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Evaluation of a Predictive Model for Upstream Fish Passage Through Culverts

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Abstract

Fish diversity in the United States has been declining because of pollution, invasive species, and continual habitat degradation and fragmentation. Recent studies have shown that culverts at road crossings can fragment habitat by acting as barriers to the upstream movement of fishes. This prevents essential spawning migrations and inhibits recolonization of streams after natural or anthropogenic disturbances. With over 50,000 road crossings on eastern National Forest lands, these crossings can represent a serious threat to the viability of native fish fauna. Currently, there are few predictive models or software available that address fish passage through culverts, and those models have not been validated with field experiments. I developed 3 models for fishes common to the Mid-Atlantic Highlands region of the United States that predict whether a culvert is impassable or passable to upstream fish movement based on physical culvert characteristics. I validated these models using a mark-recapture movement study at 26 road-stream crossings on national forest lands in Virginia and West Virginia during the summer and fall of 2004. Culverts, regardless of model classification, appeared to impede upstream movement by stream fish. Fish movement through culverts classified as impassable was lower than movement through the natural stream for Salmonids during the summer and fall and for some Cyprinids during the fall. Movement by species from the families of Salmonidae, Cyprinidae, Percidae, and Cottidae through passable culverts (76 events) occurred 5 times as often as movement through impassable culverts (16 events). Fish movement through culverts was negatively correlated with the culvert characteristics of slope, slope x length, and velocity for cyprinids. Road crossings with outlet drops < 10 cm, slope < 2.0%, and slope x length values < 25 experienced the

greatest movement illustrating the importance of those culvert characteristics in determining fish passage. The models were modified based on the results of the field experiment to increase their accuracy. The final predictive models from this study can be an effective tool for assessing fish passage through culverts and aid natural resource managers in prioritizing and implementing fish passage projects.

Introduction

Fish diversity in the United States has been declining because of pollution, invasive species, habitat degradation, and fragmentation. Fragmentation and habitat degradation from road construction is one of the most widespread anthropogenic modifications to the natural environment in the past century (Trombulak and Frissell 2000). The presence of road-stream crossings can reduce fish abundance (Whitney and Bailey 1959; Rajput 2003) and species diversity (Barton 1977) of lotic systems.

Roads change the physical environment of adjacent streams by altering the runoff pattern, increasing sedimentation, and raising the water temperature (Jones et al. 2000; Trombulak and Frissell 2000). These changes in stream hydrology are not always immediately realized, because of the infrequent nature of floods associated with small-forested watersheds (Trombulak and Frissell 2000). Changes in stream geomorphology from roads can be a determining factor in the decline of stream biota (Resh et al. 1988). Many of these changes to channel morphology (i.e. increased sedimentation) and lotic fauna can be specifically associated with culverts were roads cross streams (Wellman et al. 2000).

Warren and Pardew (1998) found overall movement of fish through culverts to be an order of magnitude lower than through other crossings types. If changes in the landscape, habitat structure, and flow regime (anthropogenic changes) occur, the construction and existence of culverts as barriers may reduce natural dispersal rates causing local extinctions (Fahrig and Merriam 1994).

Recent studies have shown that culverts at road-stream crossings can fragment habitat acting as barriers to the upstream movement of fish by preventing essential

spawning migrations and inhibiting recolonization of streams after disturbances (Derksen 1980; Utzinger et al. 1998; Warren and Pardew 1998; Trombulak and Frissell 2000) or by genetically isolating populations. Low-water bridges and culverts in forested watersheds of Arkansas impede upstream fish movement and lead to reduced species richness and abundance above road crossings (Rajput 2003). Fish populations may persist despite habitat fragmentation associated with road crossings, but they can be genetically isolated from other populations (Kershner et al. 1997). Fish movement and habitat connectivity in streams play a significant role in the life histories of many fish species (Fausch et al. 2002). Long distance movement of stream fish is common and resident stream fish can be highly mobile with large home ranges (Gowan et al. 1994; Gowan and Fausch 1996; Young 1996; Larson et al. 2002; Albanese et al. 2003; Albanese et al. 2004; Schmetterling and Adams 2004). Over 50,000 road crossings exist on eastern national forest lands (Whalen 2004), and many may represent a serious threat to the viability of native fishes. Thorough evaluation of road crossings for fish passage is an essential step in native species conservation.

Assessments of fish passage at road-stream crossings have frequently focused on anadromous species such as Pacific salmon or have considered the passage needs of only one or two target species and usually on large rivers (Wellen and Kane 1985; McKinnon and Hnytka 1985; Belford and Gould 1989; Bunt et al. 1999). Such studies usually result in specific guidelines and requirements for fish passage (Baker and Votapka 1990; Browning 1990; Gibson et al. 2005). Few studies have evaluated the passage of resident stream fish assemblages (Winter and Van Densen 2001) particularly those of small

headwater streams. This lack of research has lead to a scarcity of efficient, reliable, and validated methods to assess passage at crossings for resident species.

I developed predictive models for upstream fish passage through culverts for species of the families Salmonidae, Cyprinidae, Percidae, and Cottidae common to the eastern United States and validated those models with empirical data from a mark-recapture study of fish movement in the Mid-Atlantic Highlands region of the United States. Based on the results of the field experiments I modified the models where necessary to improve their predictive ability and establish agreement with the fish movement data. Figure 1 outlines the progressive development, validation, and modification of the models. Fisheries managers can use the models to quickly and efficiently evaluate road-stream crossings for fish passage and prioritization of remediation projects.

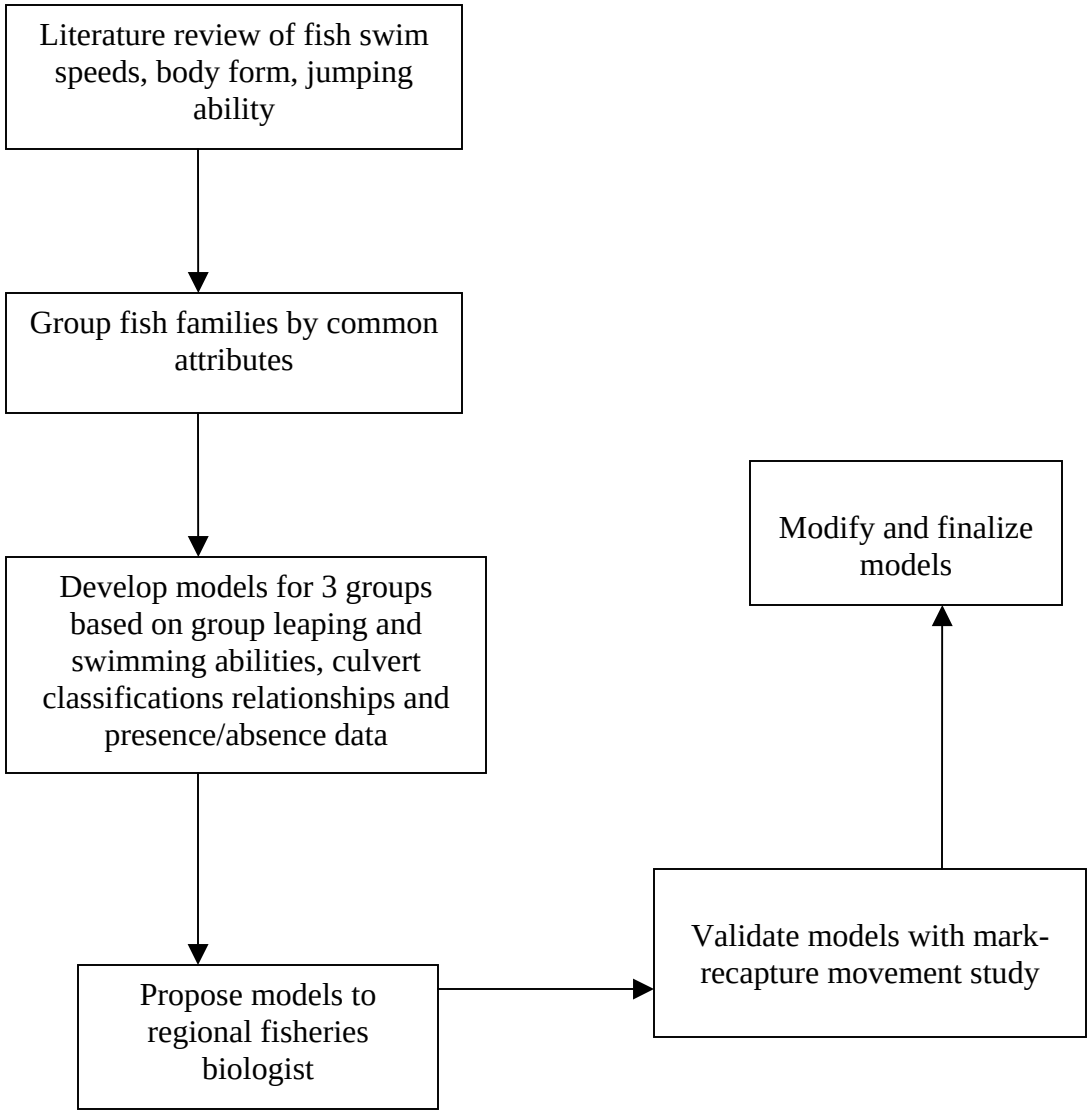


Figure 1. Flow chart detailing steps of the development, validation and modification of upstream fish passage predictive models for species in the families of Salmonidae, Cyprinidae, Percidae, and Cottidae, common to the Mid-Atlantic Highlands of the U.S.

Chapter One: Predictive Model Development

Introduction

The ability of fish to move freely through a stream network can be an important aspect of a species long-term viability (Fausch et al. 2002). Culverts at road-stream crossings can impede or prevent movement. Barriers encountered in the stream by moving fish are often magnified by road stream crossing structures. Culverts can create the following types of barriers: jump, velocity, depth, exhaustion, and behavioral barriers. For example, channel slope (Adams et al. 2000), pipe slope (Gauley 1960; Belford and Gould 1989) and water velocity (Gauley 1967; and Slatick 1971; Belford and Gould 1989) have been shown to affect upstream movement of salmonids. Vertical obstructions to the upstream movement of *Cottus gobio* have been identified as barriers reducing distribution (Utzinger et al. 1998). Behlke et al. (1991) likened a fish swimming through a culvert to a human attempting to walk up a downward moving escalator at different speeds and slopes of the escalator. Culverts that simulate natural stream conditions of velocity, substrate, width, and depth (i.e. stream simulation) are much more suitable to successful fish passage than undersized culverts that constrict flow, alter water depth, substrate and velocity. The lack of stream simulation (alteration of stream flow, water velocity, and substrate compared to the natural channel) at many culvert road crossings is most likely the cause for these barriers (Warren and Pardew 1998). Depending on the characteristics of the culvert and a stream's flow regime none, some, or all of the barriers can be present at any given time.

The ability of fish to pass through road crossings depends on the fish's swimming and leaping ability, and the timing of movement. The available data about fish swimming capacities is often limited to high profile game fish and species of economic

importance. Data about the swimming ability of non-game species often does not exist, and available data for a species can vary depending on the experimental design used to measure swimming ability. There are three accepted levels of fish swimming mode commonly referred to as (1) sustained swimming mode, (2) prolonged swimming mode, and (3) burst swimming mode. Sustained swimming is the speed that a fish can maintain for longer than 200 minutes. Prolonged swimming is the speed that can be maintained between 15 seconds and 200 minutes, and burst swimming is the speed a fish can maintain for up to 15 seconds (Webb 1975; Beamish 1978). Fish attempting to move upstream through a culvert primarily use burst swimming mode to enter and exit the culvert and prolonged swimming mode to move through the culvert.

Along with a fish's swimming ability, characteristics of the road crossing structure are also needed to effectively evaluate a crossing. Incorporating these parameters into a model is one method for evaluating culverts for fish passage. Many state and federal agencies have established predictive models for fish passage. One of the major problems with these models is that they only address one species or one life stage of a species under specific times or flow conditions. These models are adequate for the species of concern but ignore passage needs of other species. Other models (i.e. FishXing; Love et al. 1999) attempt to include assessment of numerous species under a variety of flow conditions but require detailed swimming ability and hydrology data that often are not available, especially for small ungaged headwater streams.

The geographical and data limitations of these models can be confusing and limit the scope and scale at which the models are applicable. The first objective of this study

was to develop a predictive model for upstream fish passage through culverts for a diverse group of fish that could be applied on a large geographical scale.

Methods

I reviewed journal publications, technical reports, and state and federal agency documents for relevant information on swimming behavior, capabilities at different swimming modes (burst, sustained, and prolonged), and at varying flows and depths. Fish families and species were placed in distinct groups based on existing data about fish swimming and leaping ability. Information about species body morphology and swimming mode was also collected. Culvert characteristics associated with jump, velocity, exhaustion, depth, and behavioral barriers were identified. I then developed predictive models for three groups. The models were for fishes commonly found in the Mid-Atlantic Highlands for Salmonidae (trout) (Model A), Cyprinidae (minnows) (Model B), Percidae (darters), and Cottidae (sculpins) (Model C). I based the models on the swimming and leaping ability of fishes in each group, culvert characteristics associated with barriers from a previous study that examined fish species richness and abundance above and below road stream crossings (M. Hudy unpublished data), and best professional judgment.

Results

The information collected (Appendix A) along with common characteristics in body shape, fin morphology and placement, were used to create the following groups of freshwater fish families examined in the study:

- Salmonidae (Group A)
- Cyprinidae, and young-of-year Salmonidae (Group B)

- Percidae (except *Stizostedion sp*., and *Perca flavescens*), and Cottidae (Group C).

The following culvert characteristics (Figure 1.1) were identified as contributing to the creation of barriers to upstream fish movement:

- Outlet drop and outlet perch (jump barrier)
- Culvert slope (velocity barrier)
- Culvert slope x length (exhaustion barrier)
- Presence of natural stream substrate in culvert (depth barrier)
- Relationship of tailwater control elevation to culvert inlet elevation (depth and velocity barrier).

Outlet drop was calculated as the elevation of the culvert outlet minus the elevation of the tailwater control (P_2-P_3). Outlet perch was the elevation of the culvert outlet minus the elevation of the water surface (P_2-H_2O surface). Culvert slope was the gain in elevation of the pipe divided by the length of the pipe and is reported as a percentage. Culvert slope x length was the slope (%) of the culvert times the length of the culvert. The tailwater control's elevation in relation to the elevation of the culvert inlet indicates if the pipe is backwatered or not (P_3>P_1). Predictive models for the three groups appear in Figure 1.2 (Group A), Figure 1.3 (Group B), and Figure 1.4 (Group C).

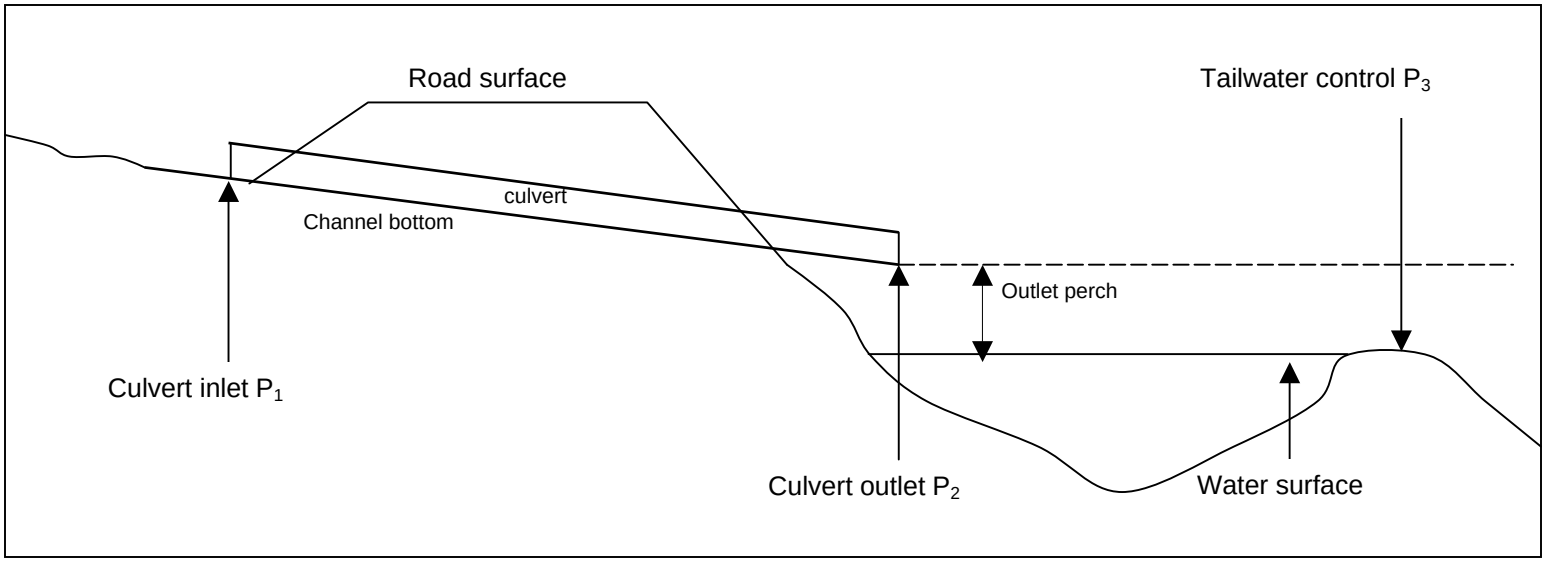


Figure 1.1. Profile of survey points used to calculate culvert characteristics associated with fish movement barriers and used in predictive models for upstream fish passage through culverts. Distance and elevation is measured for each location point designated by P_n and for the water surface. Adapted from Clarkin et al. 2003.

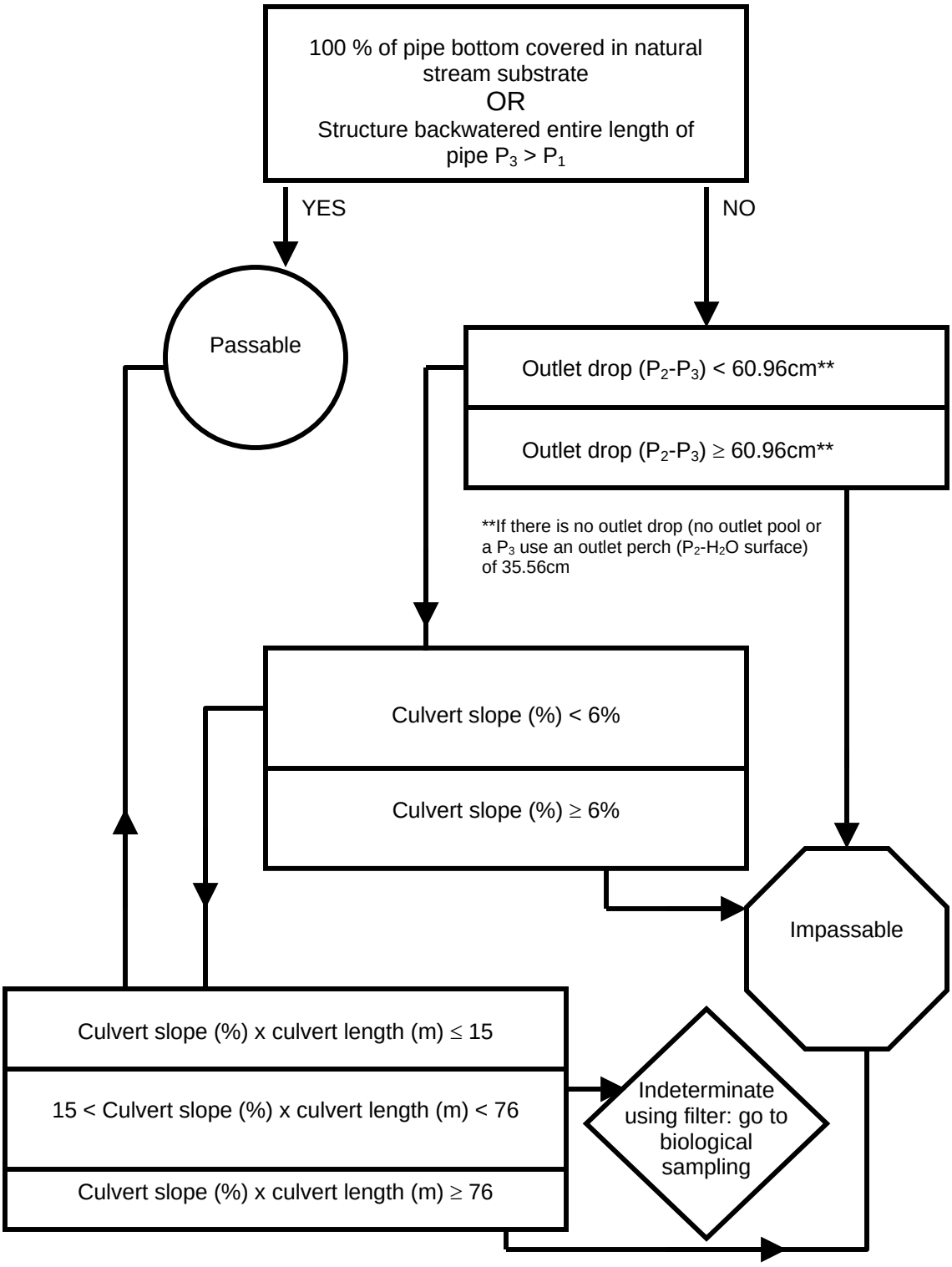


Figure 1.2. Upstream fish passage predictive model A for Salmonidae. See Figure 1.1 for profile of survey points used in fish passage predictive model. P_n = elevation measurements.

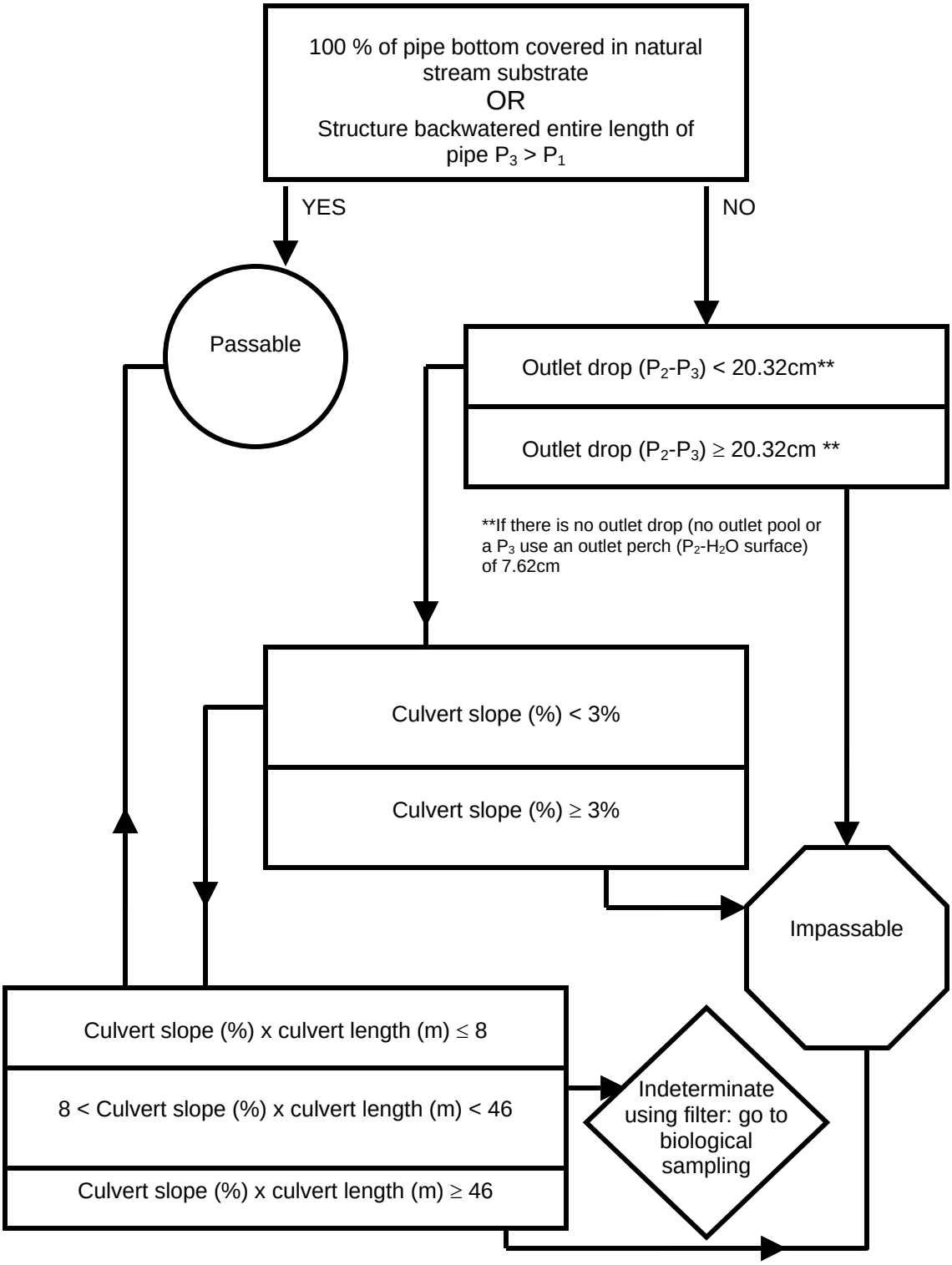


Figure 1.3. Upstream fish passage predictive model B for Cyprinidae and young-of-year Salmonidae. See Figure 1.1 for profile of survey points used in fish passage coarse filter. P_n = elevation measurements.

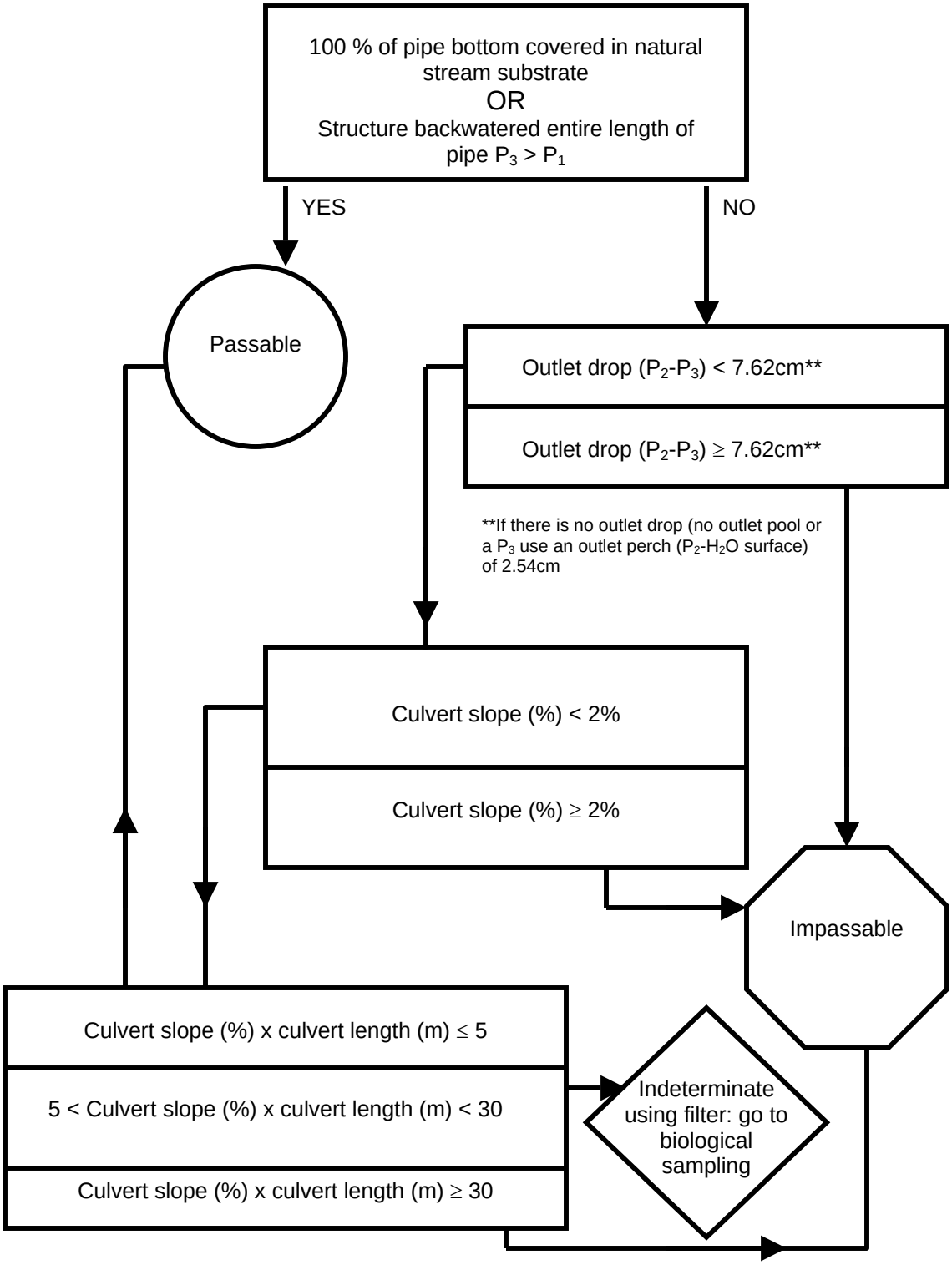


Figure 1.4. Upstream fish passage predictive model C for Percidae (except *Stizostedion sp*., and *Perca flavescens*), and Cottidae families. See Figure 1.1 for profile of survey points used in fish passage coarse filter. P_n = elevation measurements.

Discussion

Using information about fish swimming and leaping ability along with knowledge on barriers to fish movement and hydrodynamics of culverts three models for fish species common to the eastern United States were developed. These models are to be used under base flow conditions, best approximated by 50% exceedance flows if available, to classify culverts as passable (allows upstream fish passage), impassable (blocks upstream fish passage), or indeterminate (passage cannot be determined based on culvert characteristics alone). An indeterminate classification would require additional biological sampling to determine fish passage. The models are designed to address conditions at road-stream crossings in the same order a fish attempting to move upstream would encounter the associated barriers. All three models are in the same format with only the threshold values at each level varying depending on the species the model is designed for. Each step of the model addresses a different type of barrier that could exist.

The first step of the model uses the tailwater control and substrate to assess stream simulation. The elevation of the tailwater control is an important variable in determining fish passage because it can create backwatering (eliminating jump and depth barriers), reduce velocity, and dissipate energy of the water as it exits the pipe by creation of a pool (Baker and Votapka 1990). Natural substrate throughout a culvert is rare except when natural stream conditions are simulated. If the pipe bottom is 100% covered in natural stream substrate or is backwatered, the crossing simulates natural stream conditions and is classified as passable.

