ASSESSMENT OF CULVERT PASSAGE OF YELLOWSTONE CUTTHROAT TROUTIN A YELLOWSTONE RIVER SPAWNING TRIBUTARY USING A PASSIVE INTEGRATED TRANSPONDER SYSTEM

by

Andrew Anthony Solcz

A thesis submitted in partial fulfillment of the
Requirements for the degree

of

Master of Science

in

Fish and Wildlife Management

MONTANA STATE UNIVERSITY
Bozeman, Montana

August 2007

APPROVAL

of a thesis submitted by

Andrew Anthony Solcz

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the Division of Graduate Education.

Dr. Thomas E. McMahon

Approved for the Department of Ecology

Dr. David Roberts

Approved for the Division of Graduate Education

Dr. Carl A. Fox

STATEMENT OF PERMISSION TO USE

Andrew Anthony Solcz

August 2007

ACKNOLEDGEMENTS

I would like to thank Dr. Thomas McMahon for his guidance and support throughout this project and thesis. Special thanks also to my other committee members, Dr. Joel Cahoon for his insights into all things hydraulic and Dr. Robert Gresswell for his advice and deep understanding of Yellowstone cutthroat trout.

Special thanks to Jesse Patton for his early efforts to get this project underway as well as his help in the field. Thanks to Matt Blank for his initial work on Mulherin Creek that secured funding for this project. And thank you to Brian Ertel and Justin Spinelli who came to my aid when I needed another set of hands.

I would also like to thank the Montana Department of Transportation for their funding of this project, the Royal Teton Ranch for access, and the United States Forest Service for their culvert survey data.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES – CONTINUED

Figure Page

ABSTRACT

Road crossing culverts can pose passage barriers during salmonid migration. However, existing models to predict passage have not been sufficiently tested, particularly for non-anadromous species. In addition, most existing tools for evaluating culvert passage status categorize culverts as passable or impassable whereas an estimate of the probability of passage under a range of flows and hydraulic conditions would be more useful for assessing barrier status. This study used Half-duplex (HDX) Passive Integrated Transponder (PIT) tags and PIT tag reading antennas to examine the ability of migrating fluvial-adfluvial Yellowstone cutthroat trout *Oncorhynchus clarkii bouvieri* to pass through three distinct culvert types over a variety of hydraulic conditions. PIT tag detecting antennas were installed on the upper and lower ends of each culvert and below the plunge pool downstream of the culvert. This design allowed determination of (1) passage success or failure; (2) the number of passage attempts made at each culvert; and (3) the time required for passage through each culvert; and (4) the number of tagged individuals that attempted passage at a particular culvert. Factors shown to increase the probability of passage included shorter fish length, higher water temperature, lower water velocity, and small outlet drop height. Stepwise logistic regression was used to create a model that contained water velocity alone that correctly predicted the probability of passage in 88.9% of cases ($r^2 = 0.91$, $P < 0.001$). Box culverts with baffles had significantly higher passage rates and lower velocities that paralleled that observed in a natural stream channel. Congruency of observed passage with that predicted by the FishXing model was generally low (50%) suggesting the need for further field validation of the model. Study results indicated that 1) PIT tag detection systems offer distinct advantages for assessing culvert fish passage but that further testing of antenna designs is needed to increase efficacy of their use; 2) addition of baffles can increase culvert passage rates; and 3) probability of passage curves developed in this study offer a useful tool for assessing barrier status of individual culverts and estimating the need for culvert removal or retrofitting.

INTRODUCTION

Fish passage through road culverts has become a major concern of engineers and biologists when designing new culverts, retrofitting culverts with baffles or weirs, or completely replacing culverts (Baker and Votapka 1990; Votapka 1991; Lang et al. 2004; Gibson et al. 2005). With an estimated 2,600 culverts that block fish migrations on Federal Lands in Oregon and Washington (General Accounting Office 2001), nearly 2,200 culverts on Oregon state and county property that could pose fish passage problems (Mirati 1999) and limited fiscal budgets, prioritizing culverts for replacement is becoming a monumental task (General Accounting Office 2001; O'Hanley and Tomberlin 2005). Culverts were designed to move water in the most efficient way possible with little or no regard for fish passage (Klingeman 2000). In situations where agency guidelines are in place to ensure fish passage, lack of oversight during installation can lead to the lack of compliance with guidelines (Gibson et al. 2005). Culverts are now being reexamined to determine fish passage capabilities, and new guidelines for culvert installation and replacement are being created (Robison et al. 1999). In situations where replacement is not a viable option, the addition of velocity reducing baffles may be a cost effective measure for increasing passage (Lang et al. 2004; Macdonald and Davies 2007).

