	4.00	4.00	4.00	4.00	4.00	1.33	2.00	0.67	1.67	3.33	1.67
	Juveniles	3.67	3.00	3.00	2.67	1.00	2.00	3.33	0.67	1.00	2.33	2.67

may have been unclear to the experts how this information was going to be used, thus they may have been reluctant to provide answers that could possibly be misconstrued or taken out of context. My survey could have been too simplistic, which could be frustrating for scientists who are familar with the enormous complexity of these issues. My survey could have been time consuming to complete, since I was hoping for information on all northeastern stream fish. Finally, scientists who are accustomed to looking to published literature for answers may feel uncomfortable making educated guesses. There is simply not much information on the ecology and movement of northeastern stream fish, and the importance of barriers for species like blacknose dace, slimy sculpins, or tessellated darters is anybody's guess.

I found that state biologists were more open to sharing information and ideas and providing "educated guesses" than academic research scientists. It will remain a challenge to get the academic and management people to work together to provide effective short-term solutions to the complex problem of barriers assessments. I think a conservative approach will circumvent this difficulty, since we can all agree that culverts are bad and the best solution is to closely approximate a natural stream channel.

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