If the culvert is not simulating stream conditions the second step in the model assesses jump barriers with outlet drop or outlet perch (Figure 1.1). If the culvert had no

jump barriers, the third step addresses potential velocity barriers associated with culvert slope. The last step assesses exhaustion barriers as measured by slope x length. This step can produce any of the three classifications where the two previous steps can only be passable or impassable.

Conservative threshold values were selected at each step to avoid the error of classifying a culvert as impassable when it is actually passable. Replacing culverts that are barriers to fish passage can be expensive; therefore culverts classified as impassable need to truly be impassable to justify the expense of replacement. Natural resource managers use models to explain or predict occurrences and events in nature often saving time and money. However, models are only as good as the data they are constructed and validated with.

Chapter Two: Field Validation of Predictive Models

Introduction

Fish need to move freely within stream networks to meet critical life history components and resource needs such as (Fausch and Young 1995; Schlosser and Angermeier 1995), accessing suitable spawning habitat (Northcote 1997), avoiding undesirable water quality (Bergstedt and Bergersen 1997), and maintaining population distribution (Schlosser and Angermeier 1995). Large-scale movements over a varying temporal scale can be vital to the long-term persistence of stream fish (Meffe and Sheldon 1990; Schlosser and Angermeier 1995), particularly in headwater streams where dispersal and recolonization can regulate fish community structure (Schlosser 1982). Anadromous fish movement and migration have long been studied and the associated impacts of road crossings and dams as barriers have been a focal point in conservation of anadromous fishes (Moyle 1994; Schmetterling and McEvoy 2000; Muir et al. 2001; Bilkovic et al. 2002; Connor et al. 2003), but little attention has been given to the effect of barriers on movement of resident fish.

Traditional views on resident stream fish movement have held that fish are sedentary with small home ranges (Gerking 1959; Hill and Grossman 1987; Freeman 1995). This restricted movement paradigm was challenged by Gowan et al. (1994), who highlighted the inherent bias in detecting small movements because in many mark-recapture studies, recapture effort was focused at the site of marked fish release. Since that time, movement studies have documented long-distance movement of salmonids (Gowan and Fausch 1996; Schmetterling and Adams 2004), scuplins (*Cottus sp.*) (Natsumeda 1999; Schmetterling and Adams 2004), and cyprinids (Albanese et al. 2003; Albanese et al. 2004).

Riley et al. (1992) suggested mobility and long distance movement of brook trout (*Salvelinus fontinalis*) is an adaptive response to the unstable, heterogeneous nature of headwater streams. Although stream salmonid movement has been well documented (Needham and Cramer 1943; Stefanich 1952; Bjornn and Mallet 1964; Shetter 1968; Bjornn 1971; Flick and Webster 1975; Hilderbrand and Kershner 2000; Adams et al. 2000; Belanger and Rodriguez 2001; Gowan and Fausch 2002; Rodriguez 2002; Peterson and Fausch 2003), relatively little effort has been placed on movement of non-game fishes (Albanese et al. 2004; Hill and Grossman 1987; Goforth and Foltz 1998; Johnston 2000), particularly benthic fish (McCleave 1964; Brown and Downhower 1982; Mundahl and Ingersoll 1983; Greenberg and Holtzman 1987; Downhower et al. 1990; Utzinger et al. 1998; Roberts 2003). These studies have shown non-game fish can be highly mobile, demonstrating exploratory (Smithson and Johnston 1999; Larson et al. 2002) and seasonal movements which can be important for recolonization of stream reaches after local extirpations.

Rapid recolonization after local extirpations can be attributed to the high mobility of some resident fish and the proximity of a source population to the available habitat (Olmsted and Cloutman 1974; Gunning and Berra 1969; Berra and Gunning 1970; Meffe and Sheldon 1990; Peterson and Bayley 1993; Lonzarich et al. 1998; Roghair et al. 2002). This movement, whether it be seasonal or exploratory, is important to the persistence of fish assemblage. Little is known about the effects of fragmentation (i.e. population and habitat) from barriers on fish movement, and species viability. If colonization of available habitat depends on freedom of movement and proximity of

source populations the effects of impassable road-stream crossings could pose a serious threat to species viability.

Gowan et al. (1994) acknowledged that barriers could impede movement and disrupt dispersal patterns. Warren and Pardew (1998) found overall movement of fish through culverts to be an order of magnitude lower than through other crossings types, and Schaefer et al. (2003), found culverts significantly decrease the probability of movement by the threatened leopard darter (*Percina pantherina*) among habitat patches. These studies demonstrated the pervasiveness of road-stream crossing as barriers and the subsequent effects on a variety of fish species. Low-water bridges and culverts in forested watersheds of Arkansas have been shown to impede upstream fish movement and lead to reduced species richness and reduced abundance in some species above road crossings (Rajput 2003). If changes in the landscape, habitat structure, and flow regime (anthropogenic changes) occur, the construction and existence of culverts may restrict natural dispersal rates causing permanent local extinctions (Fahrig and Merriam 1994).

Two methods to determine the impacts of culverts on fish movement have been employed in the past. One is to conduct mark-recapture movement studies and determine movement from empirical data. The other is to use models to determine the passability of culverts or the degree to which culvert impede passage. I validated my predictive model culvert classifications (passable and impassable) in the field with empirical data about the movement of species from the families of Salmonidae, Cyprinidae, Percidae, and Cottidae; specifically comparing the movement of fish through a natural stream reach to the movement through classified culverts.

Study Area

Streams used in the field validation were selected from forested watersheds of the Mid-Atlantic Highlands region of the United States (Figure 2.1) specifically in the George Washington/ Jefferson National Forest of Virginia and the Monongahela National Forest of West Virginia.

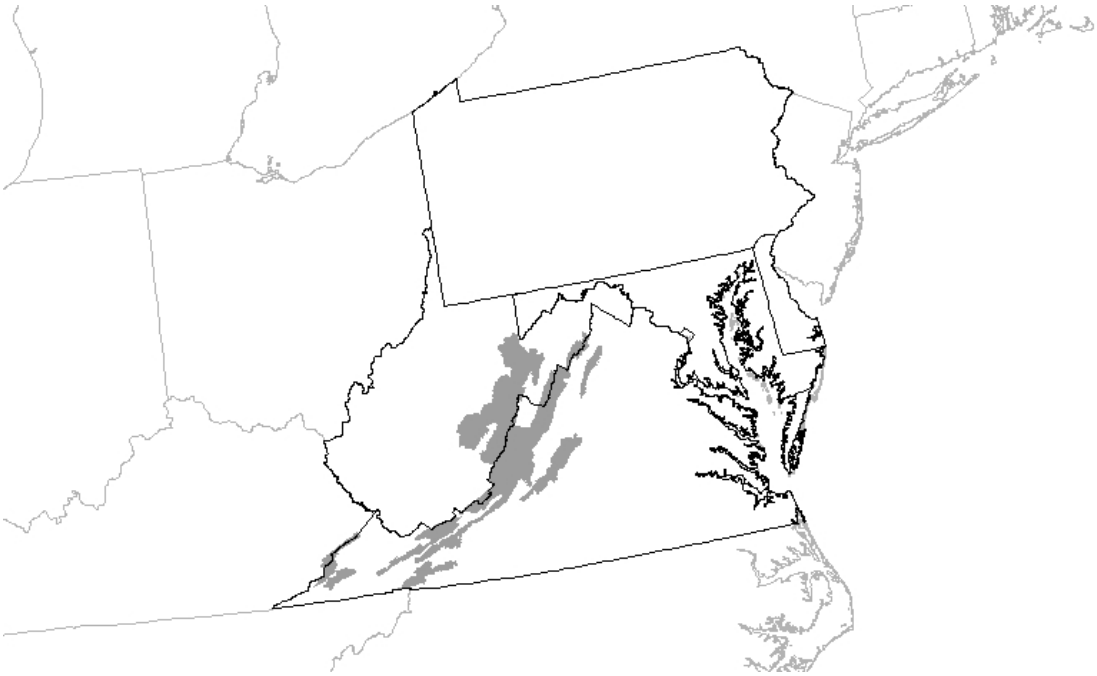


Figure 2.1. Map of Mid-Atlantic Highlands region outlined in black with Monongahela and George Washington/Jefferson National Forests shaded gray.

Methods

Site Selection

Hundreds of road stream crossings in the Monongahela National Forest of West Virginia and the George Washington Jefferson National Forest of Virginia were surveyed during the summers of 2002 and 2003. All the crossings were categorized according to my predictive models and classified as passable, impassable, or indeterminate for each fish species present below the crossing. Road stream crossings (n = 26) classified as passable or impassable were selected for the field validation based on presence/absence

and relative abundance of target species and stream order. The sites were located in the following watersheds of the Mid-Atlantic Highlands: Upper Greenbrier River, the Deer Creek/Sitlington Creek, the North Fork and South Fork of the Shenandoah River, and the South River (Figure 2.2 and Table 2.1). All sites were on first or second order streams except WF15 and WF16, which were on third order streams. A culvert can have more than one classification depending on the species present at that site. Not all culverts had all groups of fish species tested. Characteristics of each site are shown in Table 2.2.

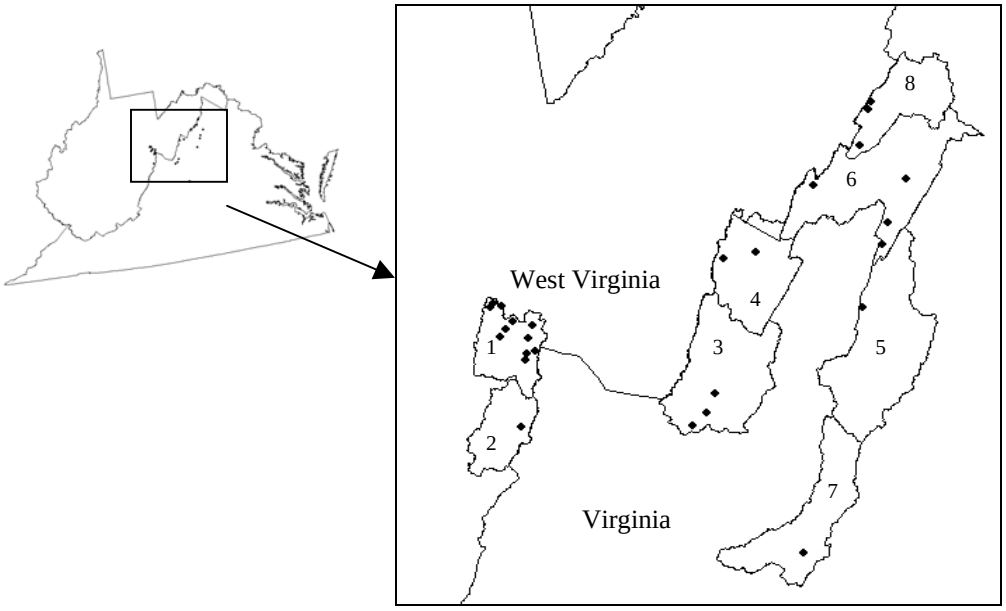


Figure 2.2. Watershed location of the study sites: (1) Upper Greenbrier River (n = 11), (2) Deer Creek/Sitlington Creek (n = 1), (3) Upper North River (n = 3), (4) Upper North Fork of the Shenandoah River (n = 2), (5) South Fork of the Shenandoah River (n = 1), (6) North Fork of the Shenandoah River (n = 4), (7) Middle South River (n = 1), and (8) Upper Cedar Creek (n = 3).

Table 2.1. Predictive model classifications for the 26 study sites used in the field validation. Sites without a classification either were classified indeterminate or lacked species for that particular model. Model A = Salmonidae, Model B = Cyprinidae, and Model C = Percidae (except *Stizostedion sp*., and *Perca flavescens*), and Cottidae families. Impass = Impassable and Pass = Passable classifications.

Study Site ID	Model A	Model B	Model C
DC01	Impass		
EF09	Impass	Impass	Impass
EF10	Pass	Pass	Pass
EF14		Impass	Impass
EF18	Pass	Pass	Pass
EF22	Impass	Impass	Impass
NR18		Impass	Impass
NR28		Impass	Impass
NR33			Impass
NSR06		Impass	Impass
NSR11	Pass	Pass	Pass
NSR15	Pass	Pass	Pass
NSR16	Pass	Pass	Pass
NSR18	Pass	Pass	Pass
NSR20	Pass	Pass	Pass
NSR21	Pass	Impass	Impass
NSR22	Impass	Impass	Impass
SR01	Pass	Pass	Pass
SSR06	Pass	Pass	Pass
SSR09	Pass	Pass	Pass
WF15	Impass	Impass	Impass
WF16	Pass	Pass	Pass
WF19	Impass	Impass	
WF20	Pass	Pass	Impass
WF25	Pass	Pass	Pass
WF35	Pass	Pass	Pass

Table 2.2. Characteristics of the 26 study sites used in the field validation. Xing types = crossing type were C = circular culvert, VF = vented ford, BA = bottomless arch, B = box, or PA = pipe arch. A negative outlet perch or drop indicates some backwatering effects. No outlet drop (NA) indicates the absence of a tailwater control. BW = backwatered. BW and Substrate in Pipe are yes (Y) or no (N) classifications. Refer to Figure 1 for a description of the parameters used to calculate slope, outlet perch, outlet drop, pipe length, and slope x length values.

Site ID	Xing type	Watershed Area(sqkm)	Avg Channel Width(m)	Pipe Width(m)	Pipe Height(m)	% Slope	Outlet Perch(cm)	Outlet Drop(cm)	Pipe Length(m)	Slope x Length(m)	BW	Substrate in Pipe
DC01	C	1.98	6.86	2.18	2.18	6.52	93.88	79.55	12.80	84	N	N
EF10	VF	30.19	13.77	0.91	0.91	0.28	-13.72	NA	4.32	1	Y	N
EF14	PA	5.04	6.12	3.89	2.57	1.57	18.90	33.83	17.04	27	N	N
EF18	C	17.12	10.90	1.63	1.63	0.71	-19.20	NA	6.45	5	N	Y
EF22	B	0.65	2.78	1.52	1.22	3.94	23.16	25.60	47.90	189	N	N
EF09	PA	6.89	6.05	2.51	1.93	1.74	68.28	75.59	10.52	18	N	N
NR18	PA	5.60	7.54	2.13	1.37	2.93	18.59	44.20	8.64	25	N	N
NR28	PA	16.99	8.18	3.96	1.83	2.96	10.67	21.34	17.37	52	N	N
NR33	PA	11.65	6.25	3.35	2.13	2.25	4.27	5.79	13.41	30	N	N
NSR06	PA	3.70	5.05	2.13	1.77	2.94	8.53	23.77	14.93	44	N	N
NSR11	C	0.21	5.99	0.91	0.91	0.16	-10.97	2.74	9.75	2	N	Y
NSR15	BA	10.23	6.81	4.79	2.74	0.77	-1.93	-0.71	25.05	19	N	Y
NSR16	C	2.90	3.65	1.01	1.01	0.32	-0.13	NA	12.34	4	N	N
NSR18	BA	11.33	7.20	2.62	1.89	0.39	-1.22	0.76	10.27	4	N	N
NSR20	BA	9.18	5.27	3.41	2.13	1.45	-1.88	-0.71	6.10	9	N	Y
NSR21	C	3.15	5.28	1.83	1.83	4.22	16.76	23.77	11.19	47	N	N
NSR22	VF	12.38	7.02	0.70	0.70	6.70	-2.51	-7.32	7.96	53	N	N
SR01	BA	11.04	4.50	3.63	1.52	1.70	-0.91	NA	12.92	22	N	Y
SSR06	BA	7.31	5.44	2.44	2.74	8.80	-21.34	0.00	7.62	67	N	Y
SSR09	BA	10.17	4.52	4.88	3.20	1.82	6.10	53.34	17.07	31	N	Y
WF15	VF	28.66	9.94	0.79	0.79	0.98	0.00	NA	4.95	5	N	N
WF16	VF	24.42	9.84	0.81	0.81	1.29	-33.22	-17.07	4.95	6	Y	N
WF19	C	0.45	2.71	0.61	0.61	6.24	7.62	8.84	9.96	62	N	N
WF20	PA	3.68	5.08	2.44	1.78	0.61	-5.79	7.62	10.54	6	N	N
WF25	PA	5.33	3.36	2.29	3.20	0.41	-10.97	NA	11.81	5	N	N
WF35	C	2.27	2.77	0.94	0.94	0.42	-3.05	6.40	8.69	4	N	N

Fish Movement

To validate the predictive models, a mark-recapture study of fish was implemented at each site. Upstream fish movement over 30 days was assessed through the culvert and through a downstream section of the stream that was undisturbed by the road crossing and free of natural movement barriers during the summer and fall of 2004. The field validation was conducted twice in the same year to capture any seasonal movements important to life histories of the species studied.

Each site was divided into six sections listed in order moving downstream to upstream: (1) mark section (M_{FC}), (2) false culvert section (FC) containing no natural movement barriers and undisturbed by the road crossing, (3) recapture section (R_{FC}), (4) second mark section (M_C), (5) the road crossing (C), and (6) second recapture section (R_C) (Figure 2.3). The two mark sections (M_{FC} and M_C) were each five times the average channel width in length or a minimum of 50 meters. The false culvert (FC) section was the same length as the road crossing (C), and the two recapture sections (R_{FC} and R_C) were each 5 times the length of an individual mark section or a minimum of 200 meters.

The minimum distance of 200 m for sections R_{FC} and R_C was based on a previous study that showed 70-90% of most species that move are collected within 200 m of the mark section (Albanese et al. 2003).

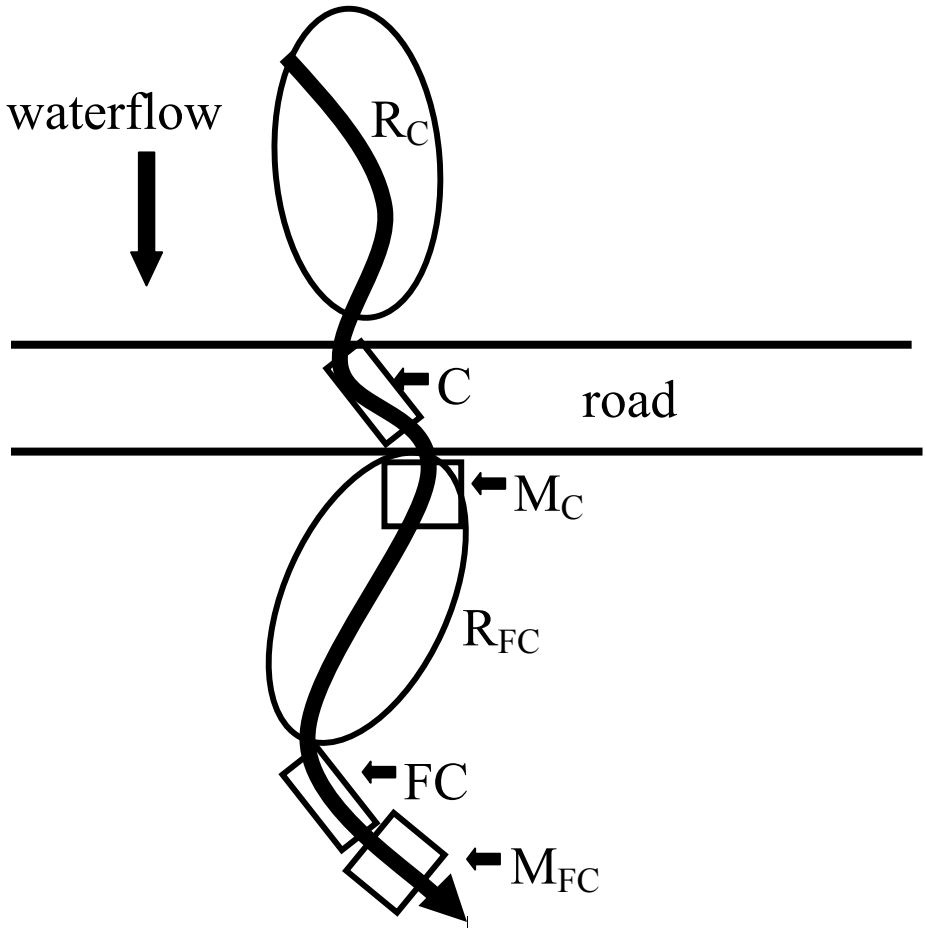


Figure 2.3. Study design for validating fish passage predictive models. M_{FC} and M_C are sections of stream where fish were initially marked. R_{FC} is the recapture section for fish from M_{FC} and R_C is the recapture section for fish from M_C. C is the culvert at the road crossing and FC is a section of undisturbed stream equal in length to C. Distances of each section are as follows: $M_{FC} = M_C =$ 5 times channel width or 50 m minimum, $R_{FC} = R_C =$ 4 times M_{FC} or 200 m minimum, and FC = C = culvert length.

Fish at all streams were marked between May 21-June 24, 2004 for the summer sample and September 7-October 12, 2004 for the fall sample. At day 0 for each site, block nets (1.61 cm^2 mesh) were placed at the downstream and upstream ends of sections M_{FC} and M_C. Three depletion passes were conducted using one or two (depending on stream size) SmithRoot model LR-24 backpack electrofishing units to collect fish for marking. All fish collected were identified to species and had total length measured to the nearest millimeter.

Fish > 40 mm were anesthetized in a dilution of MS-222 and given a fin clip unique to each section. The tip of the ventral lobe of the caudal fin was removed from fish collected in M_{FC} and the tip of the dorsal lobe of the caudal fin was removed from fish in M_C. Partial fin clips were used to minimize the effect on fish swimming ability. Fish smaller than 40 mm were not used because of difficulty in clipping and identifying clips on fish of this size. In a pilot study blacknose dace (*Rhinichthys atratulus*) with and without caudal fin clips (n = 100) held in aquaria were identified correctly 100% of the time after 30, 60, and 90 days. Caudal fin clips have been shown to have little effect on the steady cruising swimming mode of fish (Webb 1973). Previous to this study investigators have used caudal fin clips as a marking technique in mark-recapture movement studies without significant bias or effect of fin clips (Riley et al. 1992; Gowan and Fausch 1996). Webb (1977) did find that fast-start swim performance of hatchery rainbow trout (*Oncorhynchus mykss*) differed among control fish with no fins removed and groups with the entire caudal fin amputated, the entire caudal and anal fin amputated, and the ventral lobe of the caudal fin and the entire anal fin amputated. However, no differences were found among control fish and groups of fish with only either the ventral

lobe of the caudal fin or the dorsal lobe of the caudal fin removed (Webb 1977). Fish were allowed to recover from the anesthesia and then returned to their respective section of capture.

The recapture zones (R_{FC} and R_C) were sampled with one-pass electrofishing an average of 30 days (SE 0.62) (summer) and 29 days (SE 0.32) (fall) later. The time period of 30 days between capture events was selected to balance for dispersal and declining recapture rates after 30 days (Warren and Pardew 1998). All fish collected were identified to species and inspected for a fin clip. If a clip was found, the type of clip and total length of the individual were recorded along with its longitudinal distance and direction of movement in the recapture section. All fish without a fin clip were identified to species and counted. During recapture, sections M_{FC}, FC, and when possible C were also sampled with one-pass electrofishing. All sections began and ended at natural habitat breaks so block nets were not used during the recapture sample period except in the few cases where no natural habitat break existed between R_{FC} and the crossing (C). No fish were observed escaping the electrofishing by leaving a section. The recapture sections (R_{FC} and R_C) were each divided into 4 equal sections to further distinguish longitudinal distance moved by marked fish. Distance moved was calculated as the distance between the mid-point of the mark reach and the mid-point of the section of the recapture reach.

Temperature and Stream Stage

Because temperature and increased flow events have been positively correlated to upstream fish movement in some resident fish (Albanese et al. 2004), I monitored water temperature and stream stage during the study. Thermochron iButtons™ (Dallas

Semiconductors Dallas, TX) were placed in sections M_{FC} and M_C at each site and recorded temperature (°C) every hour for the duration of the study. Crest gages were placed just upstream of each crossing to measure any changes in stream stage that occurred during the duration of the experiment. Flow events were considered as a rise in water level detectable on the crest gage. At the end of the study the Thermochron iButtons™ were recovered and the maximum water level attained was measured and recorded. Maximum, minimum and mean daily temperatures were determined for each section at each site.

Water Velocity

Water velocities (cm/s) in the inlet, middle, and outlet of the crossing were measured (Marsh-McBirney Flo-Mate© flowmeter, Marsh-McBirney Inc. Fredrick, MD) at 0.6 of the water depth. Cross sectional velocity measurements of the natural stream channel were also taken at each site for comparison to the water velocities in the crossing and to calculate channel discharge. During the summer of 2004 sample, velocity measurements were only taken at the beginning of the study. During the fall sample, velocity measurements were taken at the beginning and end of the study.

Statistical analysis

At each site fish movement was assessed through the false culvert (FC) (between M_{FC} and R_{FC}) and through the culvert (C) (between M_C and R_C). I calculated fish movement as the proportion of marked fish that moved, M/N (where M is the number of marked fish that moved into either the culvert and R_C or into the false culvert and R_{FC} for M_C and M_{FC} respectively and N is the total number of fish marked for each section). I used the Freeman-Tukey modified arcsine square root transformation for proportional

data to achieve normality but present retransformed means (Zar 1996). Three-factor analysis of variance (ANOVA) was conducted to test the main effects of group (A, B, and C), culvert classification (passable and impassable), and section (FC or C), and interactions among the three on fish movement within each season. Contrasts of mean proportional movement among crossing classification and stream section for each group in seasons separately and combined were also conducted. I hypothesized that movement through the false culvert (FC) would be equal to movement through passable culverts (C), greater than movement through impassable culverts (C), and movement through passable culverts would be greater than movement through impassable culverts.

The differential movement at sites classified as passable and impassable was calculated as the difference between the false culvert movement and the culvert movement for each group in each season. The differential movement was analyzed in a two-factor ANOVA using the main effects of group and classification, with contrasts of mean differential movement between passable and impassable site for each group. I used *t*-tests to determine if body length differed among movers and stayers for each group in each season. Significance levels were $P < 0.05$ for all tests.

I tested for relationships in the crossing characteristics of slope, outlet drop, and slope x length with fish movement through the culverts using Kendall's coefficient of rank correlation for each group for seasons separately and combined (Sokal and Rohlf 1995). Water velocities in the culvert were also tested for relationships with fish movement using Kendall's coefficient of rank correlation.

Mean daily water temperatures of M_{FC} and M_C at each site were tested for differences using a split plot design ANOVA to account for any variability among

sections that could influence movement. Stream gage data for each site were analyzed for extreme high flows associated with flood events. Statistical analysis was conducted on SPSS and SAS statistical software.

Results

6,135 (summer) and 3,734 (fall) fish representing 15 species (Table 2.3) were marked. Overall 23% of the fish marked in the summer and 20% of the fish marked in the fall were recaptured. Total fish marked for each group in each season are presented in Table 2.4, along with recapture proportions for each section. Adult brook trout constituted 82% (summer) and 76% (fall) of the total fish marked in Group A. Blacknose dace comprised 56% (summer and fall) while young-of-the-year brook trout comprised 21% (summer) and 16% (fall) of the individuals marked from Group B (Table 2.5). Mottled sculpin (*Cottus bairdi*) were 62% (summer) and 71% (fall) of the individuals marked from Group C. The total proportion of fish recaptured for each group during the summer were 42.6% (Group A), 27.8% (Group B), 11.4% (Group C), and 34.5% (Group A), 24.2% (Group B), and 6.3% (Group C) for the fall. Retention of marked fish, defined as the proportion of marked fish that stayed and were recaptured in the mark section, was 21% (M_{FC}) and 17% (M_C) during the summer, and 21% (M_{FC}) and 14% (M_C) for the fall (Table 2.6).

Fish movement through the undisturbed stream section (FC) was observed at all 26 sites (n = 24 summer, n = 21 fall) in either one or both seasons. No movement through impassable and passable culverts was observed for species in Group A during the summer. During the fall at least one fish moved through 2 of 5 impassable culverts and 3 of 8 passable culverts by species in Group A. Species in Group B moved through 3 of 10

impassable culverts and 10 of 14 passable culverts during the summer, and 1 of 11 impassable sites and 9 of 14 passable sites during the fall. Species in Group C moved through 3 of 8 impassable culverts and 2 of 10 passable culverts during the summer, and 1 of 8 impassable sites and 1 of 10 passable sites during the fall. There were no differences in length among movers and stayers for Group B (t-test, P = 0.881, n(movers) = 221, n(stayers) = 902), or Group C (t-test, P = 0.745, n(movers) = 45, n(stayers) = 232) during the summer. Group A movers were 42 mm longer, on average (166 mm SE = 4.4) than stayers (124 mm SE = 9.1) during the summer (t-test, P < 0.001, n(movers) = 25, n(stayers) = 146). During the fall, movers and stayers for groups A (t-test, P = 0.537, n(movers) = 24, n(stayers) = 38), B (t-test, P = 0.744, n(movers) = 79, n(stayers) = 559), and C (t-test, P = 0.071, n(movers) = 6, n(stayers) = 54) did not differ in total length.

Table 2.3. Species sampled during the summer and fall of 2004 in the Monongahela and George Washington/Jefferson National Forests of West Virginia and Virginia and their group. yoy = young-of-year.