Culverts at road crossings have the potential to restrict or prevent migration of fishes (Belford and Gould 1989; Warren and Pardew 1998). Increased velocity, decreased depth, lack of velocity refugia, outlet drop height, and plunge pool depth are all factors that can reduce the probability of fish passage (Belford and Gould 1989; Warren and Pardew 1998; Cahoon et al. 2005). By impeding the passage of upstream migrants, culverts can result in the loss of critical spawning habitat which can greatly reduce fish production in a stream (Gibson et al. 2005). Isolation and fragmentation increases the risk of loss of genetic diversity and the likelihood of local extirpation (Beamish and Northcote 1989; Winston et al. 1991; Morita and Yamamoto 2002; Wofford et al 2005; Sheer and Steel 2006).

Studies involving both direct and indirect methods have been used to examine fish passage. Studies that employ direct methods, including mark-recapture techniques, require individuals to be captured and tagged downstream of a potential barrier and captured again when they successfully pass the potential barrier (Belford and Gould 1989; Warren and Pardew 1998; Schmetterling et al. 2002; Burford 2005). Although these studies are useful for determining if potential barriers are passable, they can be labor intensive and the number of culverts that can be monitored is limited. Additionally, capturing fish on multiple occasions can increase stress levels and may bias results because of behavioral changes (Mesa and Schreck 1989; Clements et al. 2002).

The use of radio telemetry eliminates the need for multiple captures and can determine if passage is successful. However, radio tags are large and expensive which can limit the size and number of individuals tagged. Battery life can also be limiting (Diana et al. 1990) and the exact time of passage is difficult to determine which makes conditions at time of passage difficult to ascertain.

Indirect methods of determining culvert passage include the use of software such as FishXing, which was developed in 1999 and is widely used to assess passage restriction at culverts (FishXing 1999; Lang et al. 2004; Castro-Santos 2006). This software program combines published fish swimming performance data (i.e. swimming speeds, swimming times, jumping ability, and fish length) and hydraulic computations based on culvert characteristics (i.e. shape, slope, roughness, and outlet drop) to predict fish passage. Although this method is less labor intensive than direct methods, and allows for the assessment of many culverts, it has not been sufficiently field tested to determine if resulting predictions are accurate (Karle 2005).

Another indirect method for assessing fish passage requires information about swimming speed and duration and jumping abilities under controlled conditions (Beamish 1978; Haro et al. 2004; Peake 2004; Kondratieff and Myrick 2005). Critical swimming speeds can be used to determine maximum speed and the duration that a certain speed can be maintained, and these data can be used in designing new or modifying existing culverts (Mesa et al. 2004). However, data gathered under laboratory conditions may not always be applicable under field conditions (Castro-Santos 2004).

An alternative approach for examining fish movement entails the use of passive integrated transponder (PIT) tags (Lucas et al. 1999; Olsson and Greenberg 2001; Aarestrup et al. 2003). Information gathered from PIT tags and PIT tag detecting antennas is similar to that from other remote sensing techniques such as radio-telemetry. However, PIT tags are less expensive than radio tags and do not require an internal battery which allows tagging of smaller individuals. Because it is not necessary to recapture PIT tagged fish, the possibility of behavioral modifications due to multiple captures and capture gear selectivity are reduced (Morhardt et al. 2000). Antenna arrays can also be operated nearly continuously, allowing passage monitoring over a wide range of flows and at multiple sites. The most useful feature of PIT tags is that the time of detection is recorded which can be used to associate movement with other factors (i.e., temperature and velocity).

An additional shortcoming of current methods of fish passage assessment is that structures are typically rated dichotomously as either barriers or non-barriers to movement. However, the probability of passage likely varies as a function of temperature, discharge, and fish species and size, all factors that influence the ability of individual fish to pass through a structure. For example, a culvert that is impassable at low flow may become passable at higher flows. Similarly, passage attempts and success may increase at warmer temperatures. Passage success is also influenced by the number of attempts at passage, migration distance, and the number of obstacles encountered (Reiser et al. 2006).

The use of PIT tag detecting antenna arrays provides the potential for simultaneous monitoring of these factors for a variety of culverts and over a range of environmental conditions (e.g., Lang et al. 2004). Furthermore, quantitative information on factors that influence passage success (e.g. the number of attempts, travel time through culverts, and the identification of individuals that attempted passage but failed) can be assessed. A limitation of PIT tag technology is detection range and accuracy of tags passing through an antenna (Zydlewski et al. 2002). This limitation may be particularly problematic when antennas are located near ferrous metals (OregonRFID). Another potential problem with PIT tag antennas is high flows that may destroy antennas.