Common Name	Scientific Name	Code	Group
brook trout	*Salvelinus fontinalis*	BKT	A
brown trout	*Salmo trutta*	BNT	A
brook trout yoy	*Salvelinus fontinalis*	BKTY	B
blacknose dace	*Rhinichthys atratulus*	BND	B
creek chub	*Semotilus atromaculatus*	CC	B
rosyside dace	*Clinostomus funduloides*	RSD	B
mountian redbelly dace	*Phoxinus oreas*	MRD	B
longnose dace	*Rhinichthys cataractae*	LND	B
bluehead chub	*Nocomis leptocephalus*	BHC	B
central stoneroller	*Campostoma anomalum*	STR	B
New River shiner	*Notropis scabriceps*	NRS	B
bigmouth chub	*Nocomis platyrhynchus*	BMC	B
cutlips minnow	*Exoglossum maxillingua*	CLM	B
fantail darter	*Etheostoma flabellare*	FTD	C
mottled sculpin	*Cottus bairdi*	SCLP	C

Table 2.4. Recapture percentages for each group classification (impass = impassable sites, pass = passable sites, A = Group A, B = Group B, and C = Group C) during summer and fall 2004. Total fish marked in M_{FC} (downstream mark section), M_C (mark section directly downstream of the culvert), and recaptured in R_{FC} (recapture section for M_{FC}), and R_C (recapture section for M_C).

summer	Marked M_{FC}	Recaptured R_{FC}	Marked M_C	Recaptured R_C	M_{FC} recap%	M_C recap%	overall recap%
impassA	69	42	82	36	60.9	43.9	51.7
passA	44	15	49	11	34.1	22.4	28.0
impassB	385	140	466	117	36.4	25.1	30.2
passB	1424	443	1435	332	31.1	23.1	27.1
impassC	614	74	722	72	12.1	10.0	10.9
passC	422	55	423	47	13.0	11.1	12.1
fall							
impassA	36	16	45	13	44.4	28.9	35.8
passA	30	17	54	11	56.7	20.4	33.3
impassB	480	135	452	85	28.1	18.8	23.6
passB	913	263	779	151	28.8	19.4	24.5
passC	170	14	159	3	8.2	1.9	5.2
impassC	318	28	298	15	8.8	5.0	7.0

Table 2.5. Percentage of marked fish recaptured for Group B broken down by species for impassable (impass) and passable (pass) sites during the summer and fall of 2004 at the 26 study sites. Total fish marked in M_{FC} (downstream mark section), M_C (mark section directly downstream of the culvert), and recaptured in R_{FC} (recapture section for M_{FC}), and R_C (recapture section for M_C). Refer to Table 2.3 for species abbreviations.

summer impass	Marked M_{FC}	Recaptured R_{FC}	Marked M_C	Recaptured R_C	M_{FC} recap%	M_C recap%	overall recap%
BKTY	123	38	140	42	30.9	30.0	30.4
BND	253	89	260	65	35.2	25.0	30.0
CC	5	1	18	3	20.0	16.7	17.4
BHC	8	5	11	6	62.5	54.5	57.9
MRD	12	1	43	2	8.3	4.7	5.5
STR	21	6	1	0	28.6	0.0	27.3
LND	9	3	9	3	33.3	33.3	33.3
RSD	47	13	43	14	27.7	32.6	30.0
summer pass							
BKTY	281	76	246	56	27.0	22.8	25.0
BND	808	277	773	199	34.3	25.7	30.1
CC	128	45	189	32	35.2	16.9	24.3
BHC	10	1	34	6	10.0	17.6	15.9
MRD	34	9	86	17	26.5	19.8	21.7
STR	9	5	4	0	55.6	0.0	38.5
LND	4	1	4	2	25.0	50.0	37.5
RSD	150	49	98	20	32.7	20.4	27.8

Table 2.5 continued

fall impass	Marked M_{FC}	Recaptured R_{FC}	Marked M_C	Recaptured R_C	M_{FC} recap%	M_C recap%	overall recap%
BKTY	54	28	76	20	51.9	26.3	36.9
BND	234	49	206	49	20.9	23.8	22.3
CC	2	0	9	2	0.0	22.2	18.2
BHC	26	10	9	4	38.5	44.4	40.0
MRD	46	9	8	0	19.6	0.0	16.7
STR	26	8	1	1	30.8	100.0	33.3
LND	10	4	6	0	40.0	0.0	25.0
RSD	81	27	108	9	33.3	8.3	19.0
NRS	1	0	29	0	0.0	0.0	0.0
fall pass							
BKTY	156	64	138	51	41.0	37.0	39.1
BND	557	142	465	79	25.5	17.0	21.6
CC	60	15	55	6	25.0	10.9	18.3
BHC	12	5	10	3	41.7	30.0	36.4
MRD	48	16	53	3	33.3	5.7	18.8
STR	9	1	8	0	11.1	0.0	5.9
RSD	71	20	49	9	28.2	18.4	24.2

Table 2.6. Percentage of marked fish retained in M_{FC} (downstream mark section) and M_C (mark section directly downstream of the culvert) during the summer and fall for each group classification (impass = impassable sites, pass = passable sites, A = Group A, B = Group B, and C = Group C).

summer	Marked M_{FC}	Marked M_C	Stayed M_{FC}	Stayed M_C	M_{FC} retention (%)	M_C retention (%)
impassA	69	82	34	36	49.3	43.9
passA	44	49	7	11	15.9	22.4
impassB	385	466	126	106	32.7	22.7
passB	1424	1435	353	286	24.8	19.9
impassC	614	722	53	68	8.6	9.4
passC	422	423	44	42	10.4	9.9
fall						
impassA	36	45	11	10	30.6	22.2
passA	30	54	12	7	40.0	13.0
impassB	480	452	117	84	24.4	18.6
passB	913	779	226	130	24.8	16.7
impassC	318	298	25	14	7.9	4.7
passC	170	159	13	2	7.6	1.3

Temperature and Stream Stage

Temperatures in M_{FC} and M_C over the duration of summer sampling period ranged from 25.0 ^oC to 9.0 ^oC. There was an interaction effect between site and section (ANOVA, $P < 0.0001$, $n = 24$), but the mean (0.32 ^oC) and maximum (1.17 ^oC) difference in temperature was not biologically significant. Temperatures in M_{FC} and M_C over the duration of the fall sampling period ranged from 21.5 ^oC to 3.0 ^oC for all sites. The interaction between site and section was also evident during the fall (ANOVA, $P < 0.0001$, $n = 23$), but the mean (0.26 ^oC) and maximum (0.68 ^oC) difference was not biologically significant.

During the summer sampling, no sites experienced a rise in water level over 6.1 cm and all sites were below the water level from the mark sampling at the end of the thirty days. Fall of 2004 experienced a heavy rain that resulted in bankfull flood stage at site SR01 between the mark and recapture samples. However, most of the sites at the end of the fall study period had water levels equal to or greater than the water level during the mark sampling.

Fish Movement

Proportional movement differed between groups and sections during the summer, fall, and both seasons combined (Table 2.7). Group had an effect on the differential movement between the false culvert and the culvert during the summer and when data from both seasons were combined (Table 2.8). There was no effect of classification on differential movement.

Table 2.7. Three-factor analysis of variance comparing proportional movement of fishes with the main effects of group (A, B, or C), class (impassable or passable), section (false culvert or culvert), and interactions among the three.

summer	Source of variation	df	F	P value
	group	2	8.96	0.0003
	class	1	1.57	0.2137
	section	1	25.54	<0.0001
	group*class	2	0.7	0.4970
	group*section	2	4.66	0.0120
	class*section	1	0.1	0.7519
	group*class*section	2	0.14	0.8684
fall				
	group	2	15.69	<0.0001
	class	1	0.64	0.4266
	section	1	9.52	0.0028
	group*class	2	1.74	0.1825
	group*section	2	2.61	0.0793
	class*section	1	2.55	0.1138
	group*class*section	2	0.22	0.8018
seasons combined				
	group	2	24.96	<0.0001
	class	1	0.09	0.7649
	section	1	33.11	<0.0001
	group*class	2	0.42	0.6558
	group*section	2	5.85	0.0034
	class*section	1	1.68	0.1971
	group*class*section	2	0.02	0.9831

Table 2.8. Two-factor analysis of variance comparing differential movement of fishes with the main effects of group (A, B, or C) and class (impassable or passable) and the interaction of the 2 main effects.

summer	Source of variation	df	F	P value
	group	2	4.33	0.0194
	class	1	0.09	0.7631
	group*class	2	0.13	0.8776
fall				
	Source of variation			
	group	2	3.04	0.0587
	class	1	2.97	0.0924
	group*class	2	0.26	0.7712
seasons combined				
	Source of variation			
	group	2	6.16	0.0031
	class	1	1.76	0.1884
	group*class	2	0.02	0.9821

Fish Movement Group A

Movement documented in Group A was primarily that of adult brook trout. No individuals moved through culverts during the summer, and fall movement was limited to four sites (Table 2.9). Contrasts indicated differential movement was not affected by culvert classification during the summer (P = 0.9891, n = 11), fall (P = 0.2128, n = 10), or when data for both seasons were combined (P = 0.4293, n = 21) (Figure 2.4). However, contrasts did indicate proportional movement through the false culvert (FC) was significantly higher than proportional movement through impassable culverts (C) during the summer (P = 0.0015, n = 10), fall (P = 0.0093, n = 10), and when the seasons were combined (P = <0.0001, n = 20) (Figure 2.5). Proportional movement was also higher through false culverts (FC) than passable culverts (C) during the summer (P = 0.0005, n = 12), and when the seasons were combined (P = 0.0013, n = 22) (Figure 2.5). Movement was not higher through passable culverts when compared to impassable culverts during the summer (P = 0.3369, n = 11), fall (P = 0.6632, n =10), or seasons combined (P = 0.7840, n = 21) (Figure 2.5).

Marked individuals moved a median distance of 61 m (maximum = 175 m) through natural stream sections (FC) during the summer and 60 m (maximum = 158 m) during the fall. No individuals moved through culverts during the summer but median distance moved through the culverts during the fall was 60 m (maximum = 248 m) (Figure 2.6). Seventy one percent of the marked fish that moved through the false culvert or the culvert were recaptured within 75 m of their respective mark section.

Table 2.9. Percentage of marked fish that moved through the FC (natural stream section) and C (the culvert) at each Group A site for each classification (impass = impassable and pass = passable) during the summer and fall of 2004. The number of fish marked in M_{FC} (downstream mark section) and M_C (mark section directly downstream of the culvert) are also reported.

summer impass	Site ID	Marked M_{FC}	M_{FC} moved	Marked M_C	M_C moved	%moved FC	%moved C
	DC01	27	3	14	0	11.1	0.0
	EF09	8	2	18	0	25.0	0.0
	EF22	11	1	14	0	9.1	0.0
	WF15	5	1	10	0	20.0	0.0
	WF19	17	1	21	0	5.9	0.0
summer pass							
	EF10	3	1	8	0	33.3	0.0
	EF18	9	1	5	0	11.1	0.0
	SSR06	4	0	6	0	0.0	0.0
	WF16	5	0	2	0	0.0	0.0
	WF20	9	0	9	0	0.0	0.0
	NSR15	4	4	5	0	100.0	0.0
fall impass							
	DC01	17	2	8	0	11.8	0.0
	EF09	5	1	14	0	20.0	0.0
	EF22	6	0	9	1	0.0	11.1
	NSR22	1	1	1	0	100.0	0.0
	WF19	5	1	13	2	20.0	15.4
fall pass							
	EF10	7	0	20	1	0.0	5.0
	EF18	8	0	3	0	0.0	0.0
	NSR18	1	0	7	1	0.0	14.3
	SSR06	4	2	7	0	50.0	0.0
	WF20	3	0	9	0	0.0	0.0

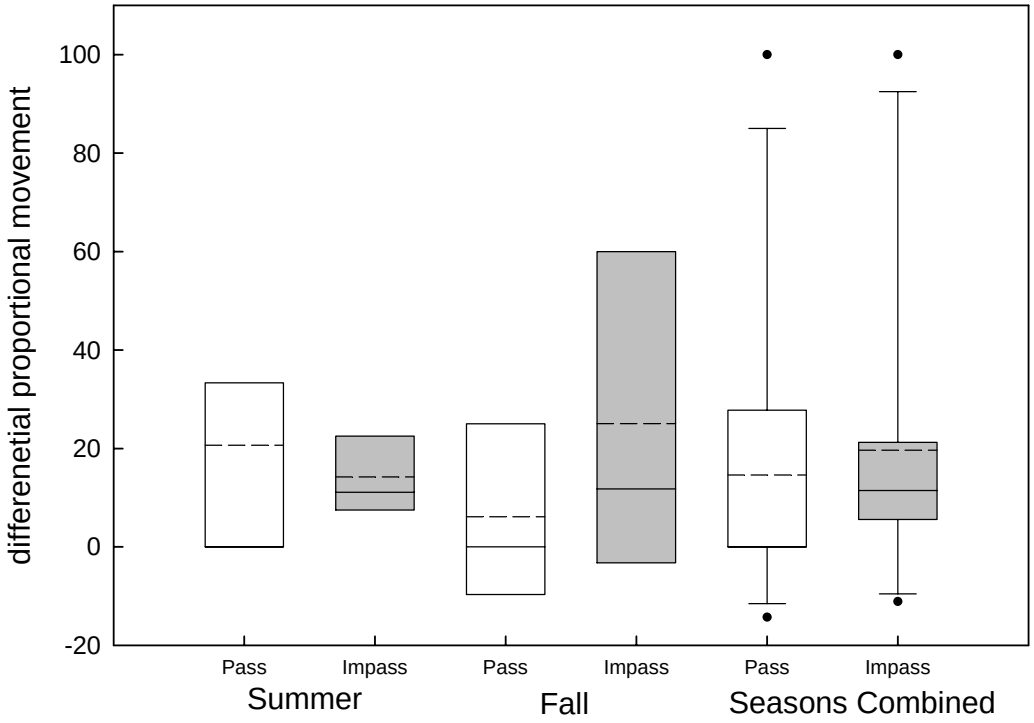
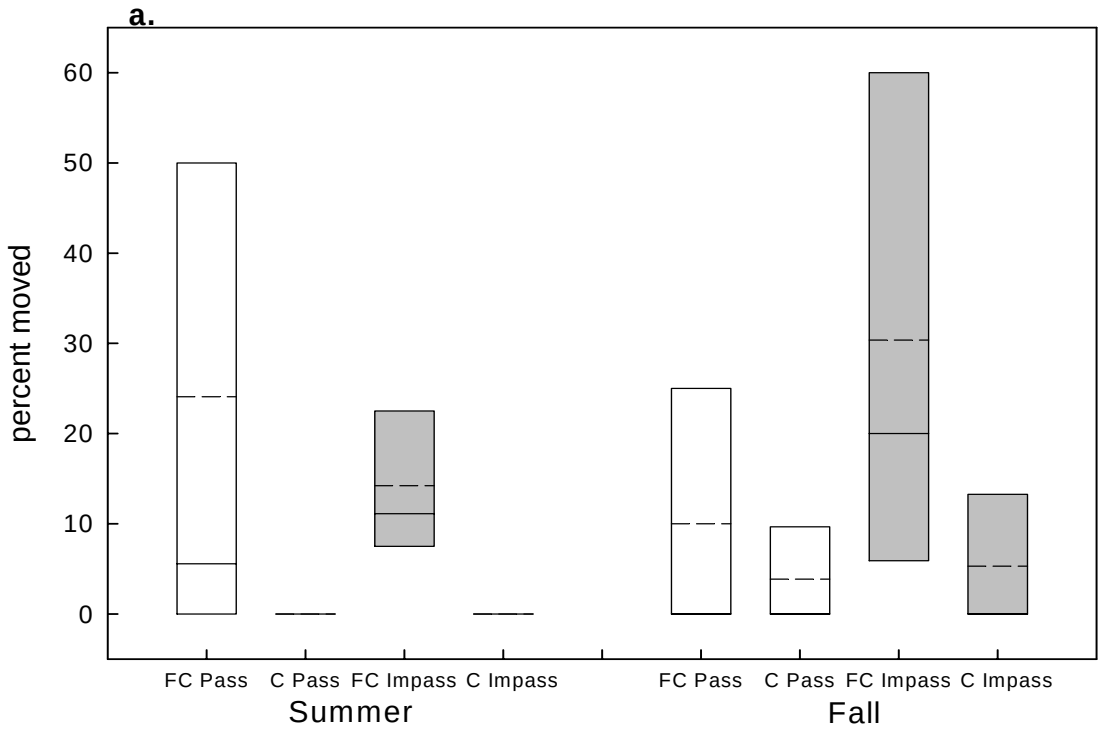


Figure 2.4. Box plots of differential movement at passable (pass) and impassable (impass) sites for Group A during the summer, fall and combined seasons. The dashed lines represent the mean and solid lines represent the median.



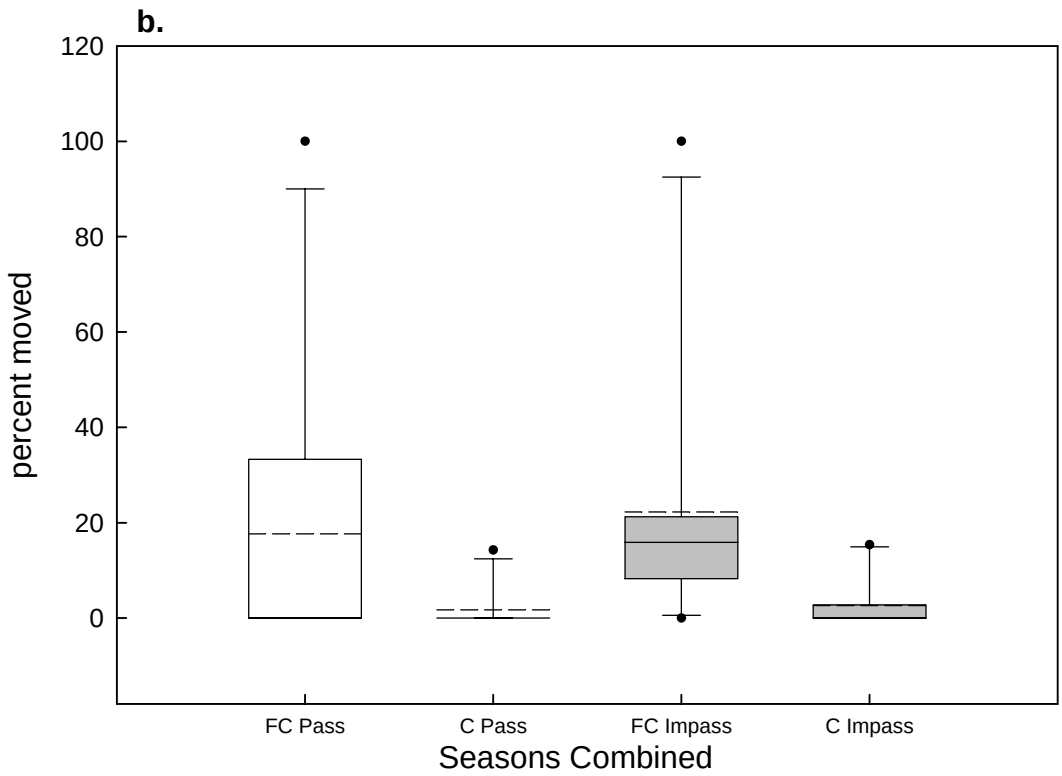


Figure 2.5. Box plots showing distribution of movement through the false culvert (FC) and the culvert (C) for passable (pass) and impassable (impass) sites of Group A. The dashed lines represent the mean and solid lines the median. Panel a shows summer and fall (2004) movement, Panel b is for the two seasons combined.

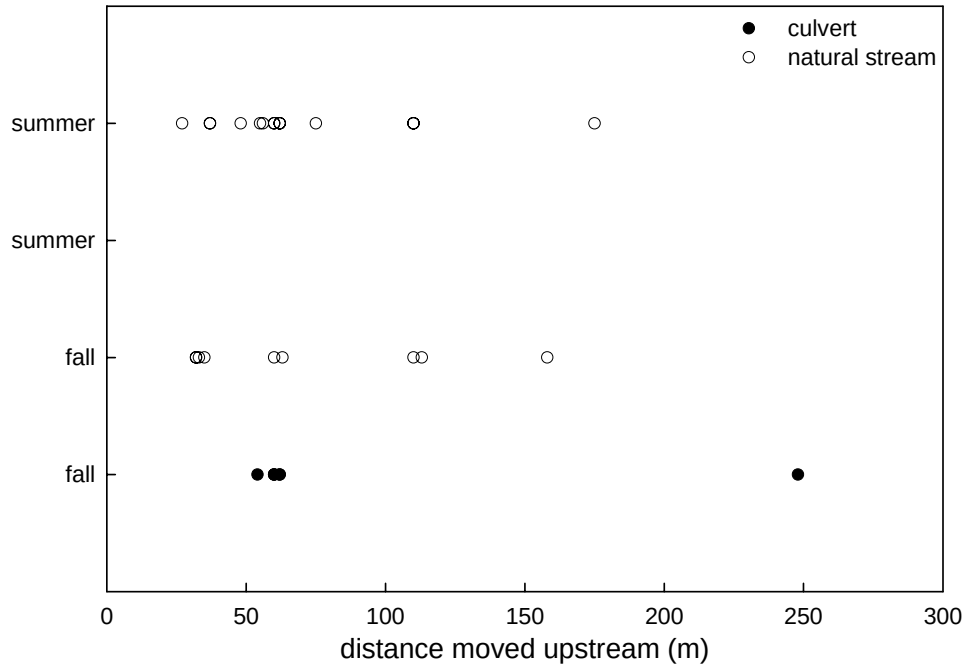


Figure 2.6. Distances moved upstream by marked fish (Group A) through the false culvert and culverts during the summer and fall 2004. No fish moved through culverts during the summer.

Fish Movement Group B

All passable culverts experienced movement during one or both seasons except SSR06, while only four of eleven impassable culverts had upstream fish movement (Table 2.10). Contrasts indicated differential movement was not higher for impassable sites compared to passable sites during the summer (P = 0.9565, n = 24), fall (P = 0.1694, n = 24), or the seasons combined (P = 0.3512, n = 48) (Figure 2.7). Contrasts showed that proportional movement through the false culvert (FC) was 17 times higher than proportional movement through impassable culverts (C) during the fall (P = 0.0053, n = 20), and 14 times higher when the seasons were combined (P =0.0026, n = 40) (Figure 2.8). Proportional movement through false culverts was also higher than movement through passable culverts for the combined seasons data (P = 0.0292, n = 56) (Figure 2.8b). Movement through passable culverts was not significantly higher than movement through impassable culverts during the summer (P = 0.5058, n = 24), fall (P = 0.2140, n = 24), or when the seasons were combined (P = 0.1714, n = 48) (Figure 2.8).

Marked individuals moved a median distance of 60 m (maximum of 217 m) through natural stream sections during the summer and 58 m (maximum of 247 m) during the fall. Median distance moved through culverts during the summer was 62 m (maximum of 205 m) and 61 m (maximum of 210 m) during the fall (Figure 2.9). Sixty seven percent of the marked fish that moved through either the false culvert or the culvert were recaptured within 75 m of their respective mark section, and 81% within 125 m. Movement was similar among species in Group B (Figure 2.10).

Table 2.10. Percentage of marked fish that moved through the FC (natural stream section) and C (the culvert) at each Group B site for each classification (impass = impassable and pass = passable) during the summer and fall of 2004. The totals marked in M_{FC} (downstream mark section) and M_C (mark section directly downstream of the culvert) are also reported.

summer impass	Site ID	Marked M_{FC}	M_{FC} moved	Marked M_C	M_C moved	%moved FC	%moved C
	DC01	13	0	4	0	0.0	0.0
	EF09	46	2	50	0	4.3	0.0
	EF14	6	0	15	0	0.0	0.0
	EF22	9	1	35	0	11.1	0.0
	NR18	55	3	27	0	5.5	0.0
	NSR06	22	1	19	0	4.5	0.0
	NSR21	53	2	67	1	3.8	1.5
	NSR22	116	2	95	3	1.7	3.2
	WF15	54	3	135	4	5.6	3.0
	WF19	11	0	19	0	0.0	0.0
summer pass							
	EF10	203	8	232	8	3.9	3.4
	EF18	60	2	133	4	3.3	3.0
	NSR11	31	7	76	0	22.6	0.0
	NSR16	210	14	80	5	6.7	6.3
	NSR18	146	12	85	7	8.2	8.2
	NSR20	99	1	113	3	1.0	2.7
	SR01	114	1	142	4	0.9	2.8
	SSR06	124	0	59	0	0.0	0.0
	SSR09	90	9	78	0	10.0	0.0
	WF16	54	5	93	2	9.3	2.2
	WF20	18	4	28	0	22.2	0.0
	WF25	73	4	117	4	5.5	3.4
	WF35	170	8	146	2	4.7	1.4
	NSR15	32	3	53	7	9.4	13.2
fall impass							
	EF09	32	0	27	0	0.0	0.0
	EF14	4	0	18	0	0.0	0.0
	EF22	7	2	18	0	28.6	0.0
	NR18	25	2	27	0	8.0	0.0
	NR28	175	4	50	1	2.3	2.0
	NSR06	27	1	16	0	3.7	0.0
	NSR21	23	2	39	0	8.7	0.0
	NSR22	67	4	128	0	6.0	0.0
	WF15	108	0	118	0	0.0	0.0
	WF19	7	3	9	0	42.9	0.0

Table 2.10. continued

fall pass	Site ID	Marked M_{FC}	M_{FC} moved	Marked M_C	M_C moved	%moved FC	%moved C
	EF10	70	2	45	1	2.9	2.2
	EF18	35	0	44	2	0.0	4.5
	NSR11	19	7	23	2	36.8	8.7
	NSR15	13	2	33	2	15.4	6.1
	NSR16	130	4	81	3	3.1	3.7
	NSR18	65	1	53	6	1.5	11.3
	NSR20	88	2	72	3	2.3	4.2
	SR01	11	1	73	0	9.1	0.0
	SSR06	121	1	52	0	0.8	0.0
	SSR09	102	2	74	1	2.0	1.4
	WF16	62	2	65	0	3.2	0.0
	WF20	16	2	18	1	12.5	5.6
	WF25	35	4	24	0	11.4	0.0
	WF35	146	6	122	0	4.1	0.0

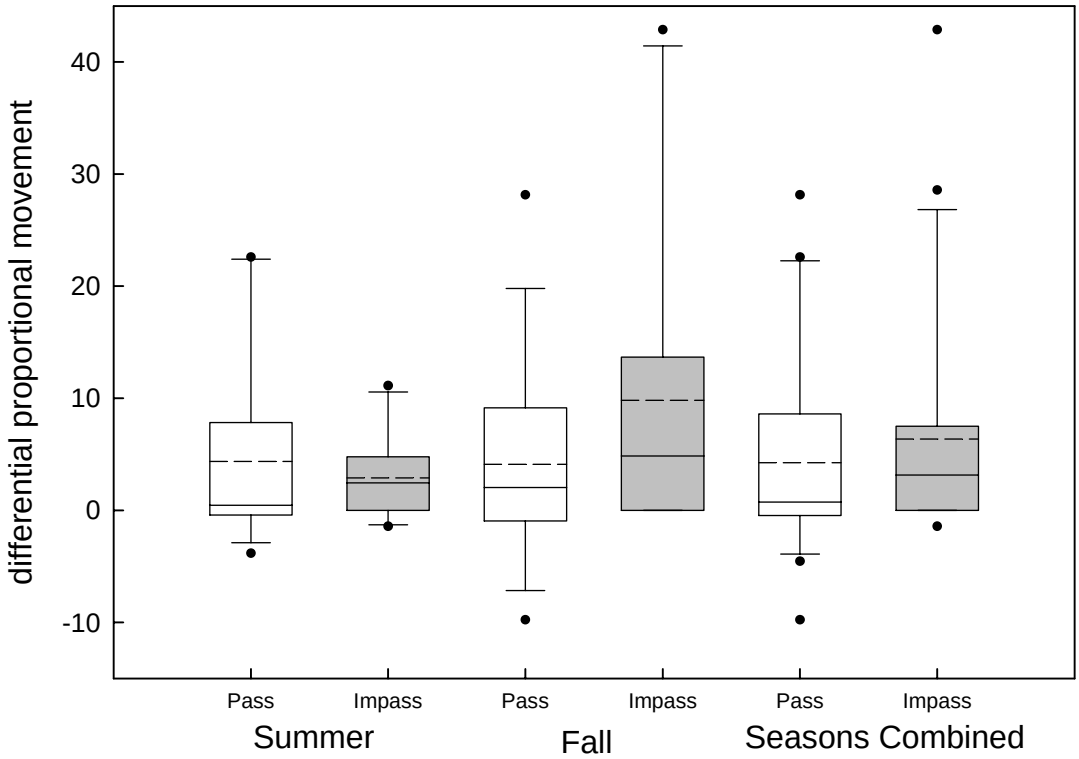


Figure 2.7. Box plots of differential movement at passable (pass) and impassable (impass) sites for Group B during the summer fall and seasons combined. The dashed lines represent the mean and solid lines represent the median.

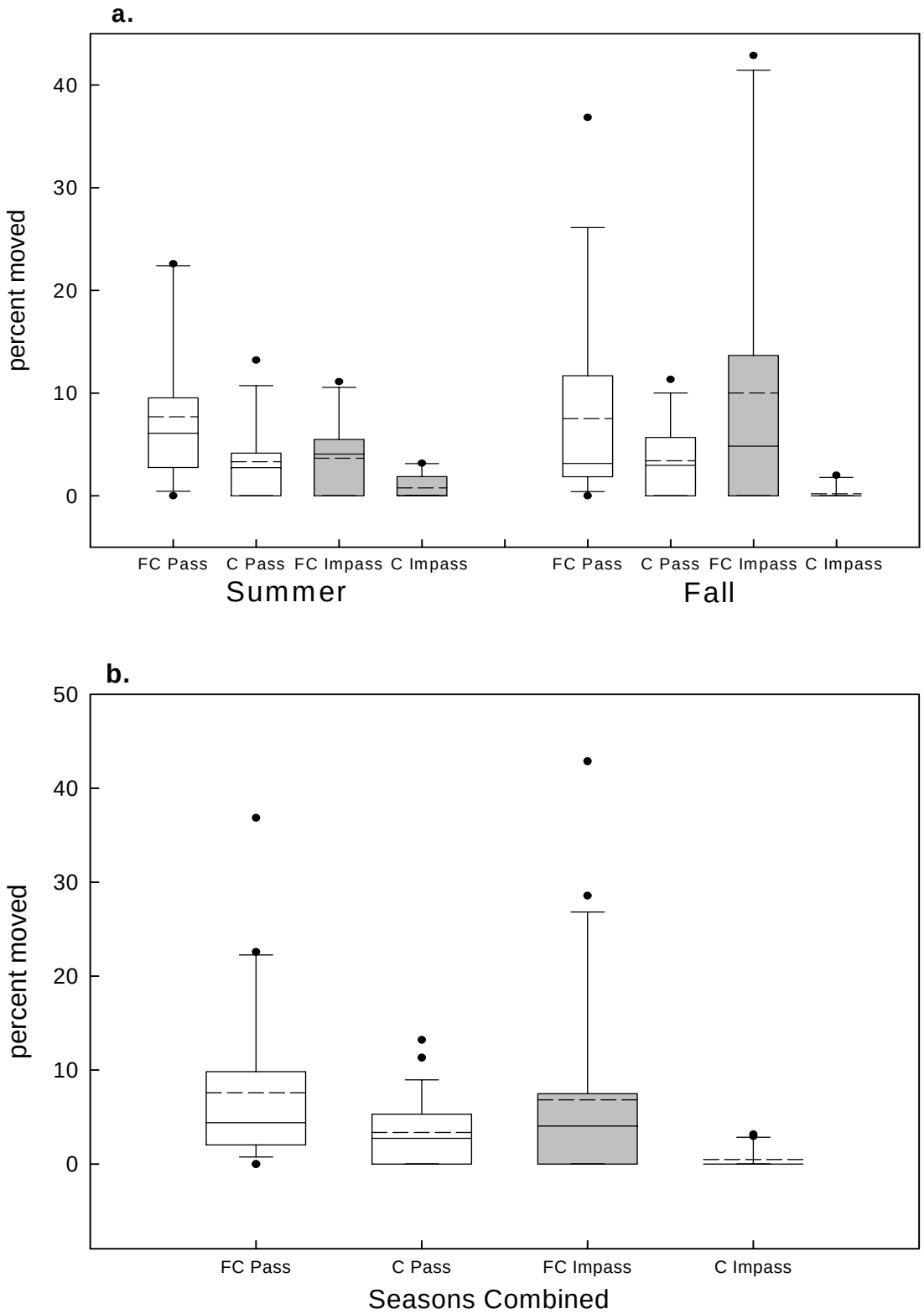


Figure 2.8. Box plots showing distribution of movement through the false culvert (FC) and the culvert (C) for passable (pass) and impassable (impass) sites of Group B. The dashed lines represent the mean and solid lines represent the median. Panel a shows summer and fall 2004 movement. Panel b is for the both seasons combined.

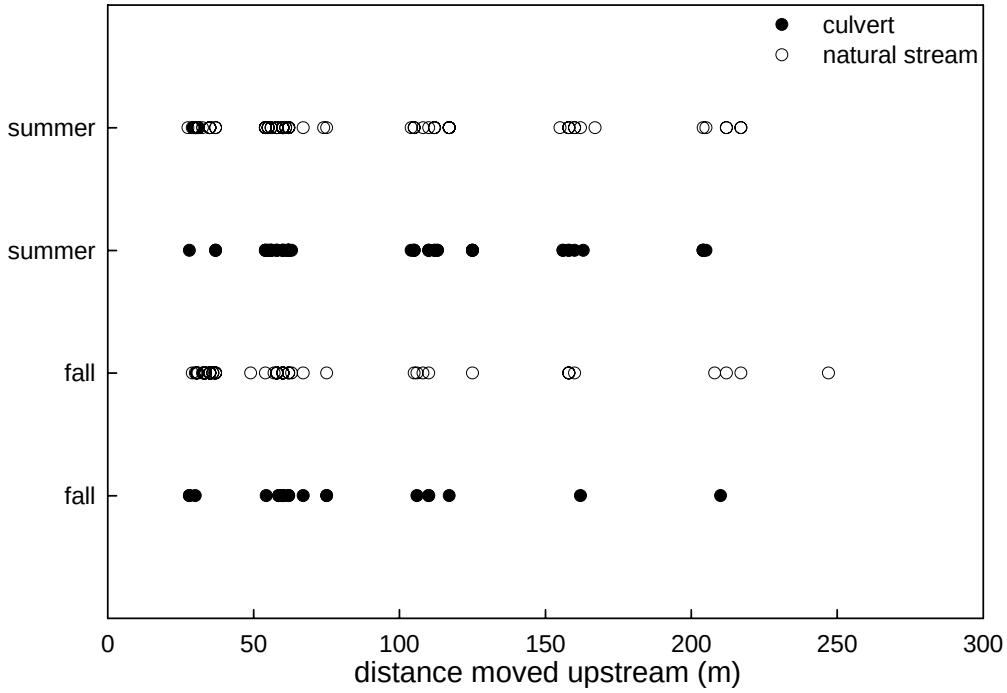


Figure 2.9. Distances moved upstream by marked fish from Group B through the false culvert and through culverts during the summer and fall 2004.

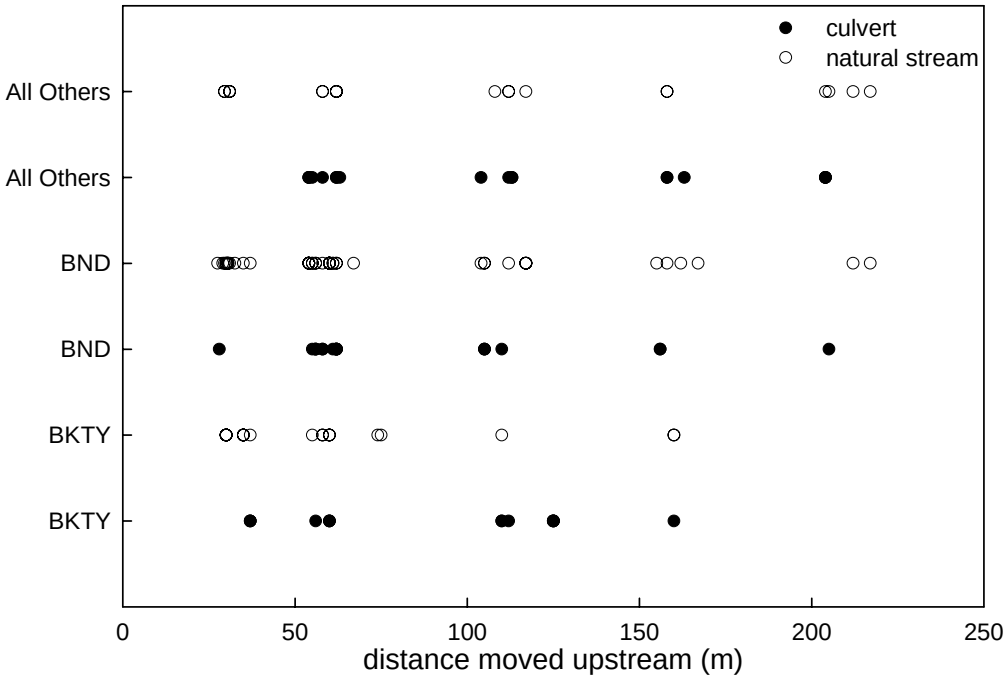


Figure 2.10. Distances moved upstream by marked fish of species in Group B through the false culvert and through culverts during the summer 2004. BKTY = brook trout young-of-year, BND = blacknose dace, and All Others = creek chub, bluehead chub, rosyside dace, longnose dace, mountain redbelly dace, and central stoneroller.

Fish Movement Group C

Movement through culverts was uncommon at all sites for fish species in Group C. Mottled sculpins and fantail darters only moved through culverts at six of fifteen sites (4 passable, 2 impassable) (Table 2.11). Differential movement at impassable sites was not higher than the differential movement of passable sites during the summer (P = 0.5696, n = 14), fall (P = 0.6845, n = 14), or the seasons combined (P = 0.5319, n = 28) (Figure 2.11). Contrasted indicated that proportional movement through false culverts (FC) was not significantly higher than movement through impassable culverts (C) during the summer (P = 0.1649, n = 14), fall (P = 0.8231, n = 16), and seasons combined (P = 0.2781, n = 30) (Figure 2.12). Movement through passable culverts was not higher than movement through impassable culverts during the summer (P = 0.7853, n = 14), fall (P = 0.6017, n = 14), or when the seasons were combined (P = 0.5823, n = 28) (Figure 2.12).

Median distance moved during the summer was higher than during the fall for Group C species. Marked individuals moved a median distance of 70 m (maximum of 124 m) through natural stream sections during the summer and 42 m (maximum of 56 m) during the fall. Median distance moved through culverts during the summer was 84 m (maximum of 113 m) and 65 m (maximum of 67 m) during the fall (Figure 2.13). Sixty four percent of the marked fish that moved through either the false culvert or the culvert were recaptured within 75 m of their respective mark section.

Table 2.11. Percentage of marked fish that moved through the FC (natural stream section) and C (the culvert) at each Group C site for each classification (impass = impassable and pass = passable) during the summer and fall of 2004. The totals marked in M_{FC} (downstream mark section) and M_C (mark section directly downstream of the culvert) are also reported.

summer impass	Site ID	Marked M_{FC}	M_{FC} moved	Marked M_C	M_C moved	%moved FC	%moved C
	EF09	104	9	152	0	8.7	0.0
	EF14	16	2	29	0	12.5	0.0
	EF22	58	3	7	0	5.2	0.0
	NR33	108	5	182	1	4.6	0.5
	NSR22	103	0	144	2	0.0	1.4
	WF15	49	1	41	0	2.0	0.0
summer pass							
	EF10	135	0	166	1	0.0	0.6
	EF18	87	2	146	3	2.3	2.1
	NSR16	83	0	90	2	0.0	2.2
	NSR20	7	0	7	0	0.0	0.0
	SSR09	38	2	23	0	5.3	0.0
	WF16	101	2	53	0	2.0	0.0
	WF25	59	3	76	0	5.1	0.0
	WF35	41	0	18	0	0.0	0.0
fall impass							
	EF09	59	1	57	0	1.7	0.0
	EF14	9	0	24	0	0.0	0.0
	EF22	30	1	10	0	3.3	0.0
	NR28	14	0	18	0	0.0	0.0
	NR33	60	0	104	1	0.0	1.0
	NSR22	59	0	41	0	0.0	0.0
	WF15	36	0	24	0	0.0	0.0
fall pass							
	EF10	26	0	20	0	0.0	0.0
	EF18	37	1	36	0	2.7	0.0
	NSR16	41	0	42	0	0.0	0.0
	SSR09	30	0	25	1	0.0	4.0
	WF16	25	0	34	0	0.0	0.0
	WF25	21	0	12	0	0.0	0.0
	WF35	10	0	3	0	0.0	0.0

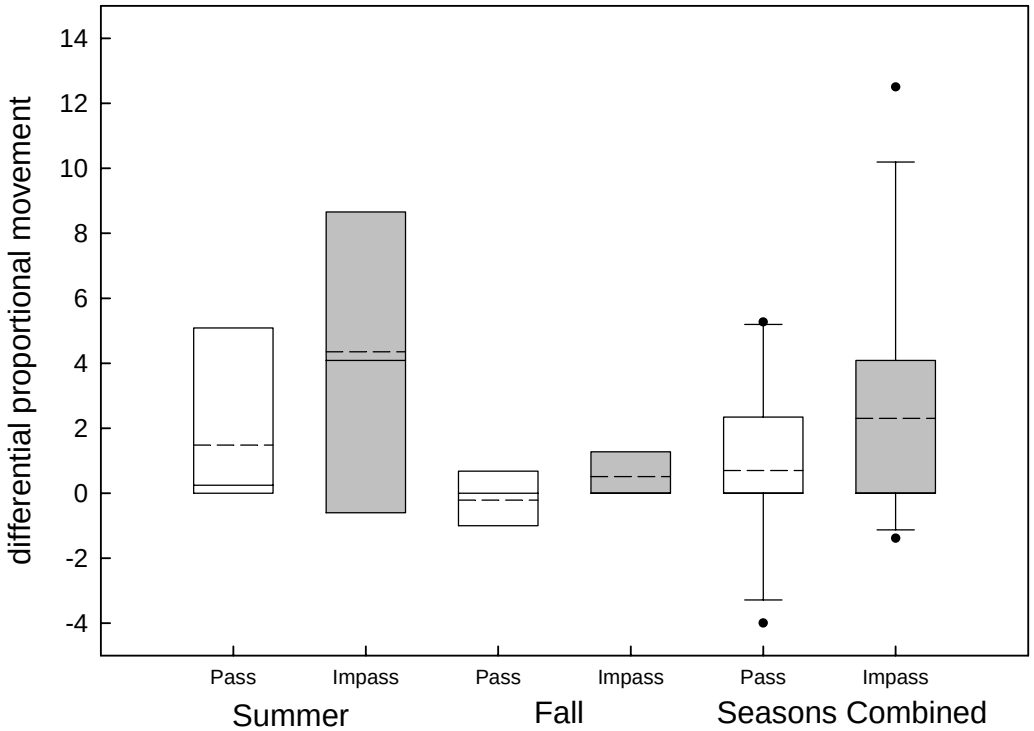
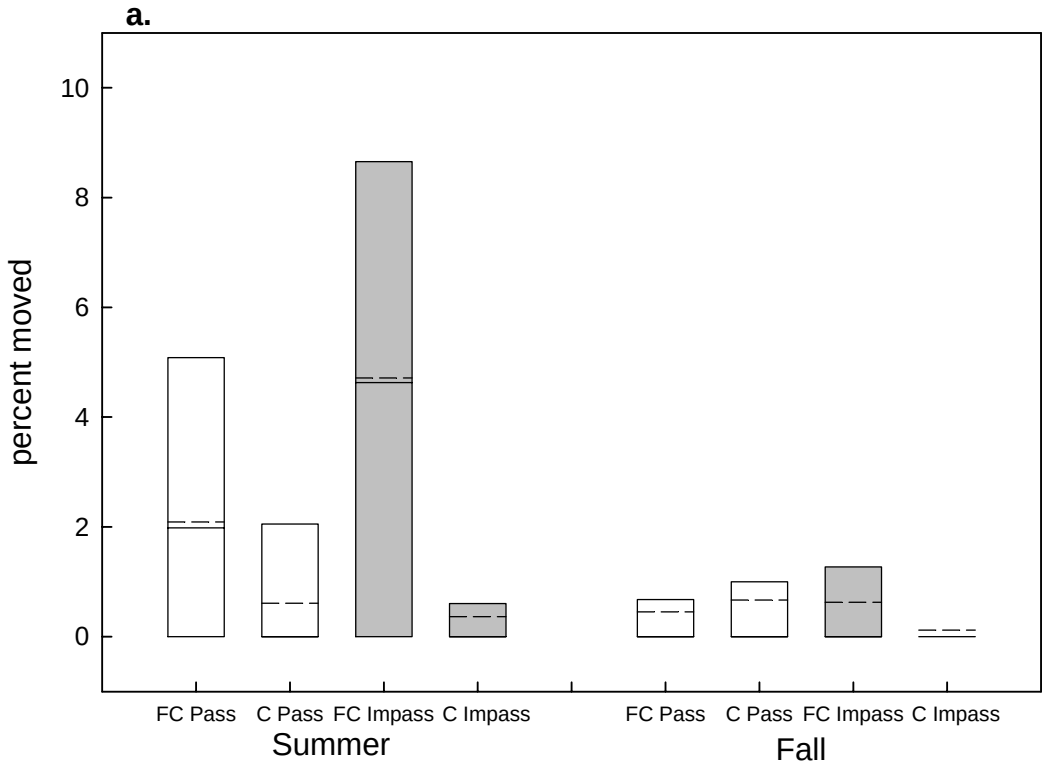


Figure 2.11. Box plots of differential movement at passable (pass) and impassable (impass) sites for Group C during the summer fall and seasons combined. The dashed lines represent the mean and solid lines represent the median.



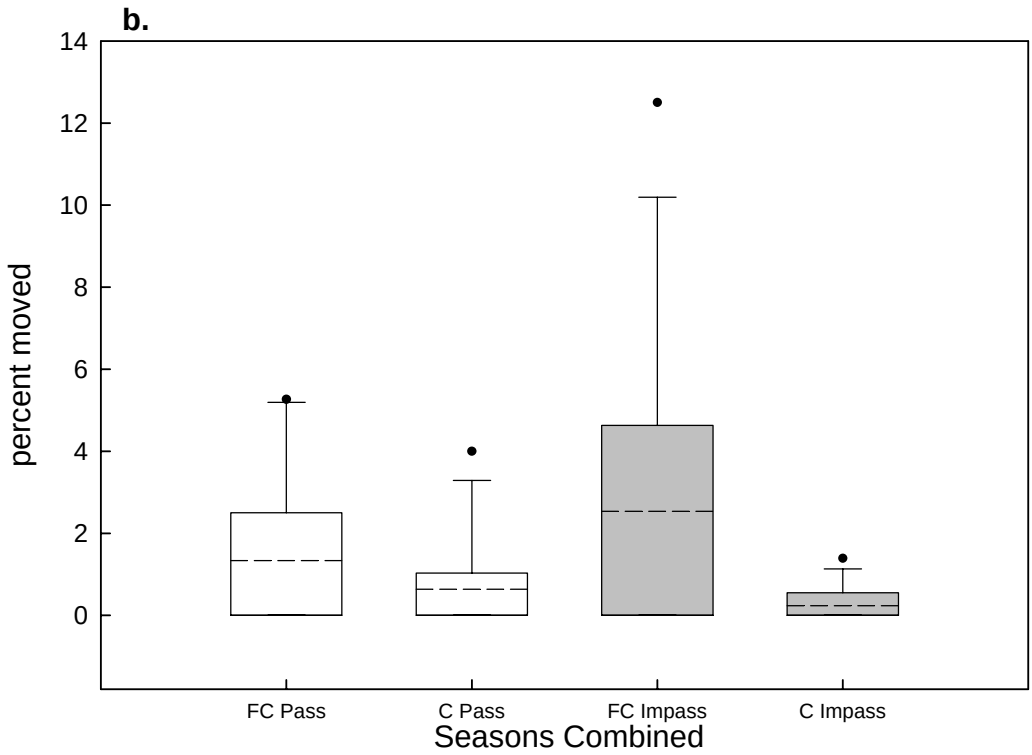


Figure 2.12. Box plots showing distribution of movement through the false culvert (FC) and the culvert (C) for passable (pass) and impassable (impass) sites of Group C. The dashed lines represent the mean and solid lines represent the median. Panel a shows summer and fall 2004 movement. Panel b is for the both seasons combined.

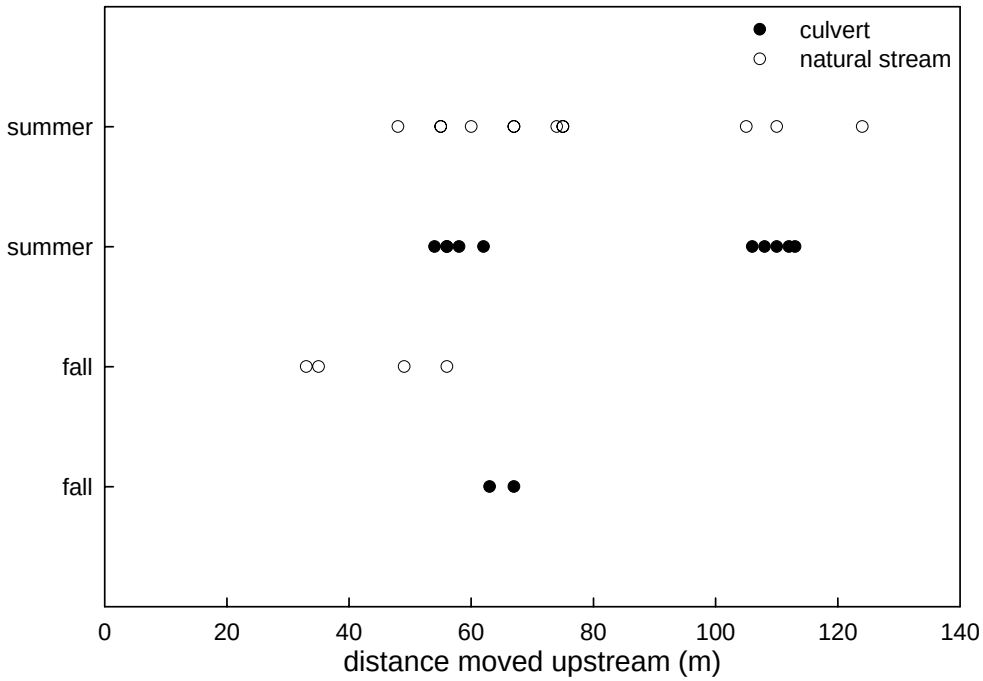


Figure 2.13. Distances moved upstream by individual marked fish from Group C through a section of undisturbed stream and through culverts during the summer and fall 2004.

Water Velocity

Fourteen of the twenty-six streams sampled had mean culvert water velocities greater than water velocities in the channel during one or both seasons. Of those fourteen sites eight were classified as impassable by one or more of the predictive models. Water velocities of those fourteen sites on average were four times higher than their associated mean channel velocities. Twelve of the twenty-six had culvert water velocities within or below the range of water velocities in the channel. One or more of the predictive models classified nine of those twelve sites as passable. I found fish movement was rare when water velocities in the culverts exceeded 75 cm/s (Figure 2.14) and velocity was negatively correlated with movement by species in Group B (Kendall's tau-beta = -0.301, P = 0.005). Graphs of the channel and culvert velocities for the 26 study sites are presented in Appendix B.

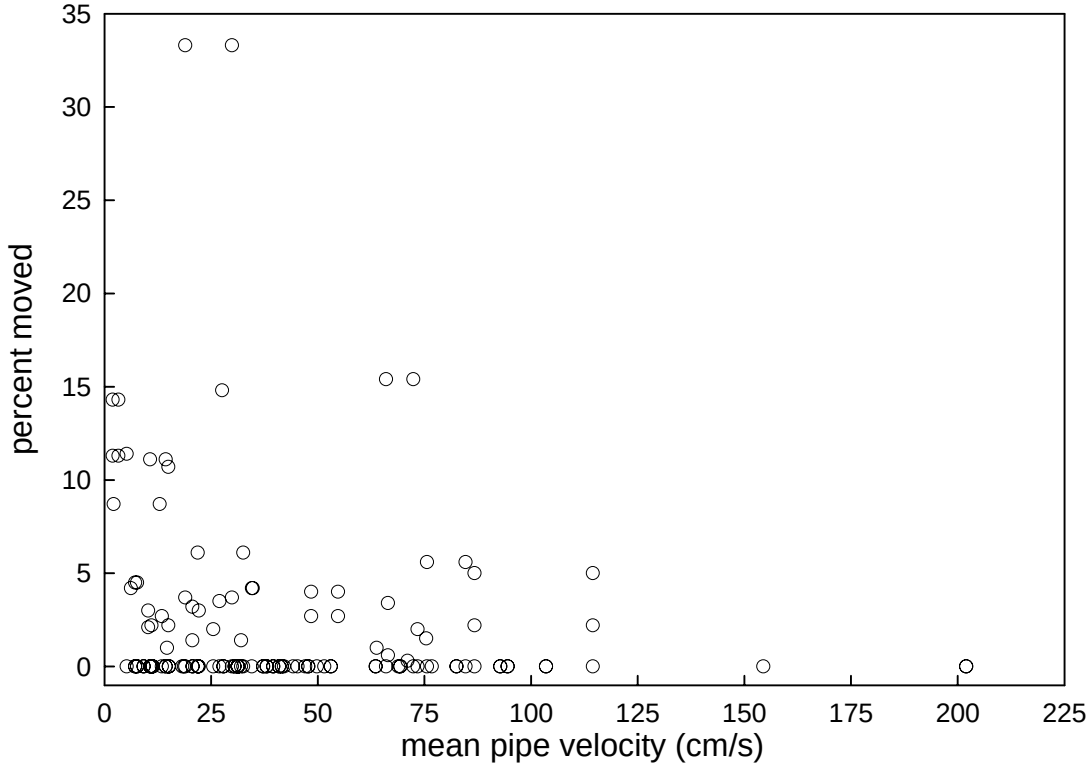


Figure 2.14. Scatterplot of proportional fish movement and mean culvert water velocities for groups A, B, and C (n = 141).

Correlations

The relationships of movement with slope (Kendall's tau-beta, $P < 0.001$ $n = 48$) and slope x length (Kendall's tau-beta, $P < 0.001$ $n = 49$) (Bonferroni adjusted α of 0.002) for the seasons combined in Group B were significant. Movement through culverts by the other groups of fishes was not highly correlated with any culvert characteristics (Table 2.12).

Table 2.12. Correlations of proportional fish movement through crossings with selected culvert characteristics. Kendall's tau-beta coefficients are presented along with the P values of the correlations in parentheses. Significance is $P < 0.002$.

Culvert	Summer		Fall	Fall	Fall	Seasons Combined	
Characteristic	Group B	Group C	Group A	Group B	Group C	Group B	Group C
outlet drop	-0.301 (0.053)	-0.102 (0.606)	-0.128 (0.608)	-0.265 (0.090)	-0.094 (0.672)	-0.267 (0.014)	-0.104 (0.470)
slope	-0.365 (0.018)	-0.307 (0.122)	-0.256 (0.305)	-0.492 (0.002)	0.094 (0.672)	-0.440 (<0.001)	-0.137 (0.343)
slope x length	-0.342 (0.028)	-0.052 (0.796)	-0.065 (0.797)	-0.423 (0.007)	0.283 (0.204)	-0.381 (<0.001)	0.083 (0.557)

Discussion

Culverts, regardless of predictive model classification, reduced the overall upstream movement of species from groups A, B, and C compared to the movement in the stream (false culvert movement). The predictive model classifications were partially accurate for groups A and B with movement through impassable culverts roughly 10% lower than through the false culverts, but the models failed to accurately classify culverts in all cases. Some species of fish moved through culverts better than others signifying the different swimming abilities and motivations of the three groups. Movement through passable culverts was comparable to movement through false culvert sections for all three groups, and movement through the stream occurred at all study sites. The majority of passable culverts experienced movement illustrating that fish were successfully passing through those culverts only not at the same rate as through the false culvert. However, fish movement through impassable sites was more limited.

Two of the three culvert characteristics used in the predictive models (slope and slope x length) proved to be determining factors in fish movement through culverts for species in Group B. The nature of conducting multiple mark-recapture studies for specific species and also specific culvert characteristics over a large geographic area

limits the experimental population size. Along with an overall lack of movement for some species large variations in the data occurred.

In a mark-recapture study one of eight scenarios can happen to a marked fish: (1) the fish dies, (2) the fish moves downstream out of the sampling zone, (3) the fish moves upstream out of the sampling zone (4) the fish moves upstream but is not sampled, (5) the fish stays in the section it was marked in and is captured, (6) the fish stays and is missed during sampling, (7) the fish moves upstream and is captured, or (8) the fish is captured but the tag is missed. Scenarios 5 and 7 accounted for 23 % and 20% of the marked fish in the summer and fall. The question then becomes, what happened to the other 80% of the marked fish?

Scenarios 2 and 3 are possible but given the length of the recapture sections I feel confident I was able to potentially capture 80 to 90% of upstream fish movement (Albanese et al. 2003). Downstream movement of stream fishes is common and in most cases equal to upstream movement (Johnston 2000; Schmetterling and Adams 2004) in situations of free passage. The presence of movement barriers at culverts may increase downstream movement of mobile fish. Rapid population turnover in headwater streams (Fausch and Young 1995) could explain why some of the tagged fish were not recovered. Fish immediately downstream (< 50 m) of undersized culverts could also be more prone to displacement by scouring during high flows (Harvey 1987; Stock and Schlosser 1991). Construction and the presence of culverted road-stream crossings has been attributed to increased sedimentation directly downstream of roads (Wellman et al. 2000), which can adversely affect fish survival. Scenario 8 is unlikely, considering I personally tagged all the fish and inspected all captured fish for a fin clip, and I correctly identify tagged fish

100% of the time in a preliminary lab study. The potential to miss sampling individuals in R_C above the pipe during one pass electrofishing existed, but that potential also existed equally in the recapture section below the pipe. Species catchability was not calculated for this study but is assumed equal above and below the pipe given similar habitat characteristics and stream flow during the sampling.

There were instances where fish did not move through culverts classified as passable. Explaining why this occurred can be difficult. Movement could have occurred but was not detected (Scenario 4 or 3). This is possible but there was only one individual from Group A marked in the M_{FC} section captured above the culvert, and that individual was a fish marked in the summer but recaptured in the fall. Only 10 individuals (representing 4.3% of those that moved) from Group B marked in M_{FC} moved through the road crossings, and no individuals from Group C marked in M_{FC} moved through the culverts. Except of Group A during the summer mobile and non-mobile individuals did not differ in length, which is consistent with previous investigations of stream fish movement (Smithson and Johnston 1999; Albanese et al. 2004; Schmetterling and Adams 2004).

Individuals may not have moved through passable culverts because they had no motivation to move upstream. However, of the 9 passable sites in Group A without culvert movement, 4 had fish move through the natural stream section and all 8 impassable sites in Group A without culvert movement had movement through the false culvert.

In addition, the passable culverts in Group A that were also passable for Group B experienced movement by species from Group B in all but one of the sites. Given that

the species in Group B are weaker swimming fish (Hunter and Mayor 1986; Carpenter 1987), jump, velocity and exhaustion barriers can be eliminated as blocking movement by brook trout. Depth was most likely not a factor in blocking fish movement during the summer, because those culverts carried depths similar to stream channel depths. Species in Group A (primarily brook trout) may have faced a behavioral barrier during the study at some culverts preventing movement. Behavioral barriers are difficult to identify and are outside of the scope of this thesis, but could be important factor in a fish's decision to move through a culvert. Motivation such as spawning needs may be necessary to overcome some behavioral barriers.

Marked adult brook trout were observed above the culvert during the fall at five sites, indicating individuals were moving. The longest distance moved was 248 m. Other studies on brook trout movement have documented longer movement but were conducted on a larger temporal and longitudinal scale (Riley et al. 1992; Gowan and Fausch 1996; Peterson and Fausch 2003). This fall movement is most likely a seasonal spawning movement to seek suitable redd habitat (Jenkins and Burkhead 1993). Toward the end of the study the fall water temperatures were beginning to reach those typically observed during brook trout spawning (3-10°C) (Jenkins and Burkhead 1993) again lending itself toward supporting that the movement was seasonal.

During the summer, motivation to move may have been limited and movement was only occurring in small segments to match local habitat conditions (Gowan and Fausch 2002). Ideal foraging habitat may have been available within the mark section limiting exploratory movement. Adult brook trout were moving and the model accurately predicted that movement in some cases. The two crossings classified as

impassable that experienced movement during the fall indicated the need for model modification.

Species in Group B moved through the natural stream section and culvert during both seasons indicating movement is not solely associated with spawning which typically occurs during the late spring and early summer for cyprinids (Jenkins and Burkhead 1993). Blacknose dace that moved had movement distances slightly less than that reported for other cyprinids (Goforth and Foltz 1998; Johnston 2000). The maximum movement detection limit (250 m) of my study may have contributed to the lower median distance documented. The duration of the study (30 days) may have limited the distance fish could have traveled also accounting for the lower median distance.

Little information has been documented on resident stream salmonid young-of-year (YOY) movements (Hunt 1965). Brook trout YOY movement is mostly considered to be downstream dispersal with floods (Phinney 1975), but juvenile coho salmon (*Oncorhynchus kisutch*), cutthroat trout (*Oncorhynchus clarki*), and steelhead (*Oncorhynchus mykiss*) have been documented moving into small tributaries as a possible avoidance of unfavorable flows and temperature (Cederholm and Scarlett 1981). YOY brook trout moved upstream during this study, although the motivation is unknown. This second most abundant species in Group B moved a median distance of 110 m (maximum of 160 m) during the summer and 61 m (maximum of 110 m) during the fall (Figure 2.10). Such movements could be important to survival, dispersal and population maintenance for brook trout in unstable headwater streams. Other species in Group B did not occur in high enough densities for individual species analysis but one bluehead chub moved 217 m upstream during the summer. Two of the three culvert characteristics

(slope, and slope x length) used in the predictive models had negative correlations with movement of Group B species indicating their influence on fish movement through culverts.