Yellowstone cutthroat trout *Oncorhynchus clarkii bouvieri* (YCT) is listed as a "species of special concern" and was petitioned for listing as a threatened species under the Endangered Species Act (United States Department of the Interior 2006). The historical range of Yellowstone cutthroat trout encompassed much of the Yellowstone River basin, including parts of the Clarks Fork River, Bighorn River and Tongue River basins in Montana and Wyoming, and parts of the Snake River basin in Wyoming, Idaho, Utah, and Nevada (Behnke 1992). Populations of YCT in the mainstem Yellowstone River have declined dramatically, in part due to the low number of spawning tributaries and associated dewatering problems (Clancy 1988). Fluvial-adfluvial populations in Montana are currently restricted to the Yellowstone River drainage, primarily upstream of Big Timber, Montana (Clancy 1988) where they occupy approximately 43% of their historical range of approximately 28,003 km (May et al. 2003).

Fluvial-adfluvial YCT migrate out of the main stem of the Yellowstone River and into tributaries to spawn from June through July on the descending limb of the hydrograph (Clancy 1988; De Rito 2004). Rainbow trout *O. mykiss* (RBT) from the mainstem Yellowstone River spawn in the same tributaries but spawn 5 - 9 weeks earlier than YCT (De Rito 2004). However, there is overlap in spawning periods, and hybridization frequently occurs (De Rito 2004; Henderson et al. 2000). Because YCT and RBT spawn at different times, discharge regimes through culverts and water temperatures can be very different, and passage of the two species may be affected in different ways. The overall goal of my study was to examine passage success of YCT and RBT in relation to varying temperatures and discharges through a series of culverts on Mulherin Creek, a major spawning tributary for both species, using PIT tag antenna technology.

Objectives and hypotheses for this study were to:

1) compare passage success of non-baffled box culverts, baffled box culverts, unbaffled pipe culverts, and a natural substrate control reach;

2) determine what factors, both biotic and abiotic, that most influence the probability of culvert passage;

3) compare passage success of non-baffled and baffled box culverts over similar temperature and discharge conditions;

4) compare observed field results to predicted results of the FishXing passage model;

5) examine the amount of potential spawning gravel both above and below culverts to determine the amount that may be lost due to impassable culverts.

Hypothesis 1. The probability of passage of fluvial-adfluvial Yellowstone cutthroat and rainbow trout through culverts varies with water velocity and culvert type.

Hypothesis 2. Passage times and number of passage attempts will be different for different type culverts.

Hypothesis 3. Total length will affect the ability of a fish to pass through a culvert.

STUDY AREA

Mulherin Creek is a high gradient second order tributary of the Yellowstone River located 12.9 km northwest of Gardiner, MT (Figure 1). Average gradient from headwaters to mouth is 11.6% (M. Blank, MSU Department of Civil Engineering, unpublished data) and total length is 17.9 km (Montana Fisheries Information System 2005). Lower reaches have a lower gradient and are dominated by small cobble and gravel substrate with numerous riffles and pools. Middle reaches are high gradient containing cascades and numerous small falls dominated by boulder and large cobble substrate with small pockets of gravel on the stream margins. Upper reaches are primarily comprised of riffles and pools with gravel and cobbles dominating. Mulherin Creek was chosen as a study site because it contains a variety of culvert types including both baffled and unbaffled box culverts as well as unbaffled steel pipe culverts. The system has a relatively large spawning population of fluvial-adfluvial YCT from the Yellowstone River. Spawning habitat was thought to be limited in the lower reaches of the stream therefore migrating fluvial-adfluvial YCT and RBT should have had sufficient motivation to pass through multiple culverts in order to reach suitable spawning habitat in higher elevation tributaries.

Native species present in Mulherin Creek include YCT, mountain whitefish *Prosopium williamsoni,* white sucker *Catostomus commersoni,* longnose sucker *C. catostomus*, mountain sucker *C. platyrhynchus,* mottled sculpin *Cottus bairdi,* and longnose dace *Rhinichthys cataractae*. Non-native species include RBT and brown trout *Salmo trutta.*

METHODS

Study Culverts

The five culverts on Mulherin Creek consisted of three different types that varied by type of construction, length, outlet drop height, and other dimensions (Figures 2 and 3). A bridge and a control reach were also identified so as to compare movement through culverts in relation to a control reach of similar length as culverts and to a road crossing at a bridge without a culvert (Figure 1). Physical measurements of each culvert were obtained with a total station surveying unit and auto level. Measurements included length, height, width and baffle size/configuration (if present), plunge pool depth, outlet height, slope of the culvert, and slope of the channel both upstream and downstream of the culvert.