Benthic stream fish in general are considered non-mobile (Hill and Grossman 1987) and could explain the short distances of movement observed in this study. But Schmetterling and Adams (2004) reported a maximum distance moved of 209 m for a freshwater sculpin and a median home range of 26 m with the greatest being 176 m. Both are longer than distances reported in earlier studies (McCleave 1964; Hill and Grossman 1987) and the longest distance (124 m) moved by sculpin observed in the present study. Natsumeda (1999) reported a range of sculpin spawning movement (0 to 100 m) similar to the distances I observed. The distanced moved by Group C species and proportion moved in the fall was lower than the summer. Summer median distance was 84 m (maximum of 124 m), while the median distance was 65 m (maximum of 67 m) in the fall. The onset of cooler temperatures and shorter days may have had an effect on mottled sculpin movement.

Long distance movement of resident fish may be rare and the temporal scale used in the present study could have been biased to short distance movement, but some long distance movement was documented (> 110 m for a mottled sculpin and > 400 m by a brook trout). These long distance movements can be important in maintaining population connectivity in stream networks (Larson et al. 2002), and contributing to the establishment and reestablishment of populations. Only a few individuals may be needed to establish a population and if those individual movements are spread out over the

course of a year the need to always meet passage requirements may become even more important to stream fish viability.

Water velocity has been identified as a limiting factor in fish passage through culverts (Warren and Pardew 1998; Jones et al. 1974). At my study sites, water velocity and culvert dimensions that affect water velocity (slope and slope x length) were inversely correlated to movement by species in Group B, demonstrating the role velocity plays as a barrier to movement. The degree to which crossings alter flow can determine the presence of barriers (Warren and Pardew 1998). In this study all bottomless arches except two had culvert water velocities within the range of their channel velocities and allowed fish passage. The two with higher velocities, SSR06 and SSR09, presented unique situations not normally encountered with bottomless arches. The bottomless arch at SSR06 spanned a natural bedrock slide (slope of 8.8%) producing high water velocities, and SSR09 had a large deposit of substrate on one side of the structure that essentially channelized the stream causing the high water velocities.

Circular culverts, known to constrict the flow of water causing increased velocity and downstream scouring, produced the highest water velocities second only to the bedrock chute of SSR06. Barriers can develop over time as the culvert alters channel morphology. The average water velocity of culverts for both seasons was 51 cm/s. This is higher than the prolonged swim speeds of 45 cm/s and 30 cm/s reported for a few species from groups B and C respectively (Layher and Ralston 1997a; Layher and Ralston 1997b). Eighteen of the twenty-six crossings had water velocities higher then the swimming ability of the species tested at least once during the study. Warren and Pardew (1998) found passage was limited for many species of fish when water velocities met or

exceeded 40 cm/s. Velocity barriers can be a leading cause of impeding passage. Stream fish species can be highly mobile and important in colonization of locally extirpated stream reaches (Peterson and Bayley 1993; Olmsted and Cloutman 1974; Phinney 1975; Larimore et al. 1959; Gunning and Berra 1969), but only when access is available.

Culverts at road crossings can impede the upstream movement of a variety of freshwater fish species (Warren and Pardew 1998; Rajput 2003; Derksen 1980). More specifically, it is the dimensions of the culvert along with flow regimes that create different barriers preventing movement. Depending on the stream flow at a given time and the characteristics of a culvert; fish passage requirements can always be met, frequently met, infrequently met, or never met. The timing and frequency of not meeting passage requirements can lead to local extirpation of species, or genetic fragmentation (Reiman and Dunham 2000). Recent developments in microsatellite analysis can be used to identify gene flow across potential barriers (Knaepkens et al. 2004), and measure dispersal in addition to mark-recapture studies (Wilson et al. 2004). Freedom of movement allows fish to exploit resources, seek suitable habitat and recolonize stream reaches after local extinctions (Olmsted and Cloutman 1974; Meffe and Sheldon 1990; Peterson and Bayley 1993; Schlosser and Angermeier 1995; Ensign et al. 1997; Gowan and Fausch 2002; Roghair et al. 2002).

Many stream fishes have specific spawning substrate requirements and long distance movement may be necessary to locate suitable habitat and persist in dynamic stream environments where stream channel morphology is constantly being modified by natural and anthropogenic processes. My results indicate that culverts impede fish passage regardless of predictive model classification. The degree to which passage is

impeded can be of interest concerning the predictive model classifications. The current situation of road-stream crossings may be that all crossings impede movement only at different rates. I identified characteristics and the extent of those characteristics that create barriers for upstream fish passage using the predictive models and field experiments. To assess fish passage for a wide array of species the models I have developed and tested in the field that incorporate the characteristics of outlet drop, slope, and slope x length can be assets to natural resource managers with road stream crossing inventory and assessment responsibilities.

Chapter Three: Model Modification and Improvement

Introduction

The models I developed to predict upstream fish passage through culverts failed to accurately classify culverts for passage the majority of the time, although classifications for groups A and B were partially accurate. The models failed in situations where the fish contradicted the classifications and moved through impassable culverts. Tagged fish moved upstream through seven sites classified as impassable for one or more of the groups. To address these instances, I tested for correlation of the proportion of the marked fish that moved with the physical culvert characteristics used in the model and identified trends and thresholds in the data indicating where the models failed and where they could be improved.

Model Modification

Group A

Brook trout moved through two impassable sites during the fall of 2004 (WF19 and EF22). Outlet drop for Group A was not adjusted because no individuals moved through culvert with drops greater than 60.96 cm (Figure 3.1). WF19 was classified as impassable with a slope > 6.0% (6.24%), and EF22 was classified as impassable based on its slope x length value > 76 (189). Identification of a threshold value for these culvert characteristics for Group A is difficult because of small sample size but fish did not appear to move when slope was greater than 6.5% (Figure 3.2). Again zero values for fish movement above 6.5% are limited, but these data along with review of the literature documenting trout movement through stream channels and culverts at varying slopes were used to adjust the slope threshold to 7.0%. Under the new standard for slope WF19 is classified as indeterminate. This classification was not tested in the field because of

the nature of the classification. Indeterminate indicates fish passage cannot be determined by culvert characteristics alone and additional empirical data on fish movement is needed to make a determination. A classification of passable indicates passage is possible at base flows approximated by 50% exceedance flows. When fish move through culverts classified as indeterminate it could mean (1), the culvert is actually passable at base flows and based on the fish movement data could be reclassified as passable, or (2) depending on the temporal and hydrologic flow regime that culvert may meet passage requirements infrequently. In these instances the classification of indeterminate is useful because managers can make site-specific determinations of passage and base remediation efforts on the specific passage needs of the species in question if that information is known. In general though, aiming for passage at base flows can insure movement under most hydrologic conditions.

Site EF22 had two brook trout move through the crossing. One was a fish marked in M_{FC} during the summer captured above the pipe during the fall. The other was a fall M_C marked fish. EF22 was a long box culvert (47.9 m) of moderate slope (3.94%) with a small outlet drop (23 cm). The slope x length value for EF22 is 2.5 times that of the current model's value (Figure 3.3). It is difficult to make inferences from this graph due to the small sample size, but generally movement is highest for slope x length values <25. Lack of resting pools within culverts can contribute to exhaustion barriers for fish passage (Baker and Votapka 1990). If no velocity refuge exists in long crossings, a fish will tire before exiting the culvert and be washed back downstream. However, this was not the case at site EF22 where, under certain flow conditions, passage was possible. Under these conditions unseen hydrologic dynamics in the culvert could have produced

zones of low velocity providing passage through the 50 m culvert without defined resting pools.

EF22 is similar to WF19 in that it probably meets passage needs infrequently for brook trout. If the timing of brook trout movement does not coincide with the infrequent conditions of fish passage detrimental effects to an individual and a population could arise. The values for slope and slope x length were adjusted for the Group A predictive model (Figure 3.4). These adjustments changed EF22, and WF19 from impassable to indeterminate trigging biological sampling to evaluate fish movement.

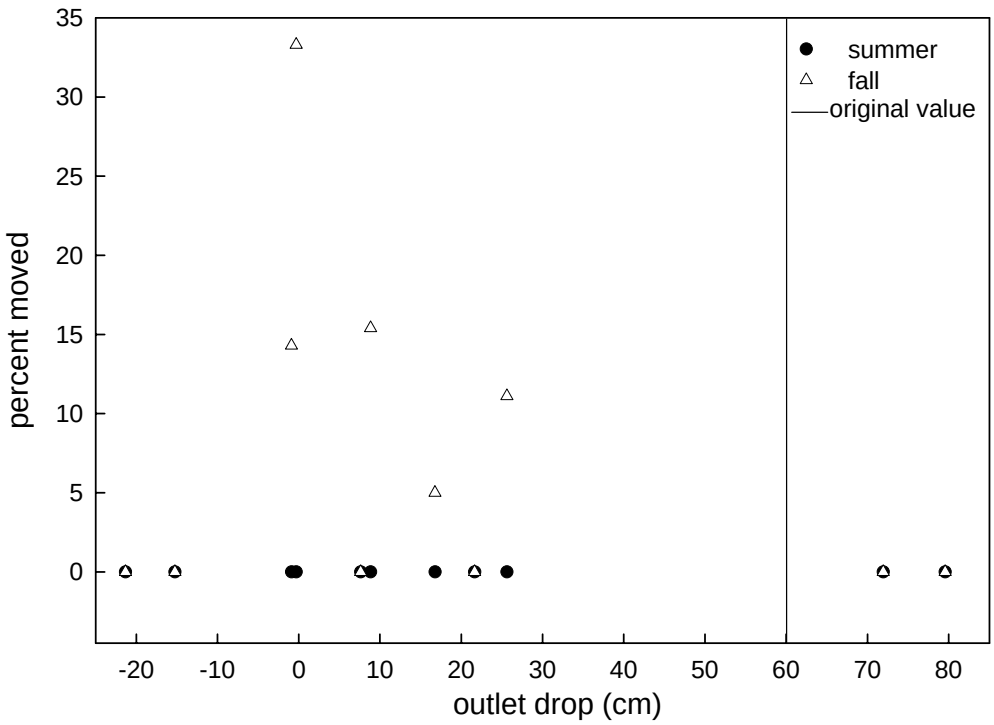


Figure 3.1. Scatterplot of outlet drop and proportional fish movement through culverts for Group A during the summer and fall of 2004 (n = 22). The vertical line (60.96 cm) is the threshold used in the original and modified models.

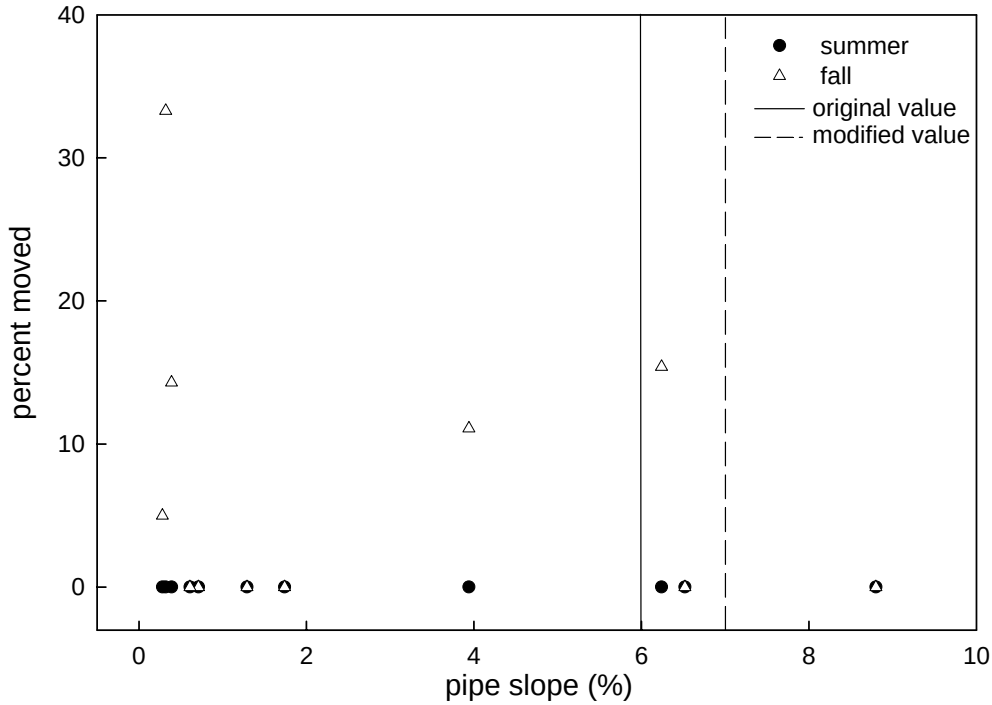


Figure 3.2. Scatterplot of pipe slope and proportional fish movement through culverts for Group A during the summer and fall of 2004 (n = 22). The vertical lines solid (6.0%) and dashed (7.0%) are the thresholds used in the original and modified models, respectively.

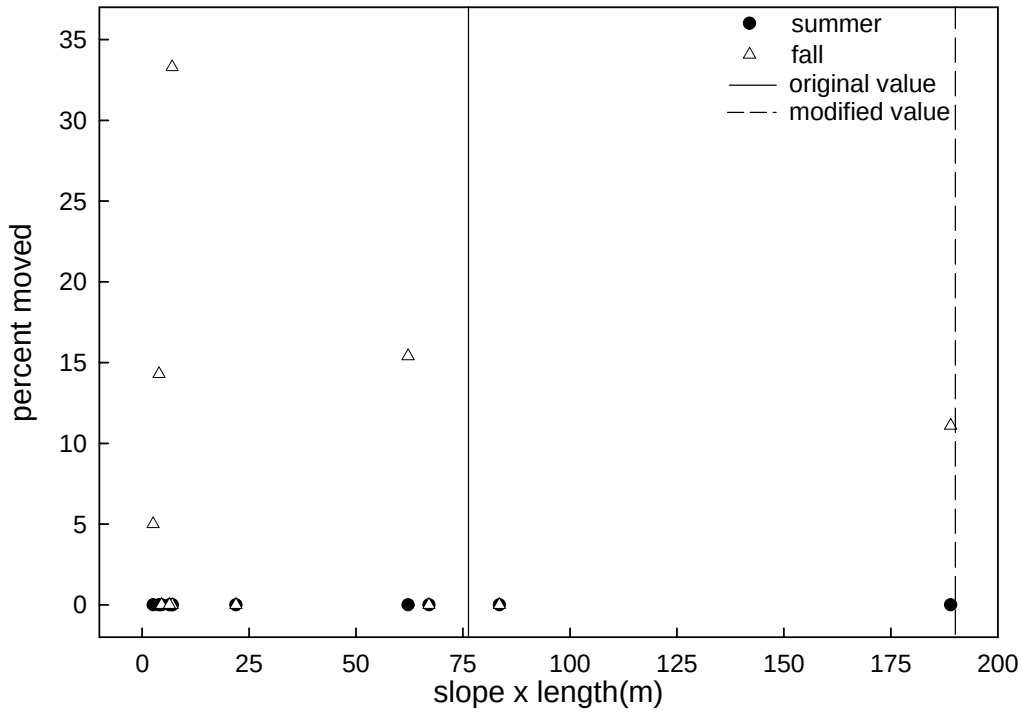


Figure 3.3. Scatterplot of pipe slope x length and proportional fish movement through culverts for Group A during the summer and fall of 2004 (n = 22). The vertical lines solid (76) and dashed (190) are the thresholds used in the original and modified models, respectively.

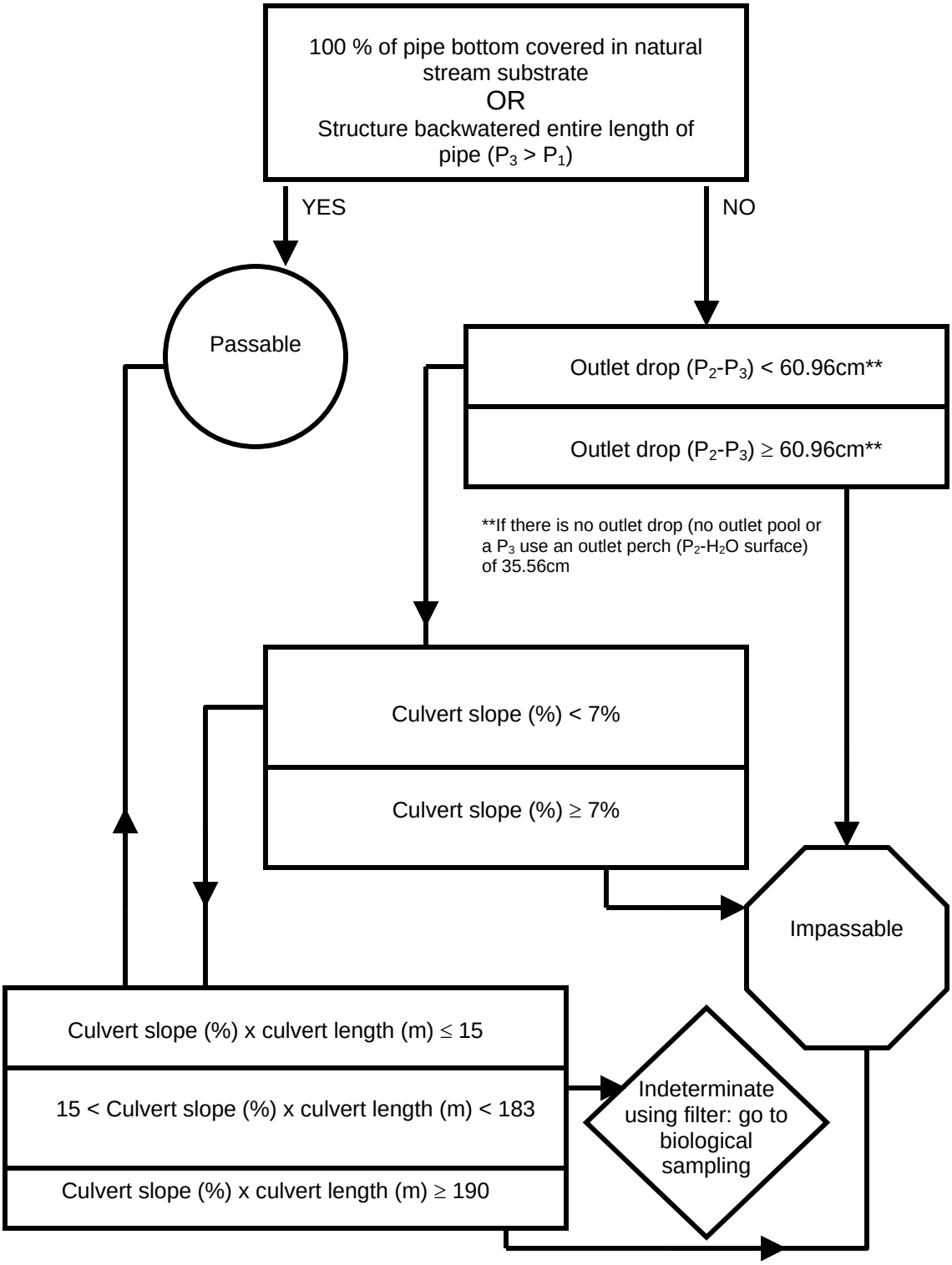


Figure 3.4. Modified upstream fish passage predictive model A for Salmonidae. See Figure 1.1 for a profile of survey points used in fish passage coarse filter. P_n = elevation measurements.

Group B

Individuals in Group B moved through three culverts classified as impassable during the summer (NSR21, NSR22, WF15) and one during the fall (NR28). The species that moved through impassable culverts were blacknose dace (n = 6), longnose dace (n = 1), and bluehead chub (n = 1). Sites NSR21 and NR28 were classified impassable with outlet drops exceeding the limit of the model. One blacknose dace moved upstream through the culvert at site NSR21 (outlet drop 23.77 cm) (Figure 3.5). This data point is an outlier because during the recapture sampling it became apparent water was flowing under the culvert during the study and the individual that moved likely moved upstream via this route. In addition, no fish moved through NSR21 during the fall. Only one bluehead chub moved through the culvert at NR28 (outlet drop 21.34 cm).

Sites NSR22 and WF15 presented unique situations of varying culvert slope for NSR22 and the presence of an outlet apron for WF15. NSR22 had one longnose dace and two blacknose dace move through the culvert. NSR22 was a vented ford with essentially two slopes. The culvert was bent and did not demonstrate the typical slope used in the model, compromising the model. It appeared that the culvert was backwatered to the bend at which point the slope of the culvert increased eliminating backwatering effects. The interaction of the two slopes could explain the fish movement but is not accounted for in the models. It is unclear if a flood topped the crossing, which could have allowed passage. Stream stage was not monitored daily, and a prediction of water level in the culvert is difficult to obtain given unknown hydrologic dynamics occurring in the culvert during high water events. Stream stage did increase some during

the period the movement occurred and because of the different slopes in the culvert could have created backwatering the entire length of the pipe.

NSR15 was a multiple pipe low water ford with an outlet apron to dissipate water energy as it exits the culvert to prevent scouring. The apron creates a sheet of water across the apron eliminating an outlet drop, but the apron does have a slope of 5.0%. The dynamics of aprons at vented fords during high flows could increase the chance of backwatering effects providing passage, although those times of passage could be infrequent. Despite these outliers culvert slope and slope x length had a strong negative relationship with fish movement for Group B. These data also illustrate the conditions where fish movement is mostly likely to occur. The majority of movement is centered on culverts with no outlet drop, slopes of 1.0%, and slope x length values of 10 (Figure 3.5, 3.6, and 3.7). Outlet drop, slope, and slope x length values were increased slightly to reduce the likelihood of inaccurately classifying a culvert impassable (Figure 3.8).

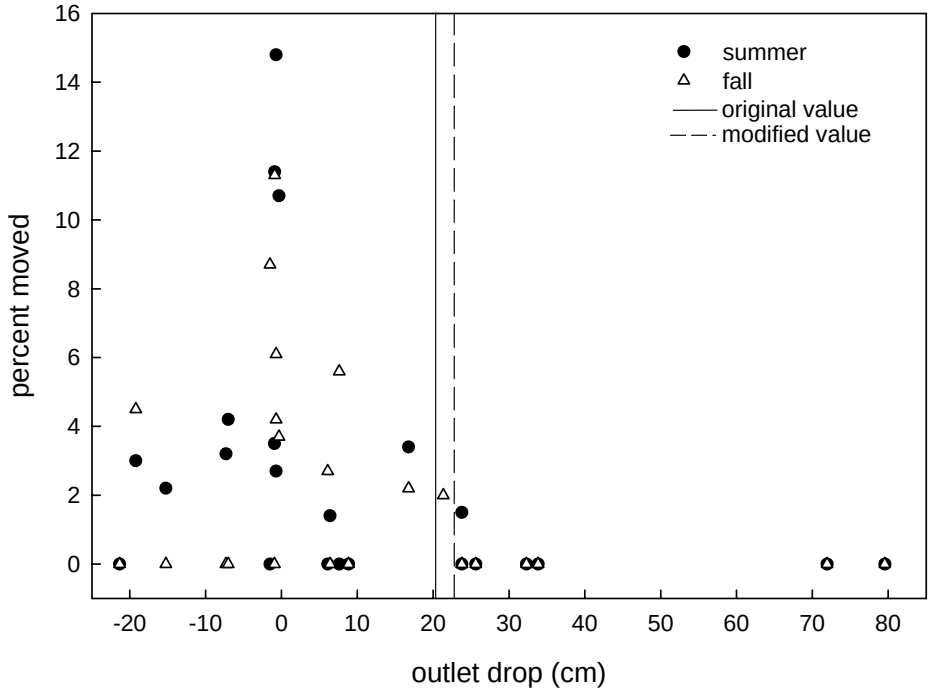


Figure 3.5. Scatterplot of outlet drop and proportional fish movement through culverts for Group B during the summer and fall of 2004 (n = 47). The vertical lines solid (20.32 cm) and dashed (22.86 cm) are the thresholds used in the original and modified models, respectively.

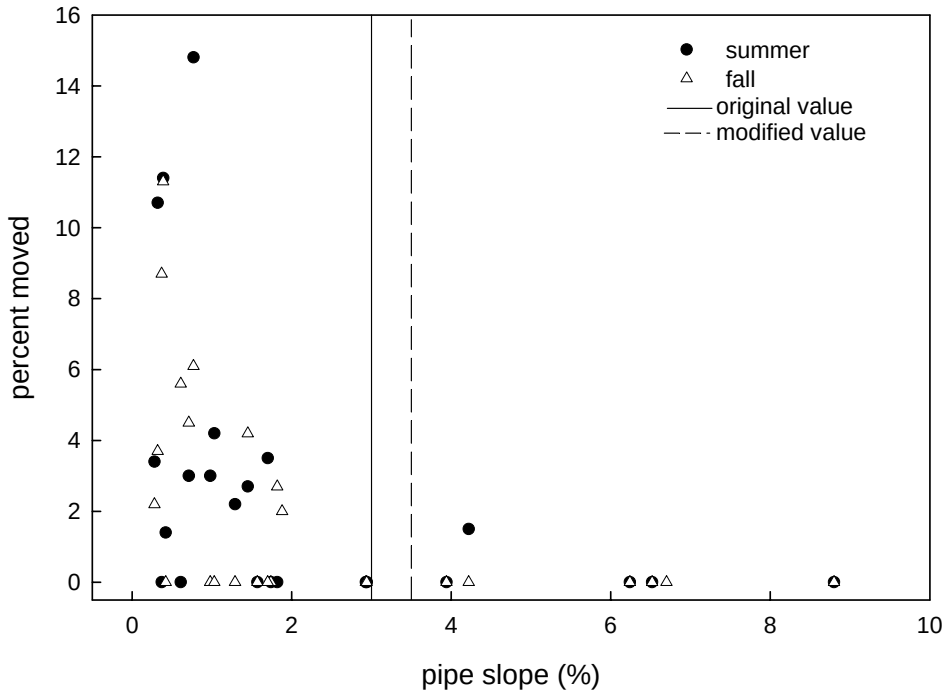


Figure 3.6. Scatterplot of culvert slope and proportional fish movement through culverts for Group B during the summer and fall of 2004 (n = 48). The vertical lines solid (3.0%) and dashed (3.5%) are the thresholds used in the original and modified models, respectively.

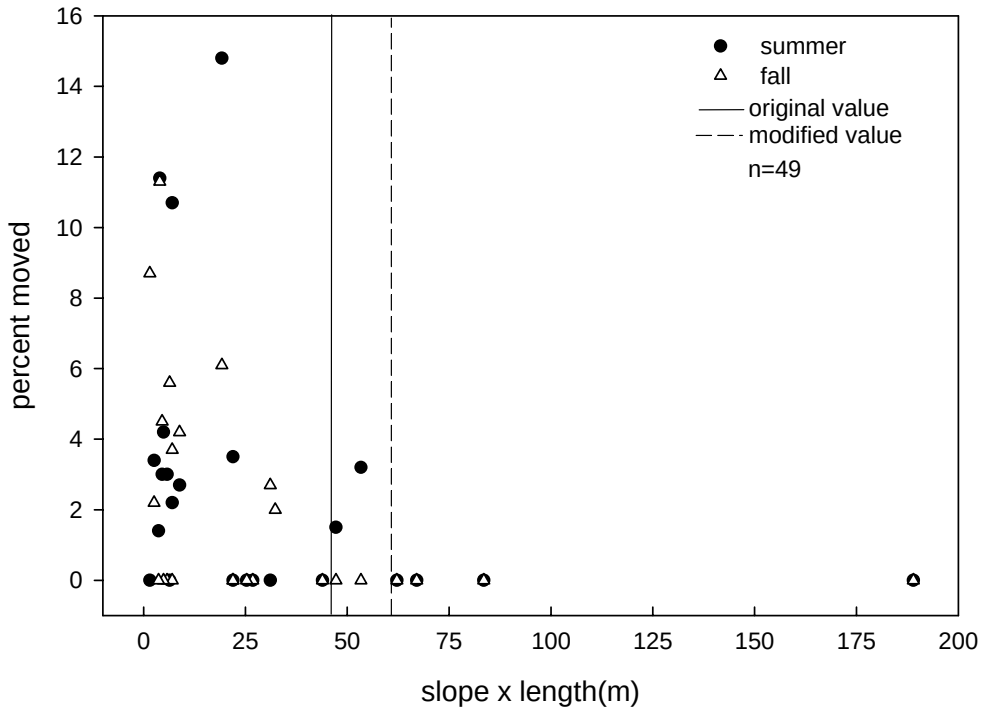


Figure 3.7. Scatterplot of culvert slope x length and proportional fish movement through culverts for Group B during the summer and fall of 2004 (n = 49). The vertical lines solid (46) and dashed (61) are the thresholds used in the original and modified models, respectively.

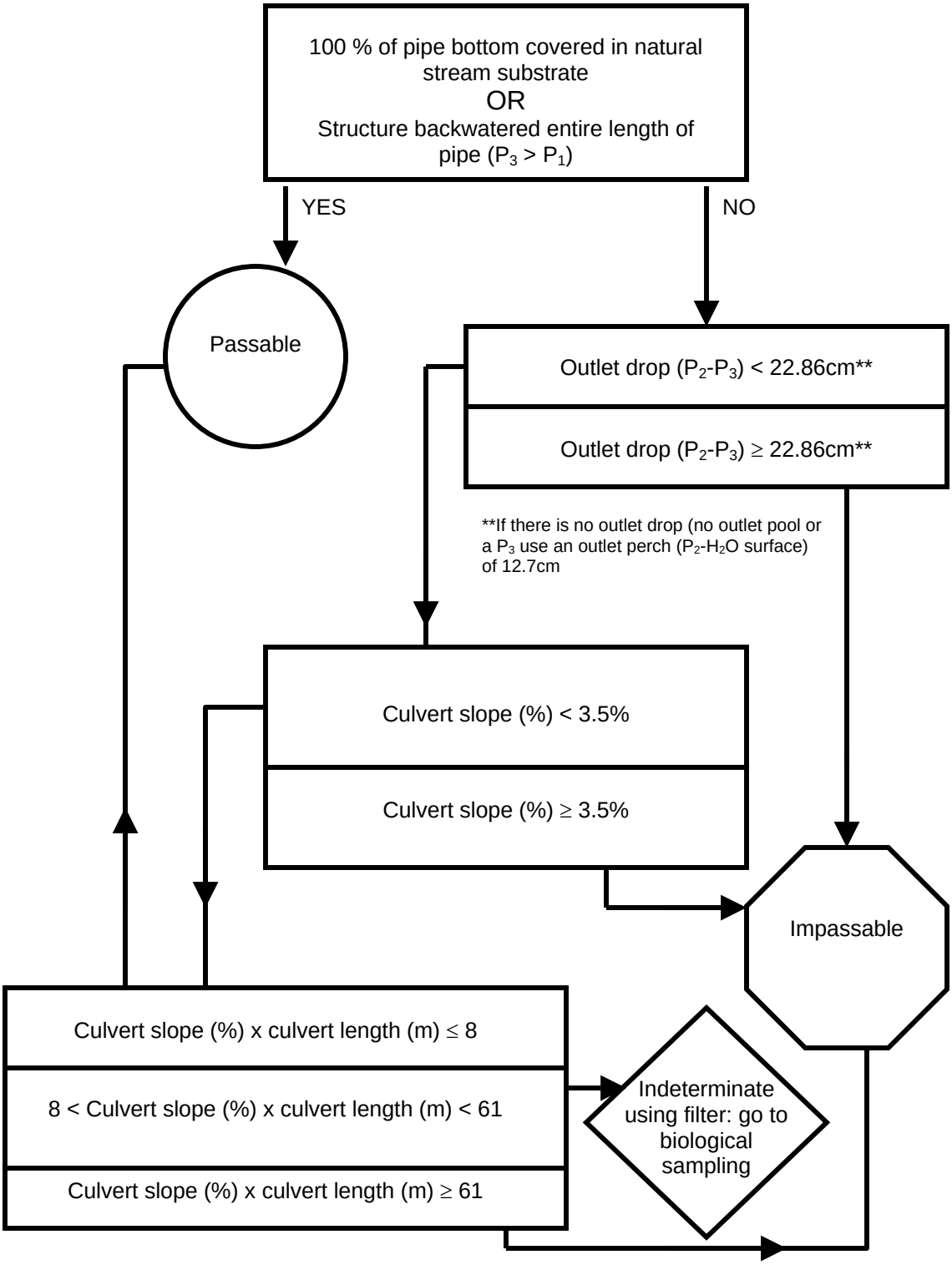


Figure 3.8. Modified upstream fish passage predictive model B for Cyprinidae and young of year salmonids. See Figure 1.1 for profile of survey points used in fish passage coarse filter. P_n = elevation measurements.

Group C

One mottled sculpin moved through the preliminarily classified impassable culvert at site NR33 and two through the culvert at site NSR22. Passage by sculpins at NSR22 can be explained with the same reasoning used for Group B, which was summarized previously. NR33 was classified impassable based on its outlet drop. This crossing also presents a situation where passage might be obtainable infrequently depending on flow conditions. It had a gentle slope (2.54%) that conveyed little water at base flow, but providing a fish could enter the pipe barrel the barriers would be limited. Entry in the culvert would have required higher flows and NR33 did see an increase in water level (3.1 cm) but it is difficult to determine if that would have been enough to eliminate the jump barrier. The scatterplots for Group C movement and culvert characteristics were not strongly correlated, but like the two previous groups movement was most prevalent at sites simulating stream conditions with culvert characteristic values at or near zero (Figure 3.9, 3.10, and 3.11). The variables of the predictive model were again increased to reduce the likelihood of inaccurately classifying an impassable culvert (Figure 3.12). The adjusted predictive model now classifies NR33 and NSR22 as indeterminate indicating passage needs may not be meet year round and biological monitoring should be implemented to fully assess passage.

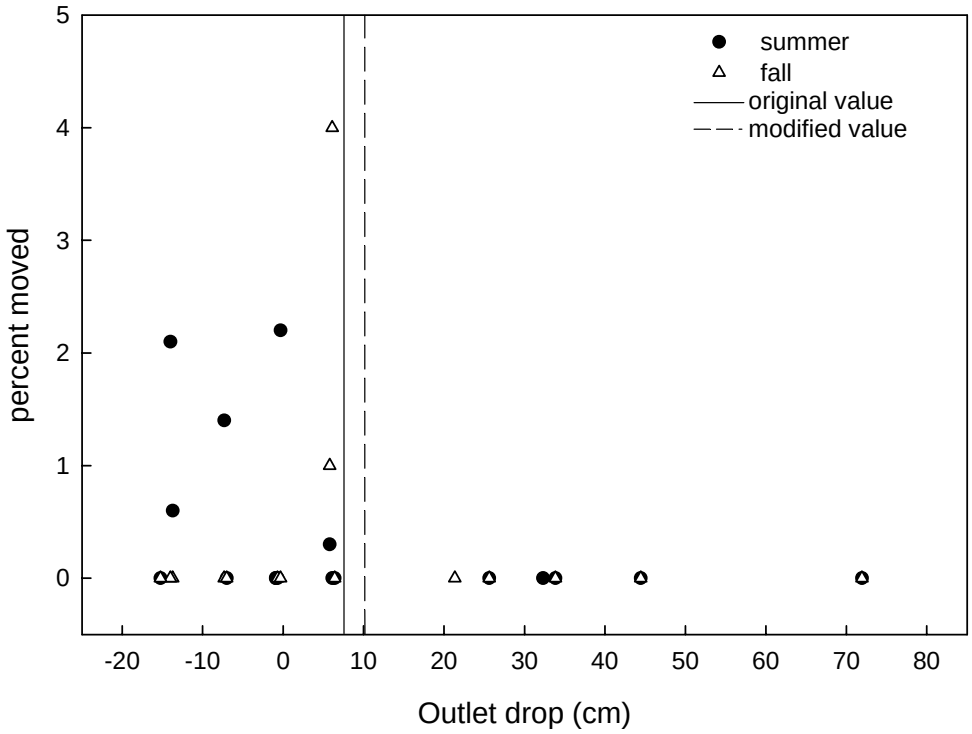


Figure 3.9. Scatterplot of outlet drop and proportional fish movement through culverts for Group C during the summer and fall of 2004 (n = 32). The vertical lines solid (7.62 cm) and dashed (10.16 cm) are the thresholds used in the original and modified models, respectively.

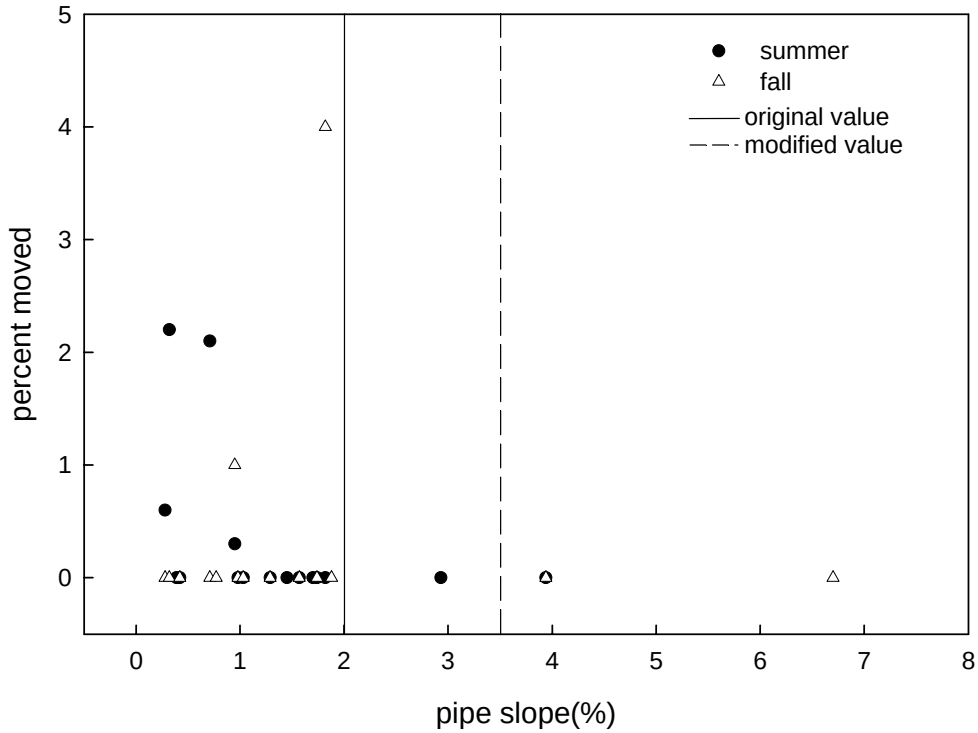


Figure 3.10. Scatterplot of culvert slope and proportional fish movement through culverts for Group C during the summer and fall of 2004 (n = 31). The vertical lines solid (2.0%) and dashed (3.5%) are the thresholds used in the original and modified models, respectively.

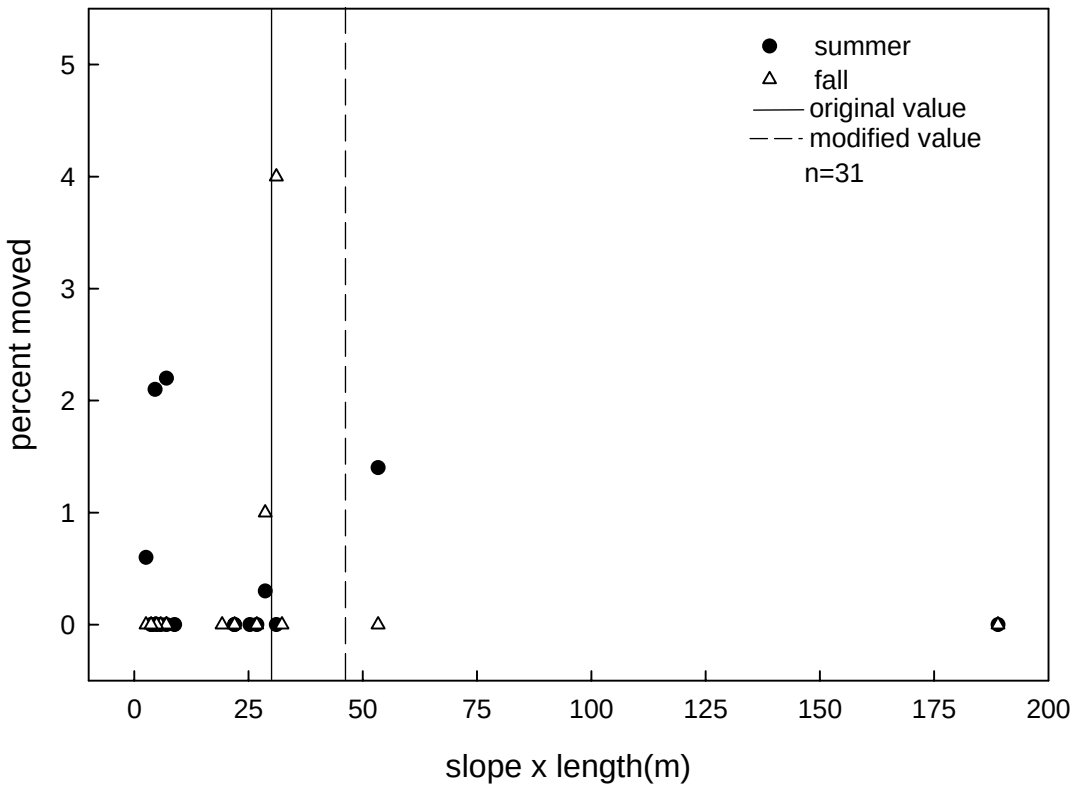


Figure 3.11. Scatterplot of culvert slope x length and proportional fish movement through culverts for Group C during the summer and fall of 2004 (n = 31). The vertical lines solid (30) and dashed (46) are the thresholds used in the original and modified models, respectively.

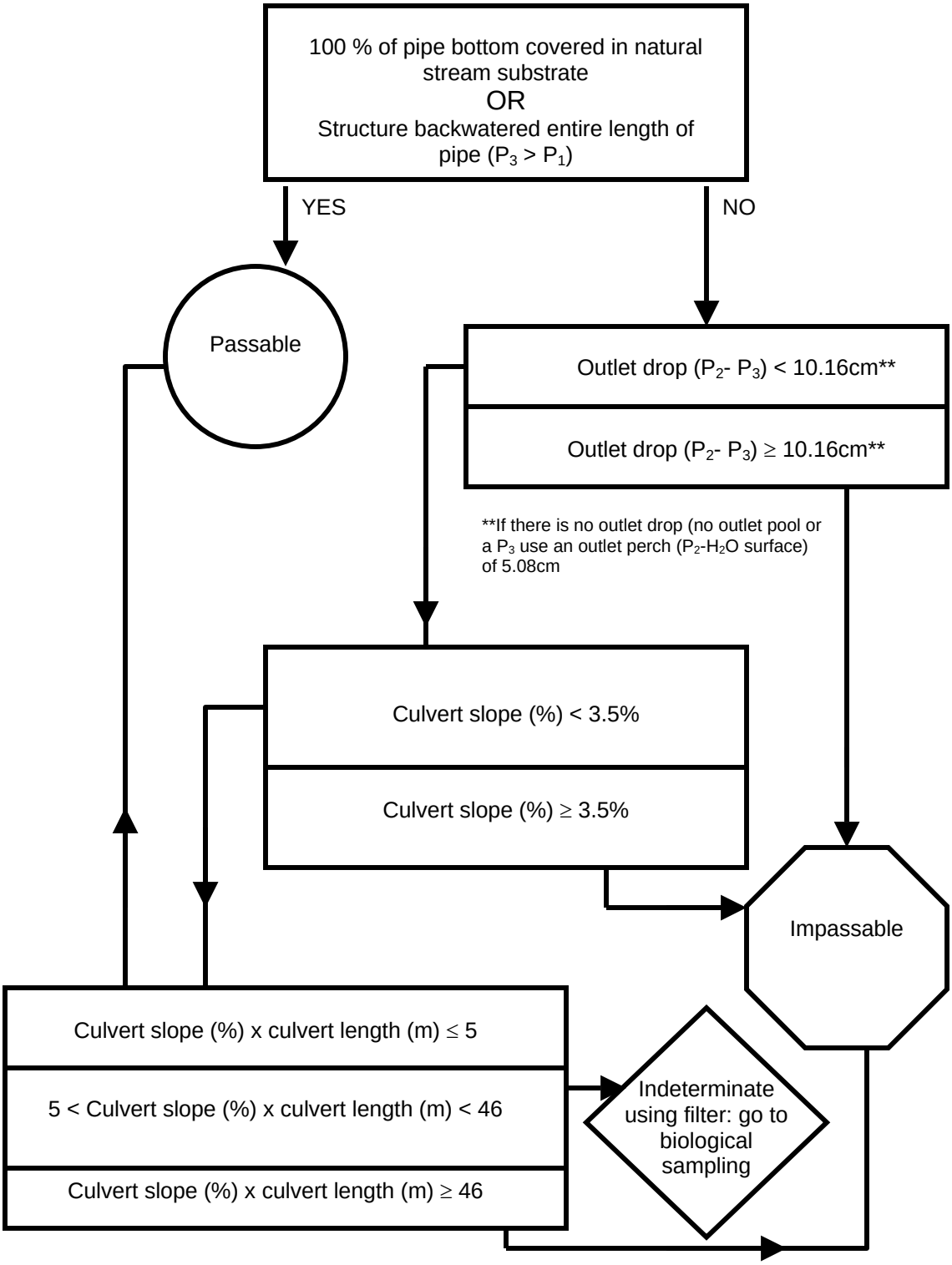


Figure 3.12. Modified upstream fish passage predictive model C for Percidae (except *Stizostedion sp*., and *Perca flavescens*), and Cottidae families. See Figure 1.1 for profile of survey points used in fish passage coarse filter. P_n = elevation measurements.

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. These conditions are difficult to meet with straight circular culverts. Bottomless arches and bridges can meet these conditions at a higher frequency than culverts or vented fords because they more closely simulate the stream conditions of slope, substrate, and width. Despite all the benefits of bottomless arches to fish passage, their use as crossing structures is limited. Installation of bottomless arches can be cost prohibitive (Murphy and Pyles 1989) and require more extensive installation procedures than other crossings types. Culverts are the cheapest crossing type to install and therefore are the most prevalent in forested watershed but can create the most passage problems (Baker and Votapka 1990). The modified predictive models incorporate empirical data about fish movement giving more credence to their classifications. The situations where movement through culverts classified impassable did occur was most likely related to the interaction of the culvert with increased flows. The dynamics of culverts under different flow conditions can complicate passage predictions, and even though passage did occur at those sites with preliminary classifications of impassable it may be too infrequent to maintain natural population dynamics. To ultimately insure these new models are accurate they need to be tested on a larger data set of culverts with characteristics values across the entire spectrum.

Synthesis and Management Implications

Culverts at road-stream crossings impeded fish movement in the study area for the species collected. The degree to which upstream movement is impaired depends on those physical characteristics of the culvert that create jump, velocity, exhaustion, depth and behavioral barriers. The incorporation of those characteristics into a model to predict fish movement produces classifications of passable or impassable. These preliminary classifications proved partially accurate in that (1) upstream fish movement through impassable culverts was either reduced compared to movement through the natural stream or did not occur and (2) upstream movement through passable culverts was comparable to natural stream movement.

Threshold values of the culvert characteristics used in the preliminary model for fish movement were identified and used to improve the model. These models could prove useful to natural resources managers assessing fish passage at road-stream crossings, because they can be an efficient method to screen thousands of road-stream crossings in forested watersheds of the eastern United States for a large assemblage of species. Providing passage to native fishes and preserving habitat connectivity should be a high priority for state and federal agencies. Conversely, impassable culverts may prevent the spread of nonnative invasive species, emphasizing the need for careful watershed prioritization for native species conservation.

Future culvert design and installation should take into consideration the thresholds of the culvert characteristics identified in this study to provide adequate passage for resident stream fish. The preservation of natural stream morphology and hydrology should be a goal of culvert design. This appears best achieved with bottomless arches or

bridges. Although they can be cost prohibitive, the benefit of increased habitat connectivity by bottomless arches and bridges for at risk species may outweigh the costs.

Appendix A

A literature review of source data used to place freshwater fish families into seven groups based on swimming and leaping ability as well as body form characteristics.

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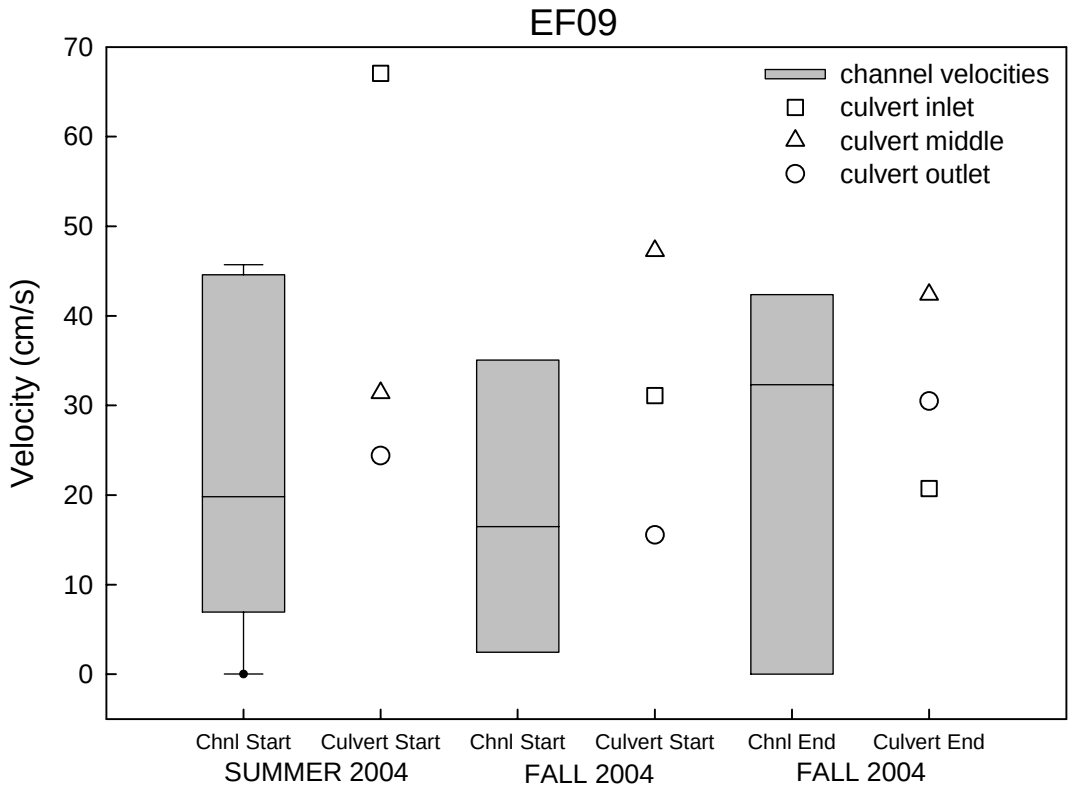
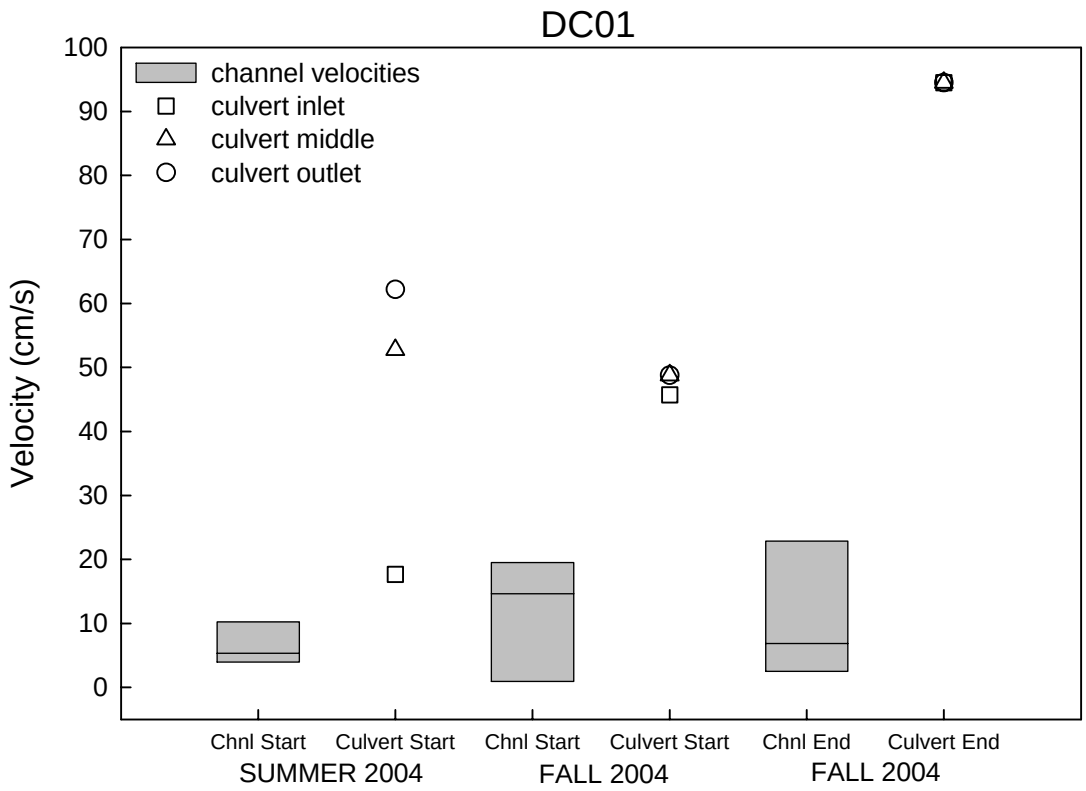
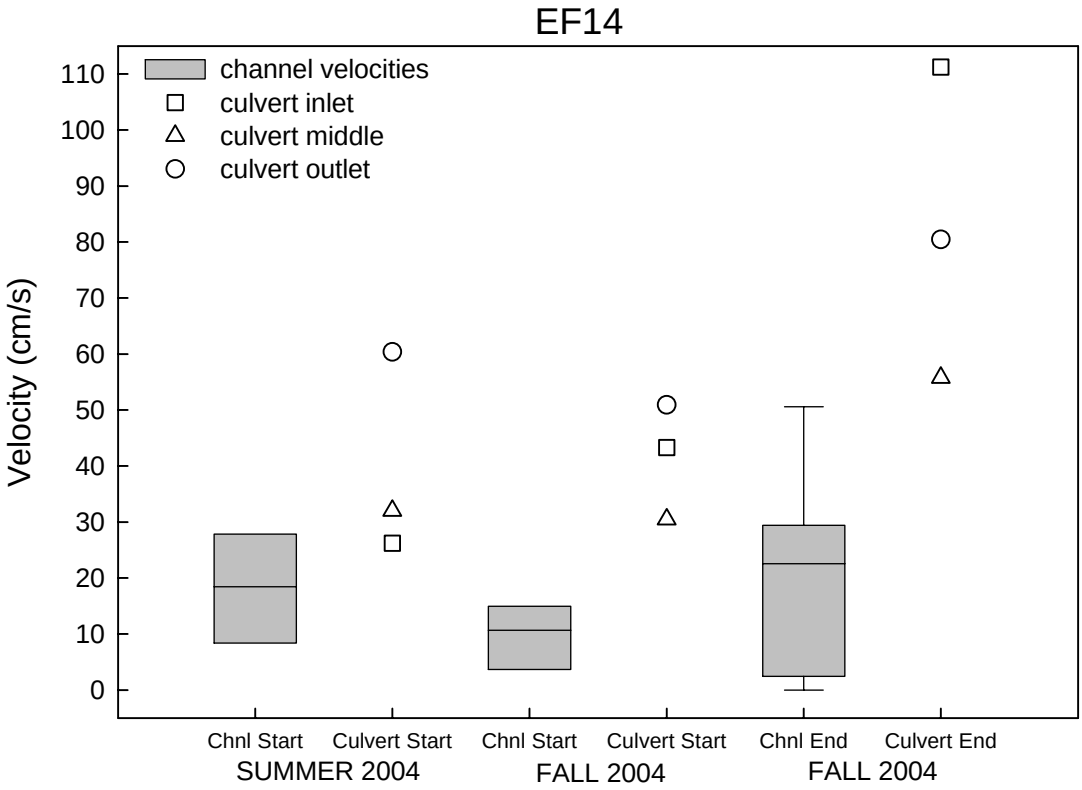
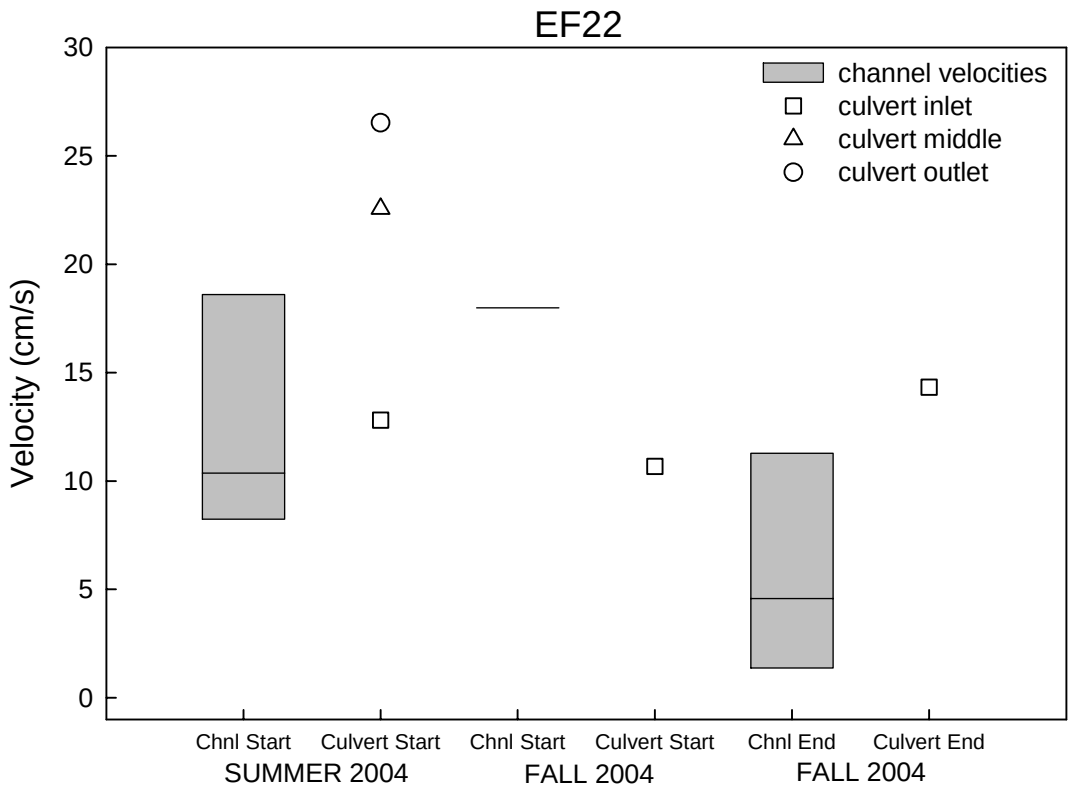
Appendix B

An archive of stream channel (Chnl) and culvert velocities for the 26 sites from the field validation experiment during the summer and fall of 2004 in the George Washington/Jefferson and Monongahela National Forests. The velocity measurements were taken at the start of the experiment during the summer and the fall, and at the end of the experiment during the fall.




DC01
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
0
10
20
30
40
50
60
70
80
90
100
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


EF14
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
0
10
20
30
40
50
60
70
80
90
100
110
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


EF22
Velocity (cm/s)
30
25
20
15
10
5
0
channel velocities
culvert inlet
culvert middle
culvert outlet
Chnl Start
Culvert Start
Chnl Start
Culvert Start
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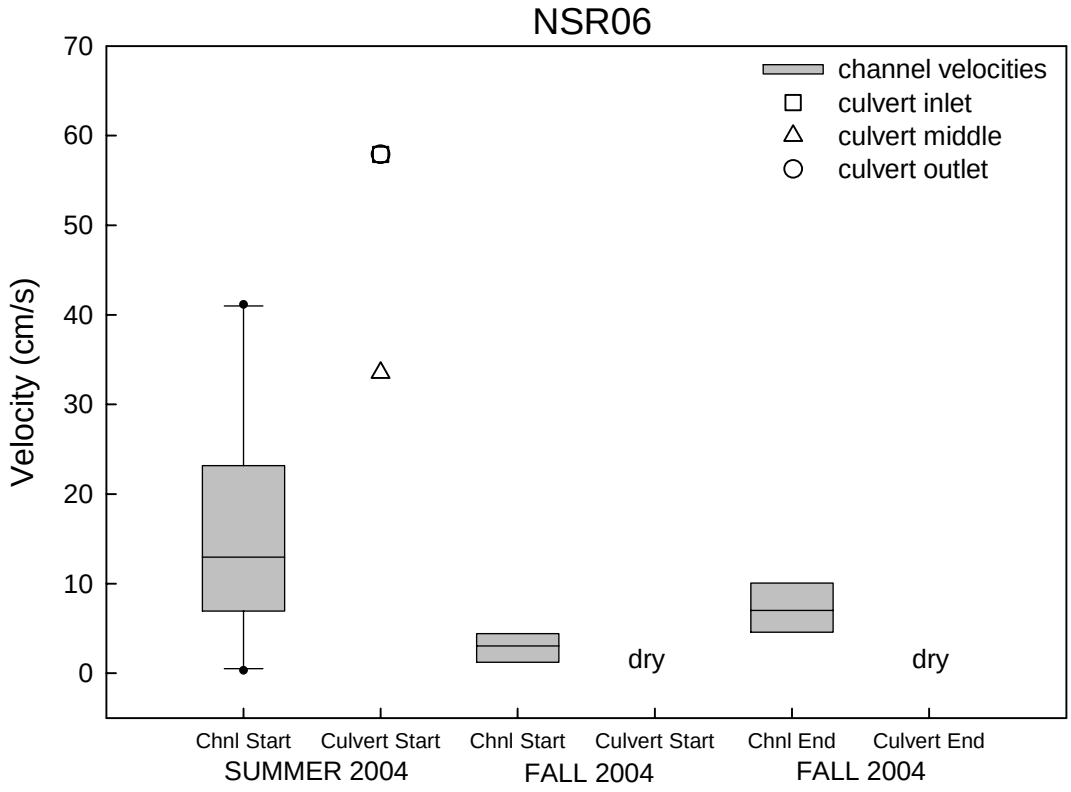
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


NSR06
Velocity (cm/s)
70
60
50
40
30
20
10
0
channel velocities
culvert inlet
culvert middle
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dry
dry
Chnl Start
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Chnl Start
Culvert Start
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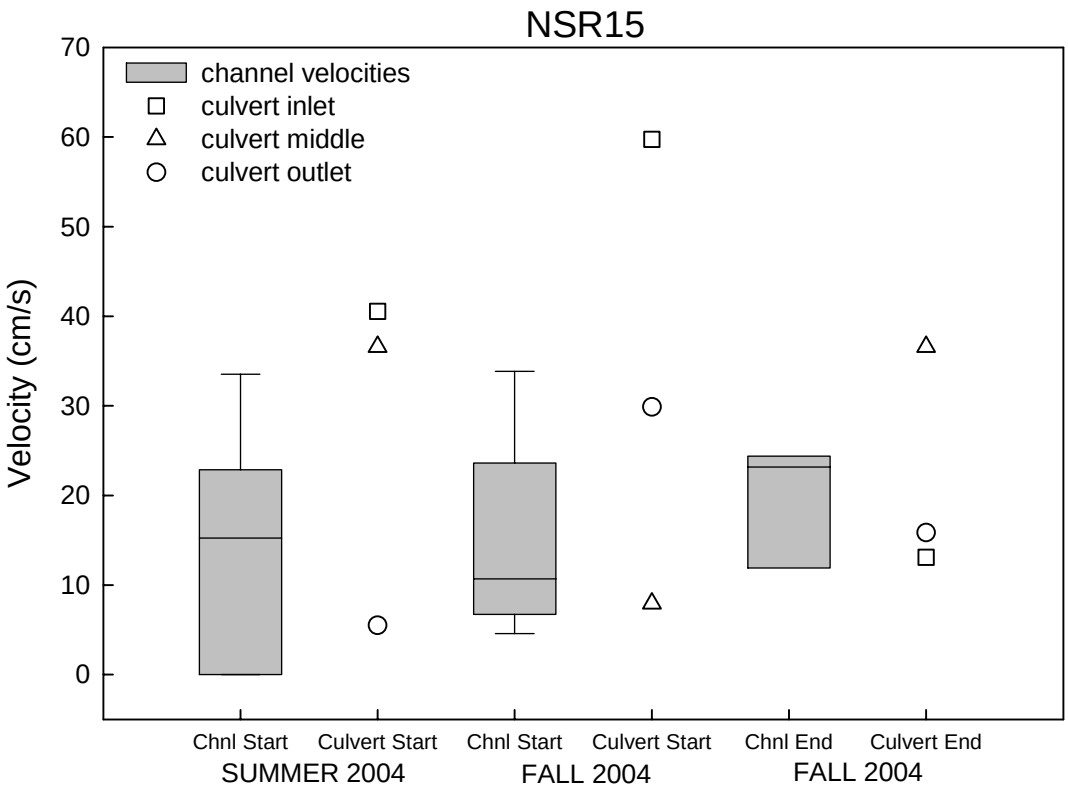
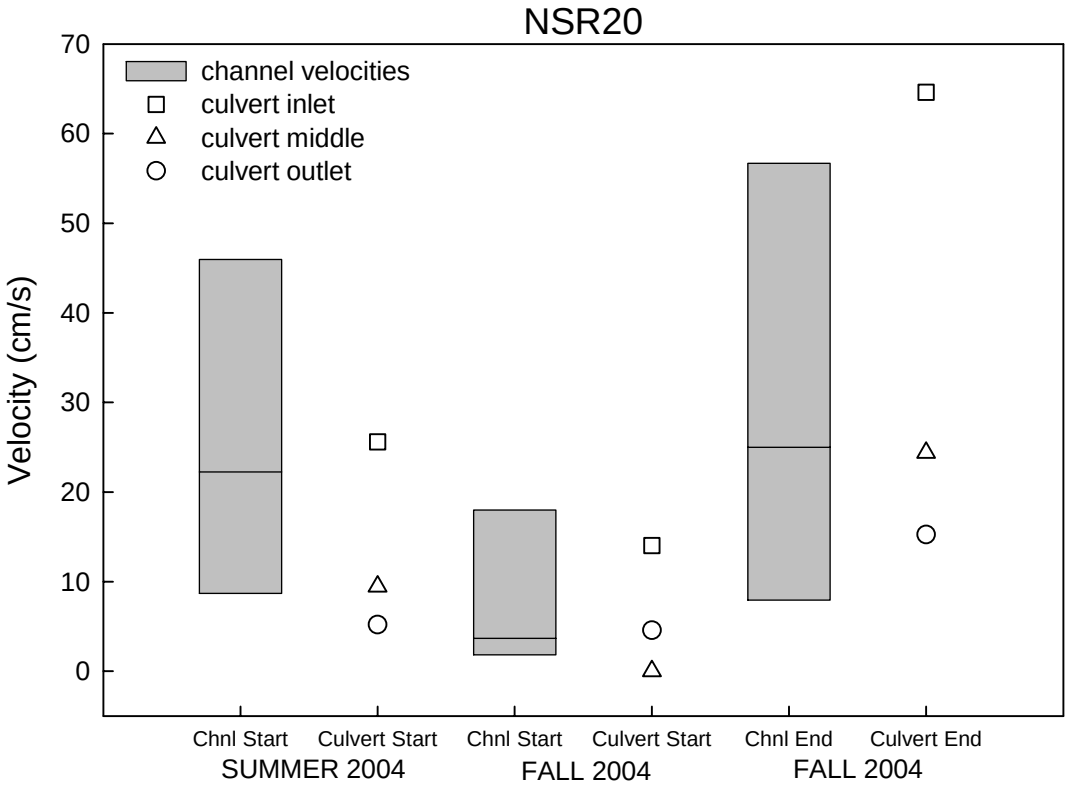
SUMMER 2004
FALL 2004
FALL 2004


NSR15
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
70
60
50
40
30
20
10
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


NSR20
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
70
60
50
40
30
20
10
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
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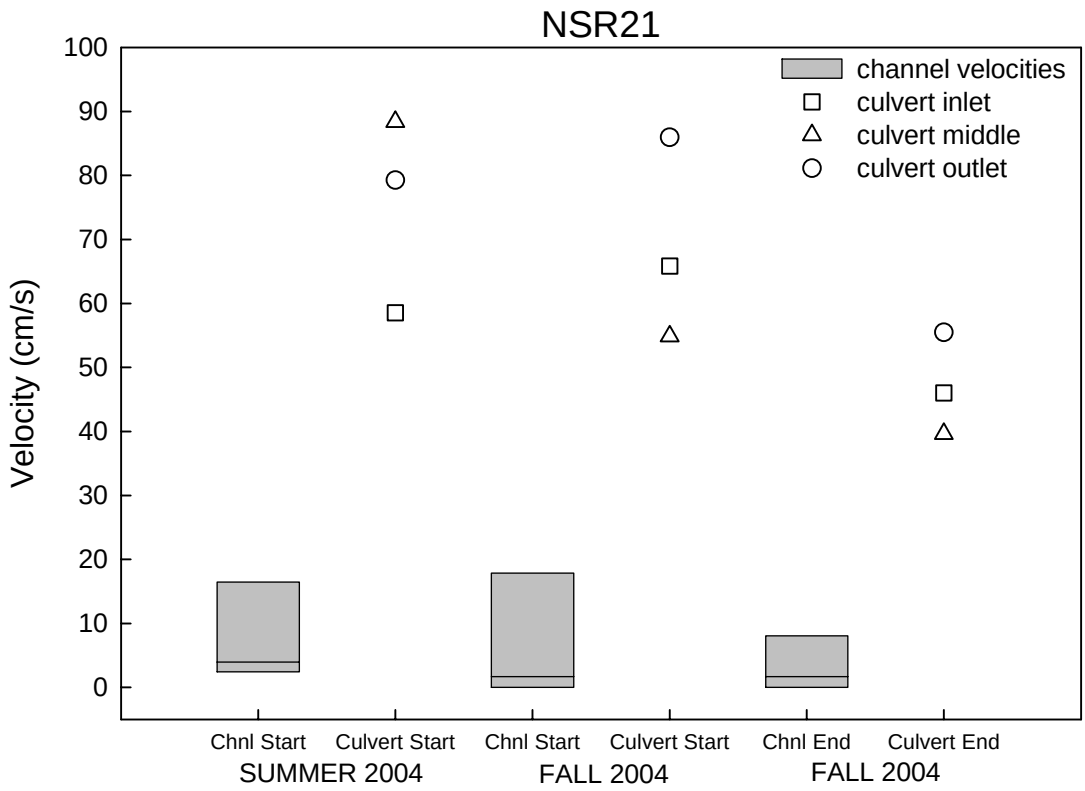
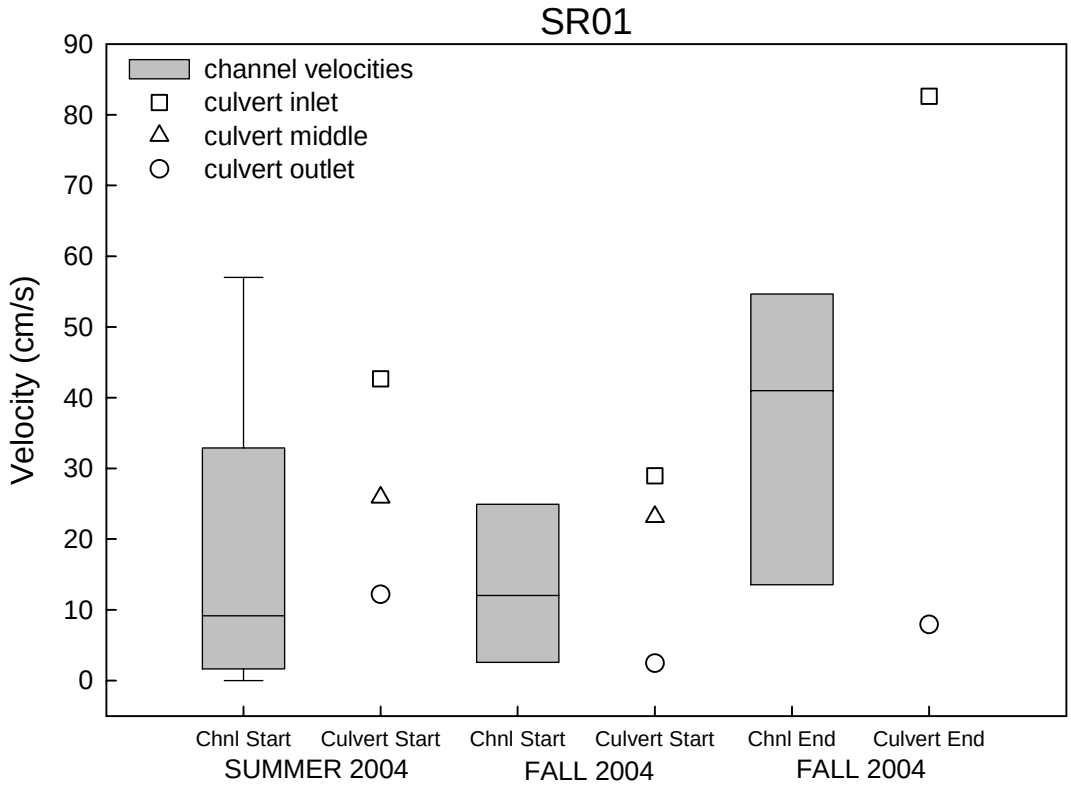
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


NSR21
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
100
90
80
70
60
50
40
30
20
10
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


SR01
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
90
80
70
60
50
40
30
20
10
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
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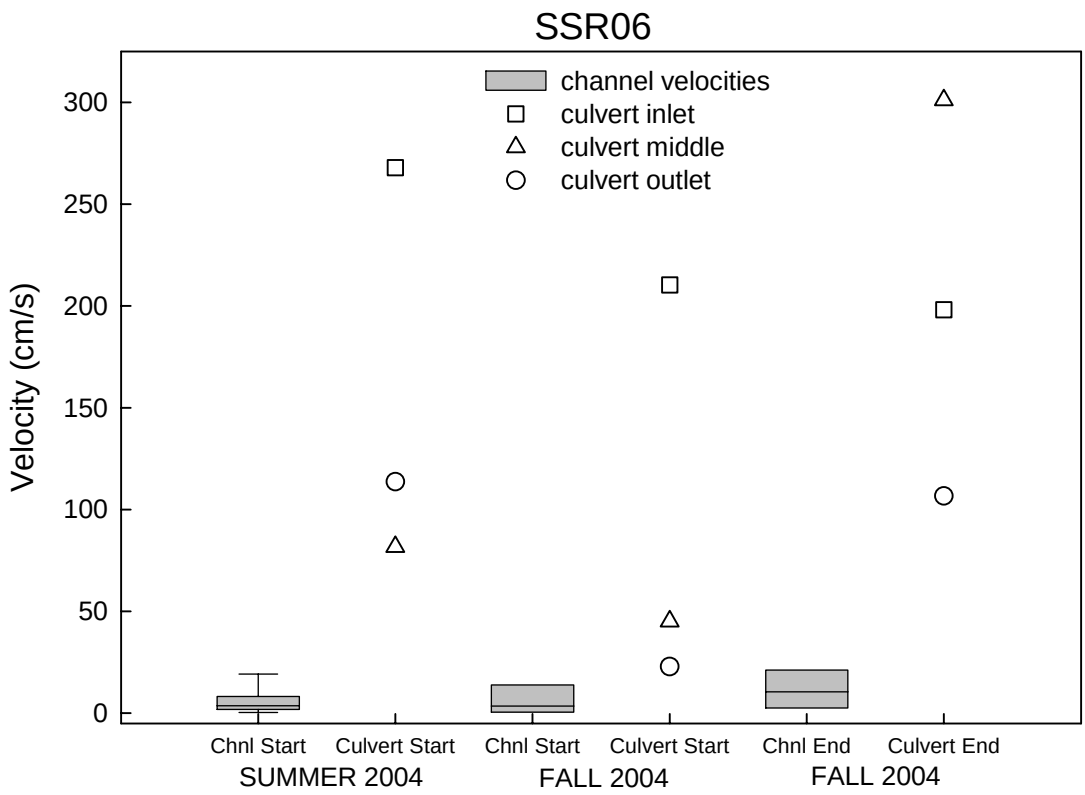
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


SSR06
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
300
250
200
150
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50
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Chnl Start
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Chnl Start
Culvert Start
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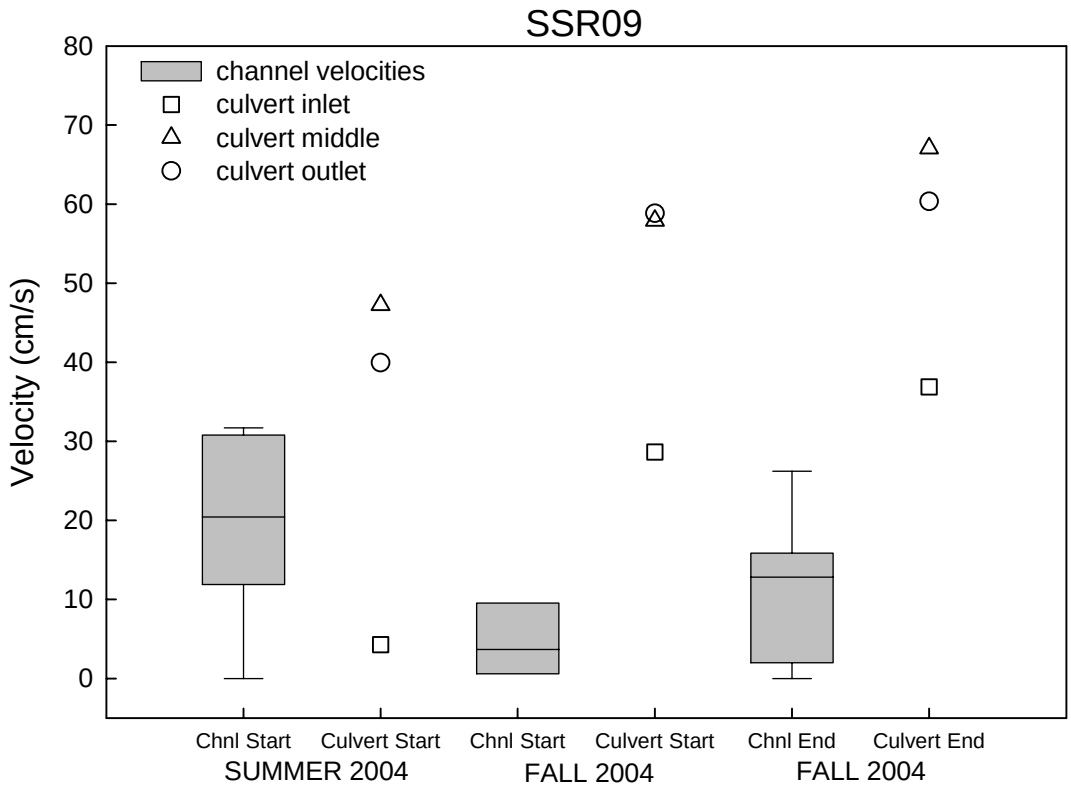
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


SSR09
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
80
70
60
50
40
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10
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Chnl Start
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Chnl Start
Culvert Start
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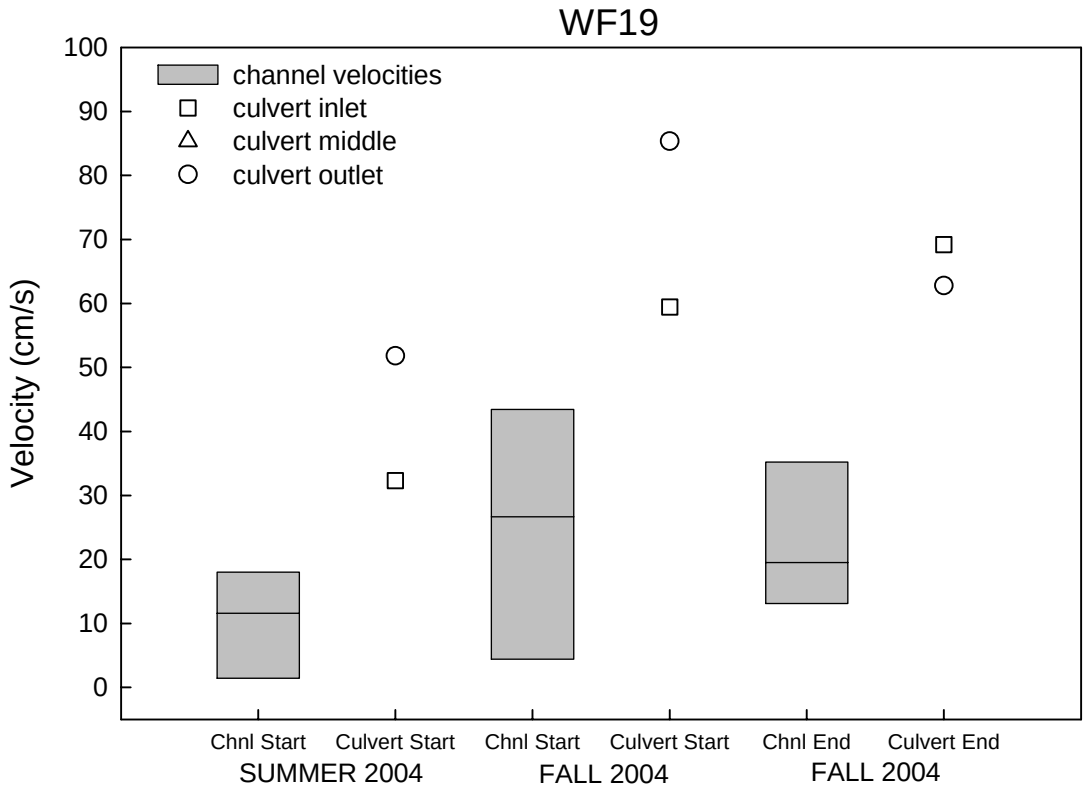
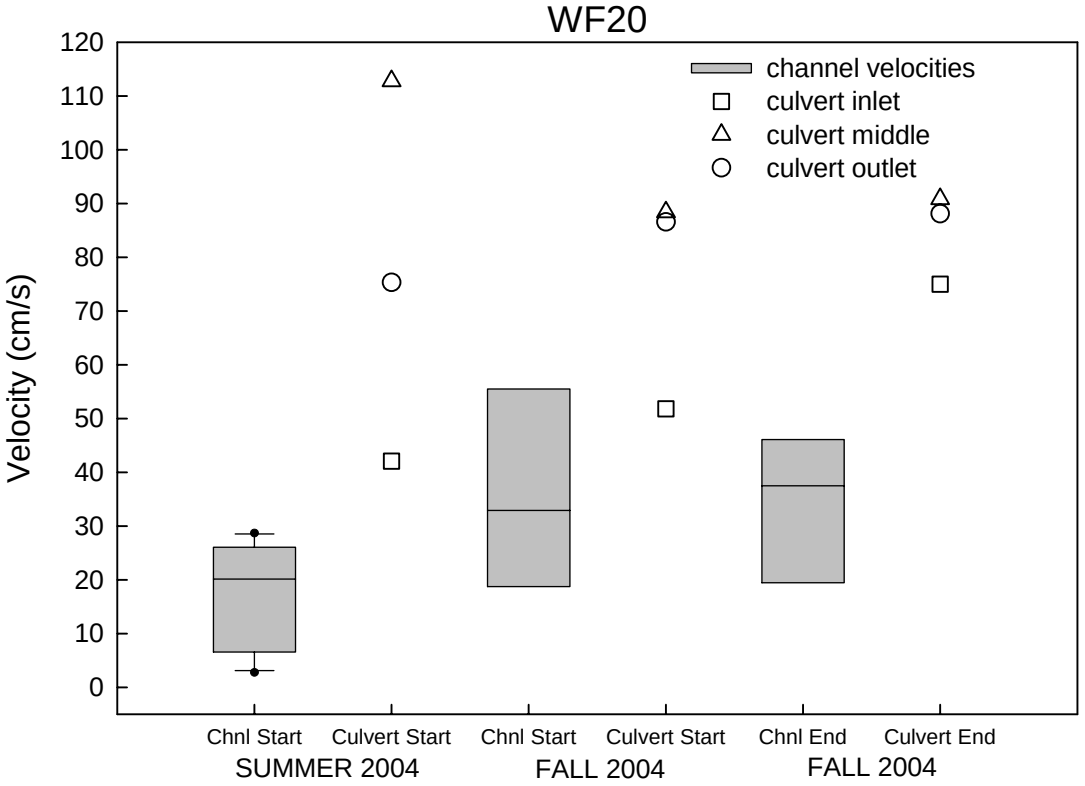
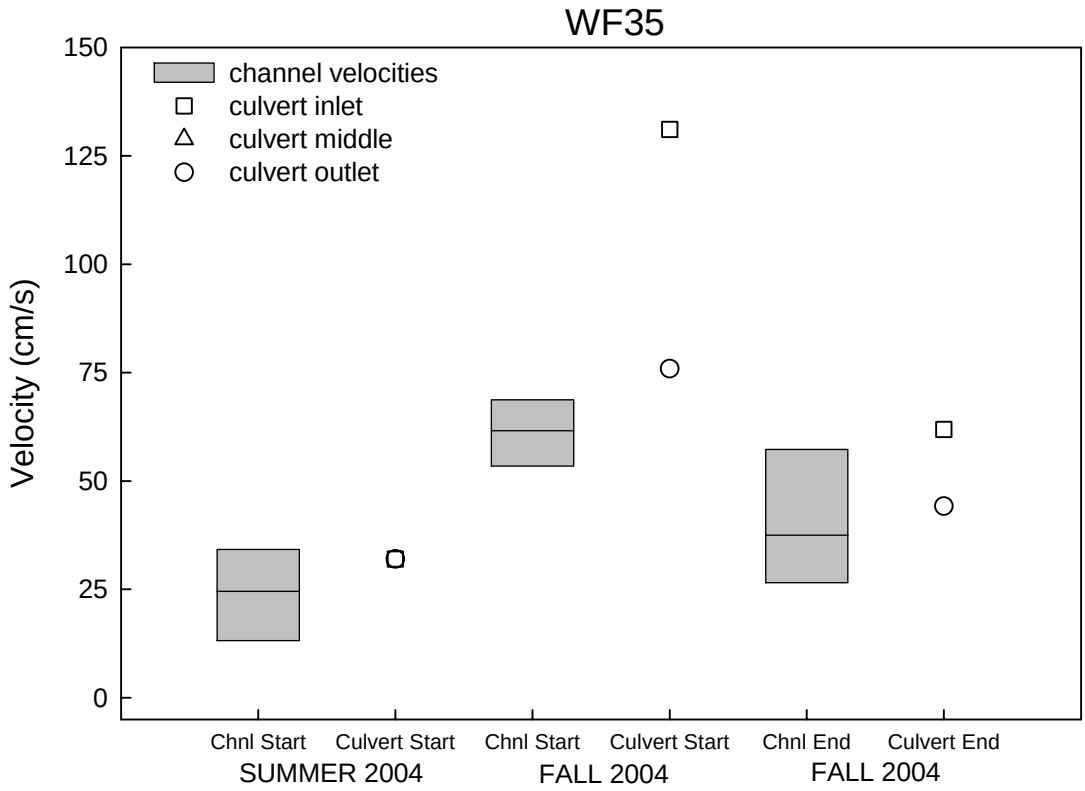
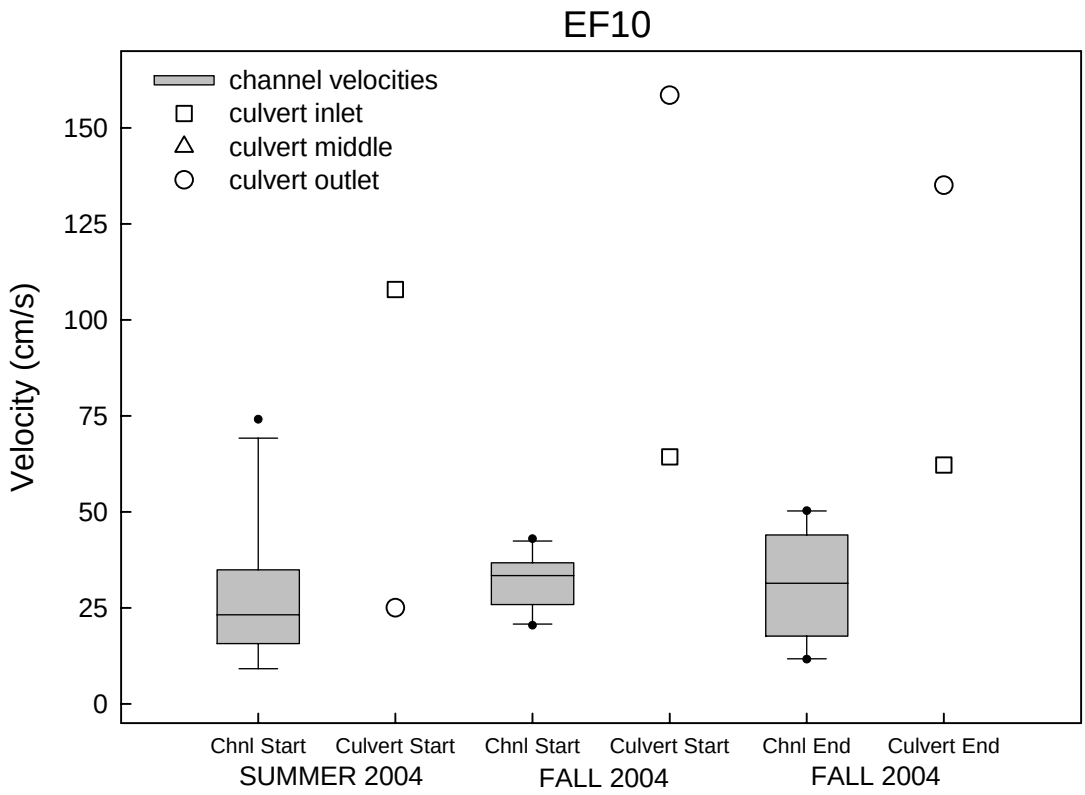
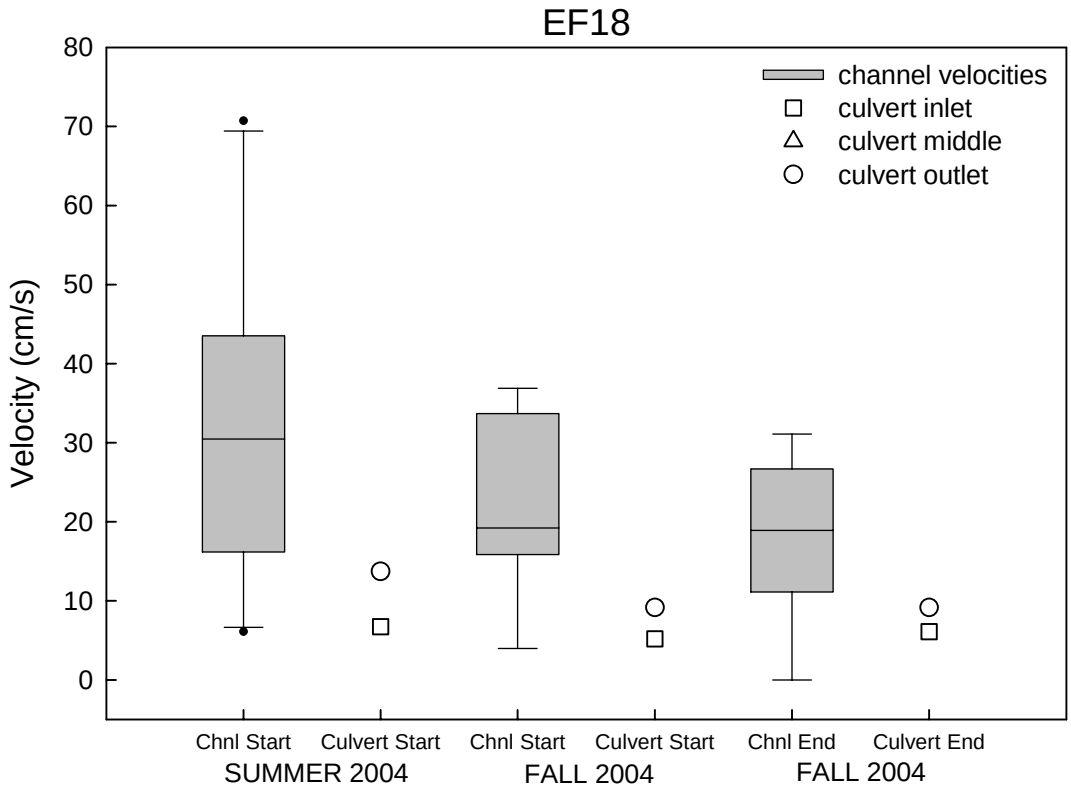
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

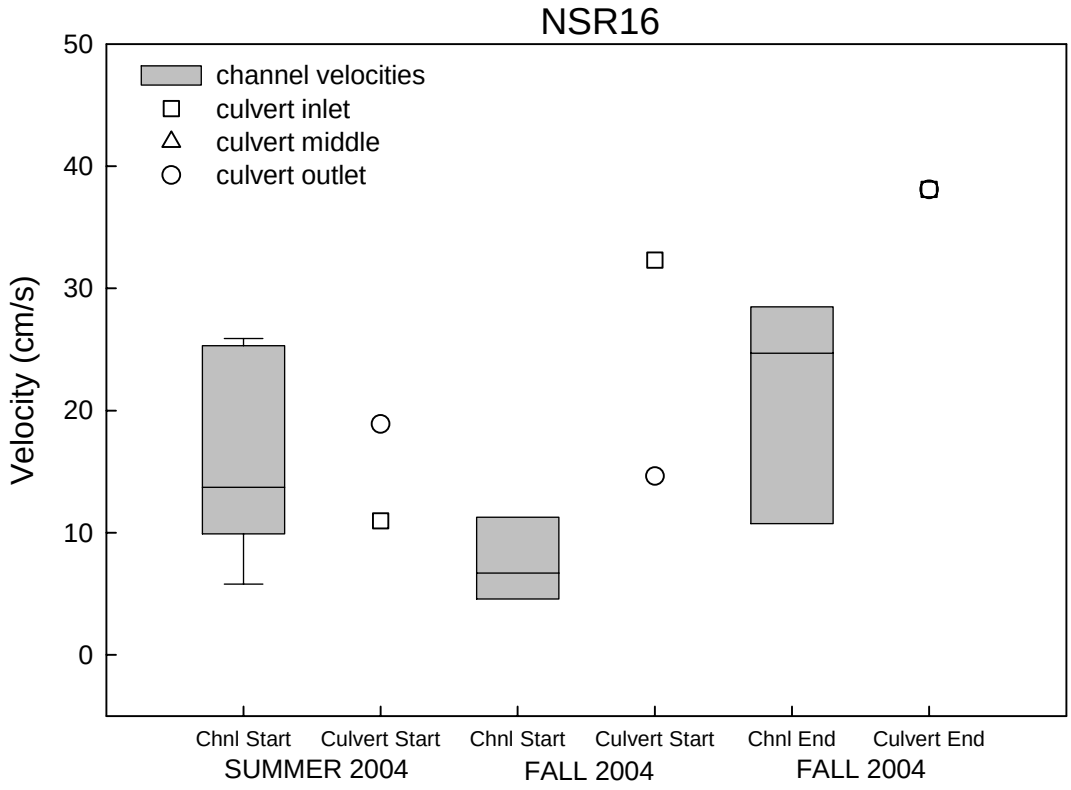

WF19
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
0
10
20
30
40
50
60
70
80
90
100
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

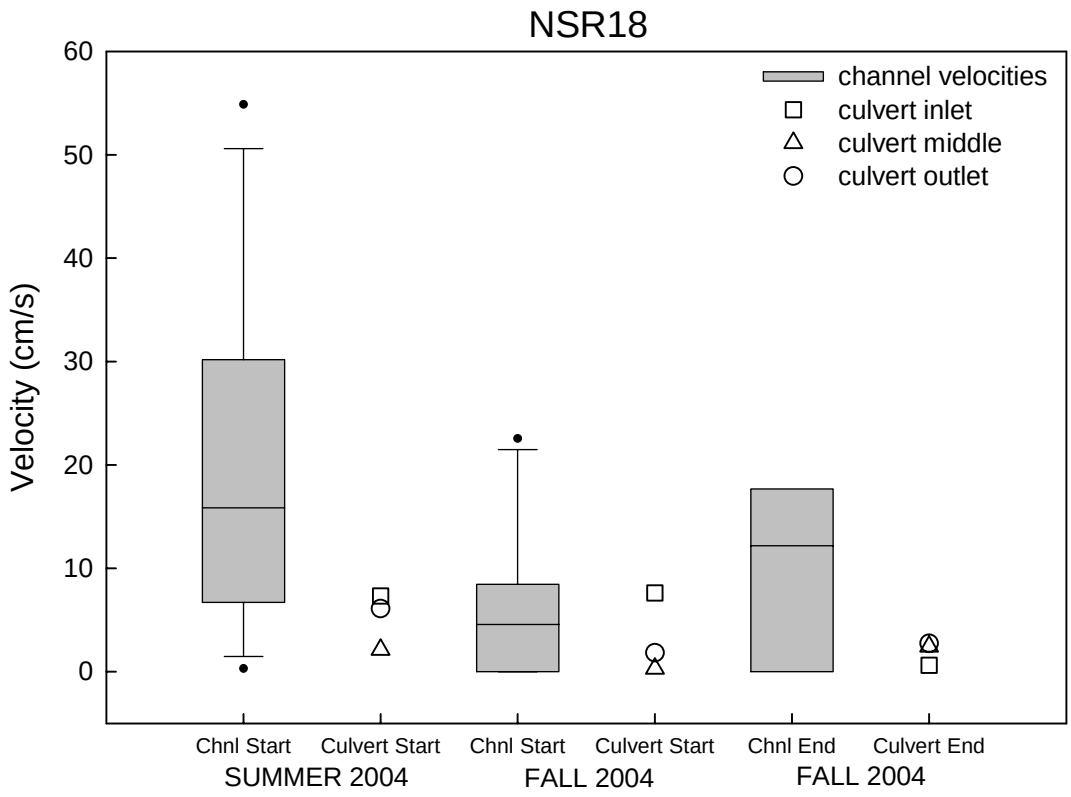

WF20
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
0
10
20
30
40
50
60
70
80
90
100
110
120
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

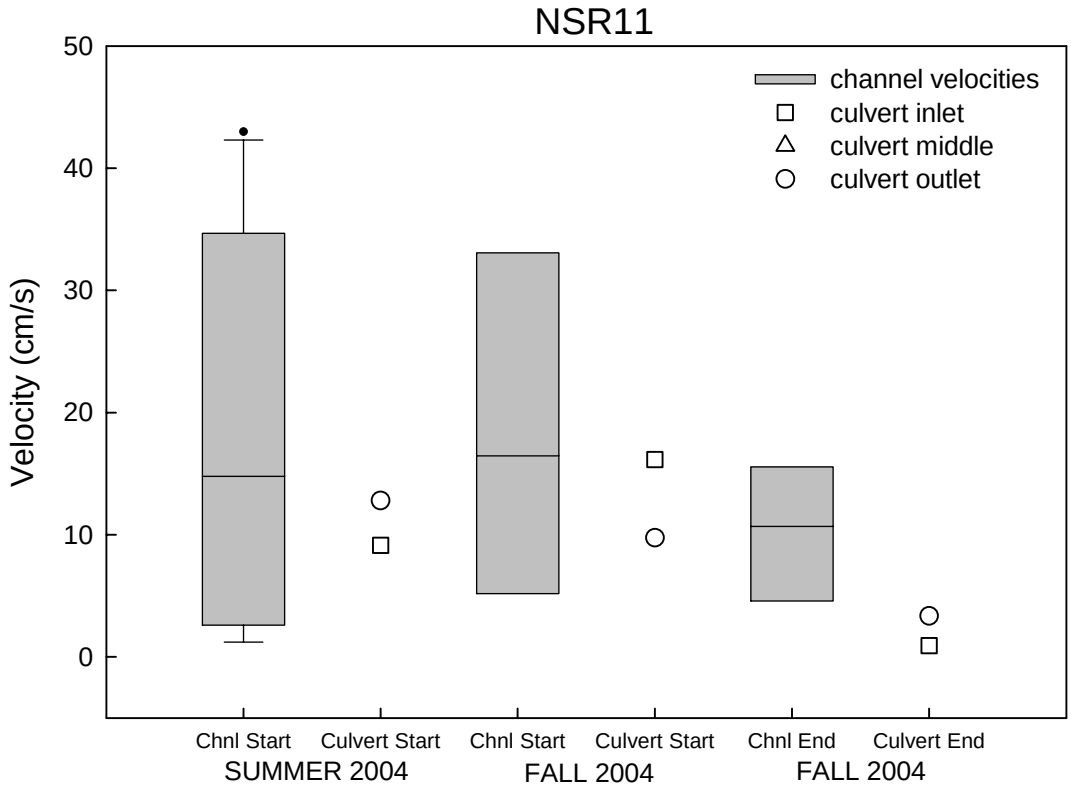

WF35
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
150
125
100
75
50
25
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

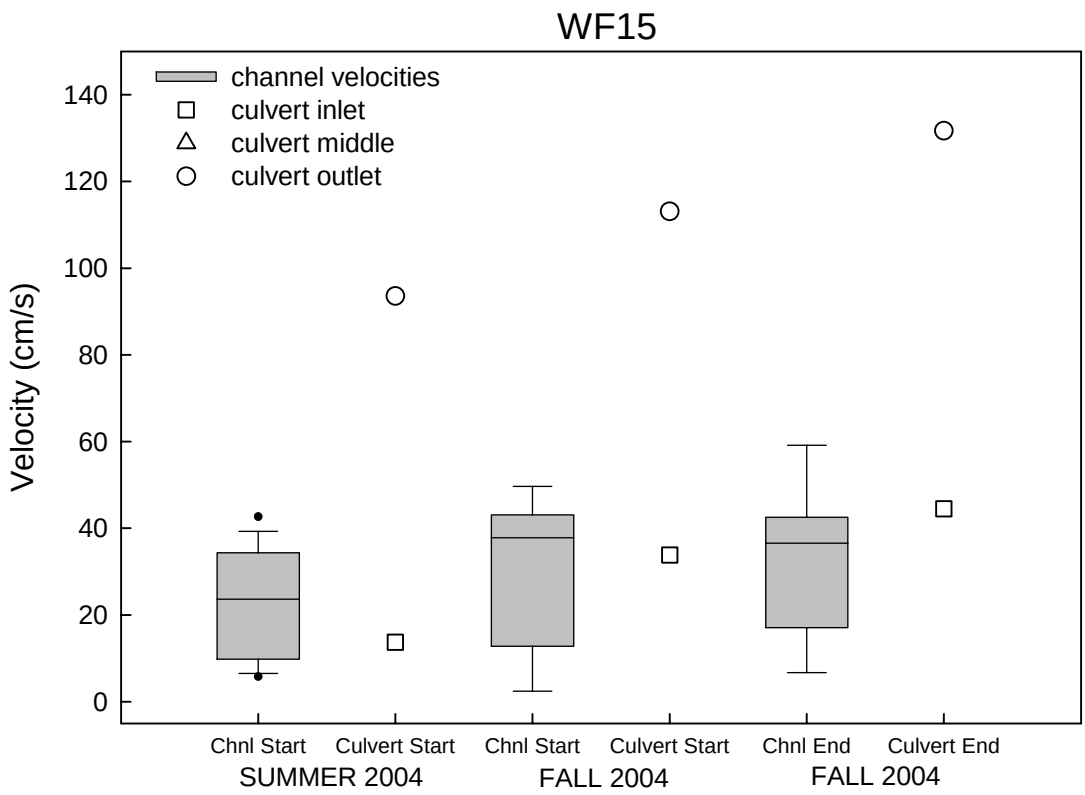

EF10
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
150
125
100
75
50
25
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

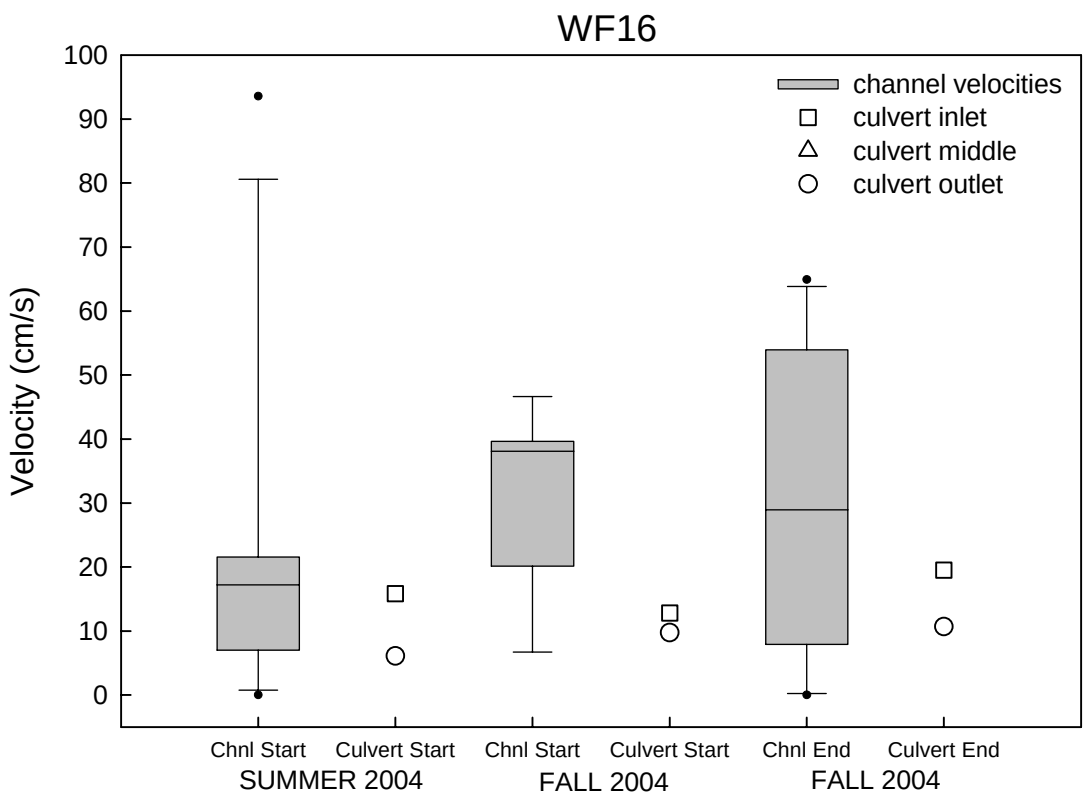

EF18
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
80
70
60
50
40
30
20
10
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

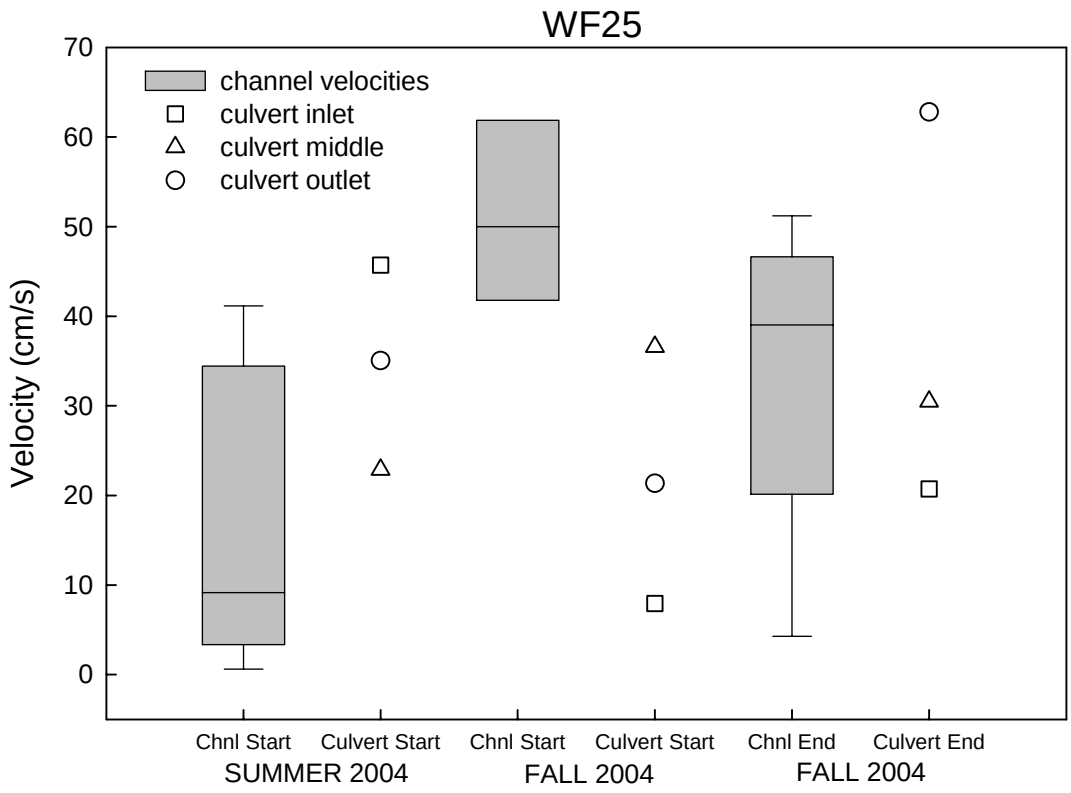

NSR16
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
50
40
30
20
10
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

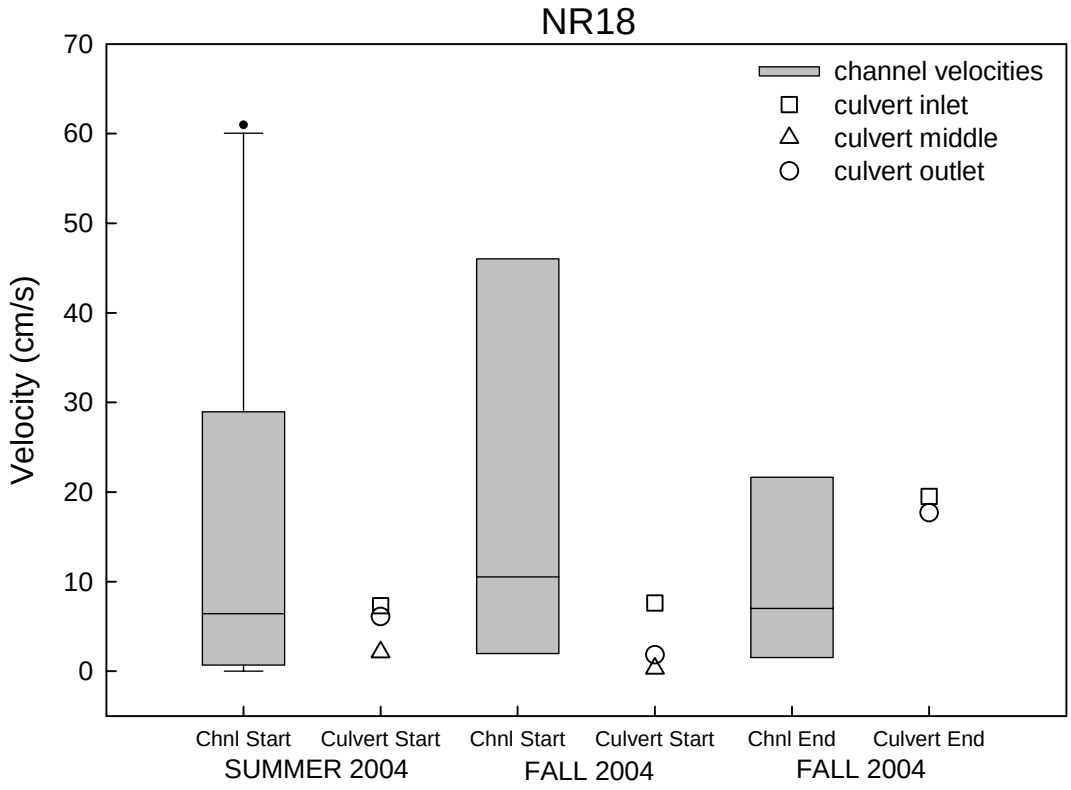

NSR18
Velocity (cm/s)
60
50
40
30
20
10
0
channel velocities
culvert inlet
culvert middle
culvert outlet
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

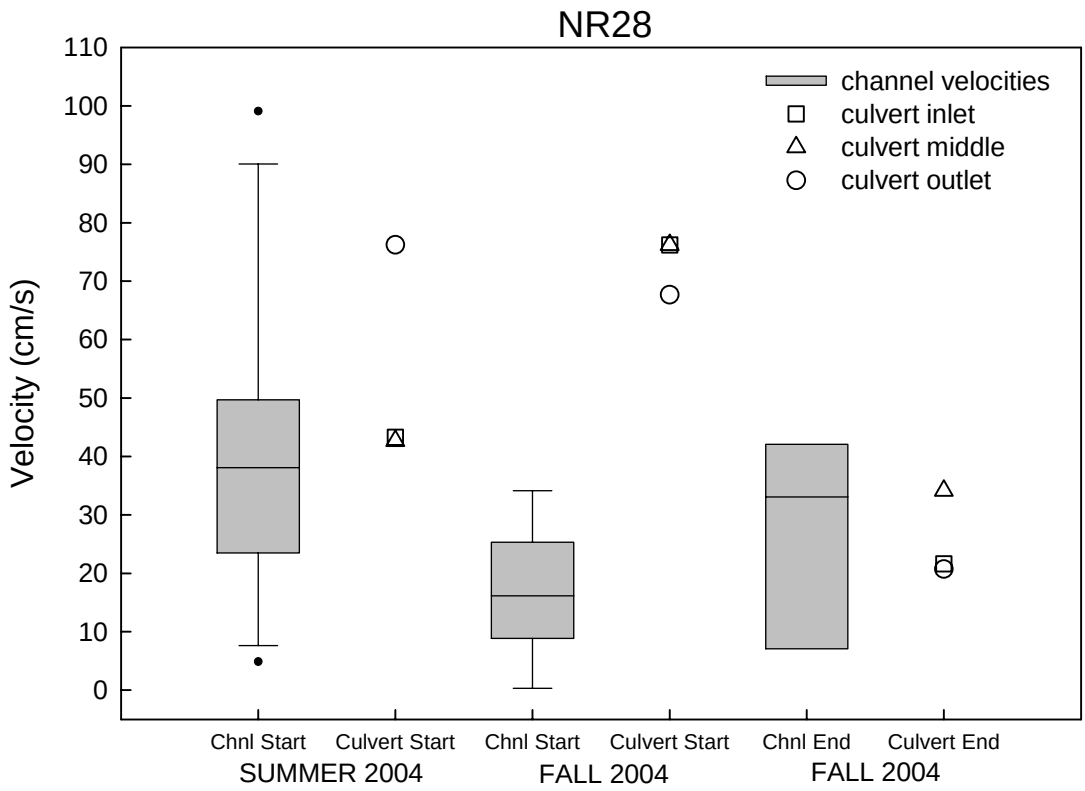

NSR11
Velocity (cm/s)
50
40
30
20
10
0
channel velocities
culvert inlet
culvert middle
culvert outlet
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

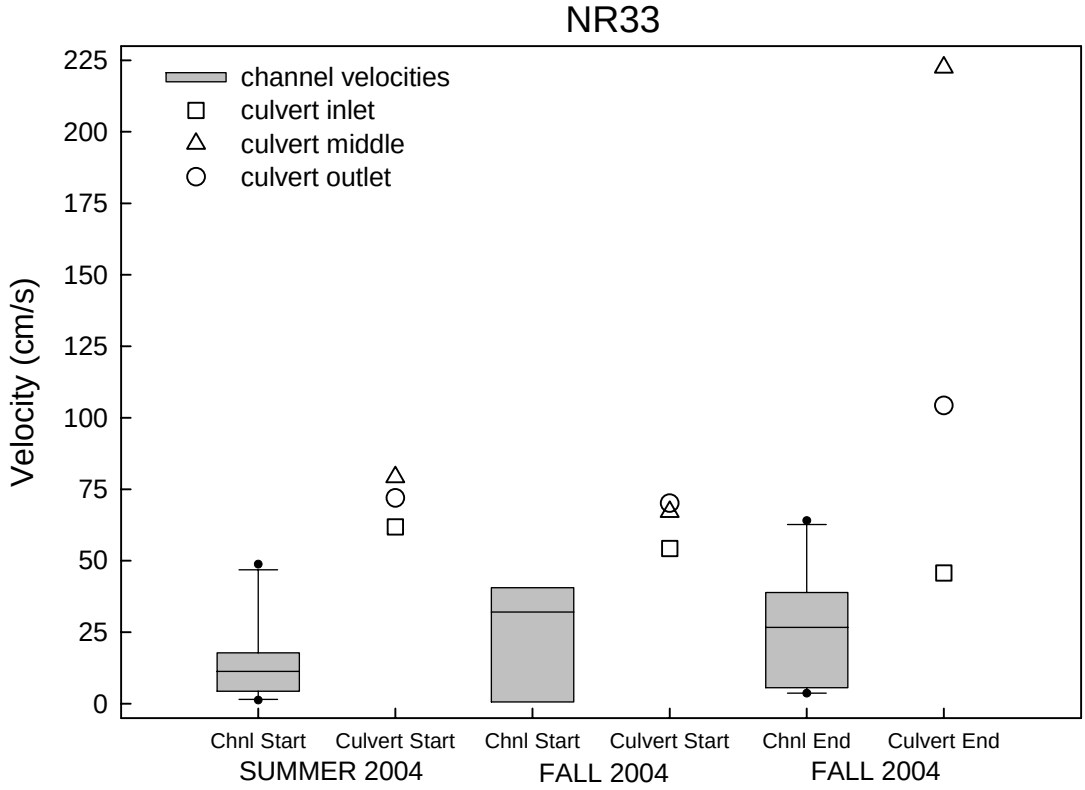

WF15
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
0
20
40
60
80
100
120
140
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

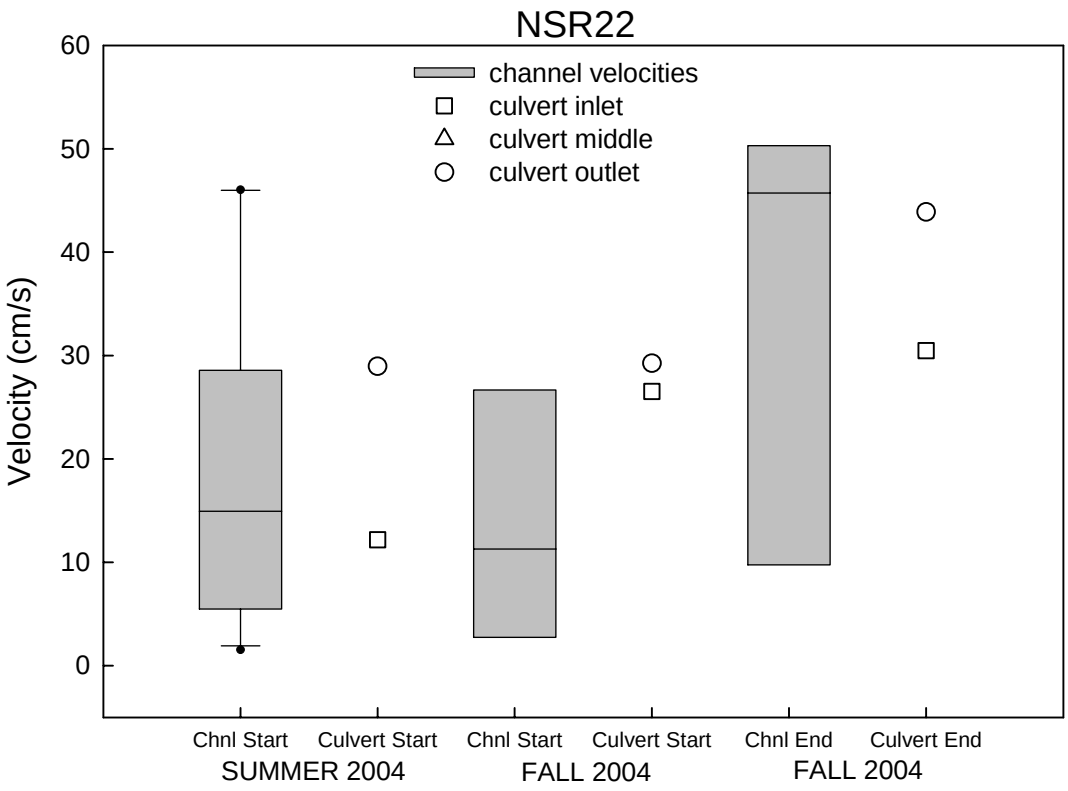

WF16
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
0
10
20
30
40
50
60
70
80
90
100
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


WF25
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
70
60
50
40
30
20
10
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


NR18
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
70
60
50
40
30
20
10
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


NR28
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
0
10
20
30
40
50
60
70
80
90
100
110
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


NR33
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
0
25
50
75
100
125
150
175
200
225
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004


NSR22
channel velocities
culvert inlet
culvert middle
culvert outlet
Velocity (cm/s)
60
50
40
30
20
10
0
Chnl Start
Culvert Start
Chnl Start
Culvert Start
Chnl End
Culvert End
SUMMER 2004
FALL 2004
FALL 2004

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