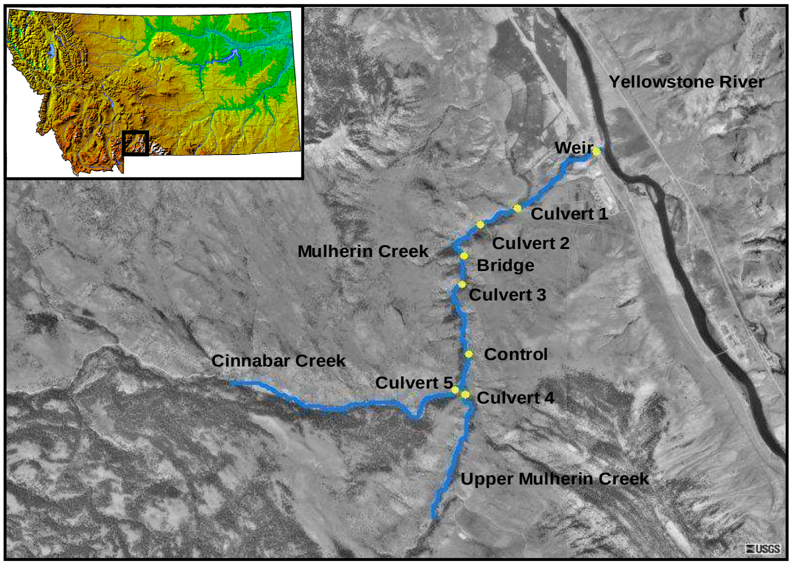
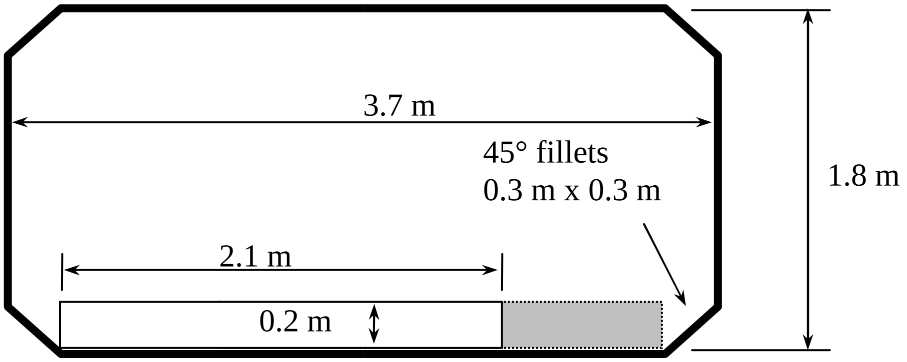


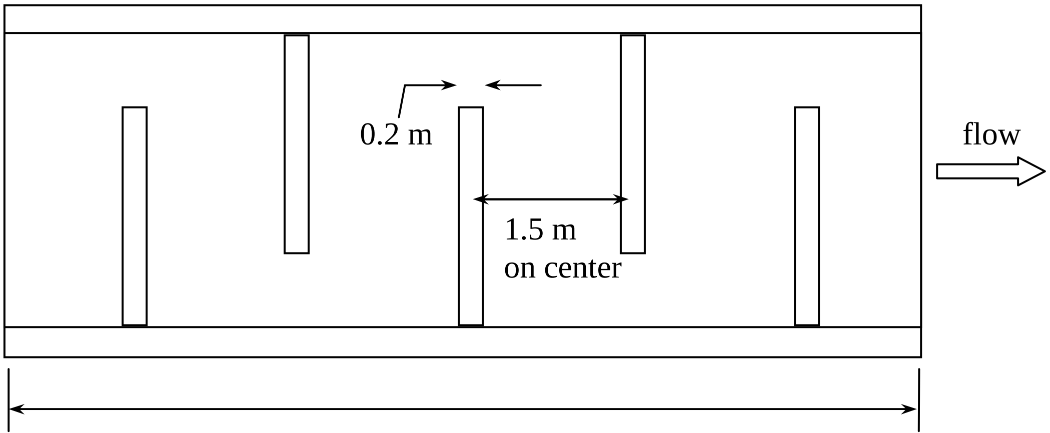
Figure 1. Location of the weir trap, five study culverts, the bridge, and the control reach on Mulherin Creek, Montana.

Cross-section of culverts 1, 2, and 3



culvert 1: 11.4 m, outlet drop: 17.0 cm

Plan view of culverts 2 and 3



culvert 2: 9.3 m, outlet drop: 11.0 cm
culvert 3: 9.7 m, outlet drop: 0.0 cm

Figure 2. Cross-sectional and plan view of concrete box culverts 1, 2, and 3. The three culverts have the same dimensions however, culvert 1 has no baffles.

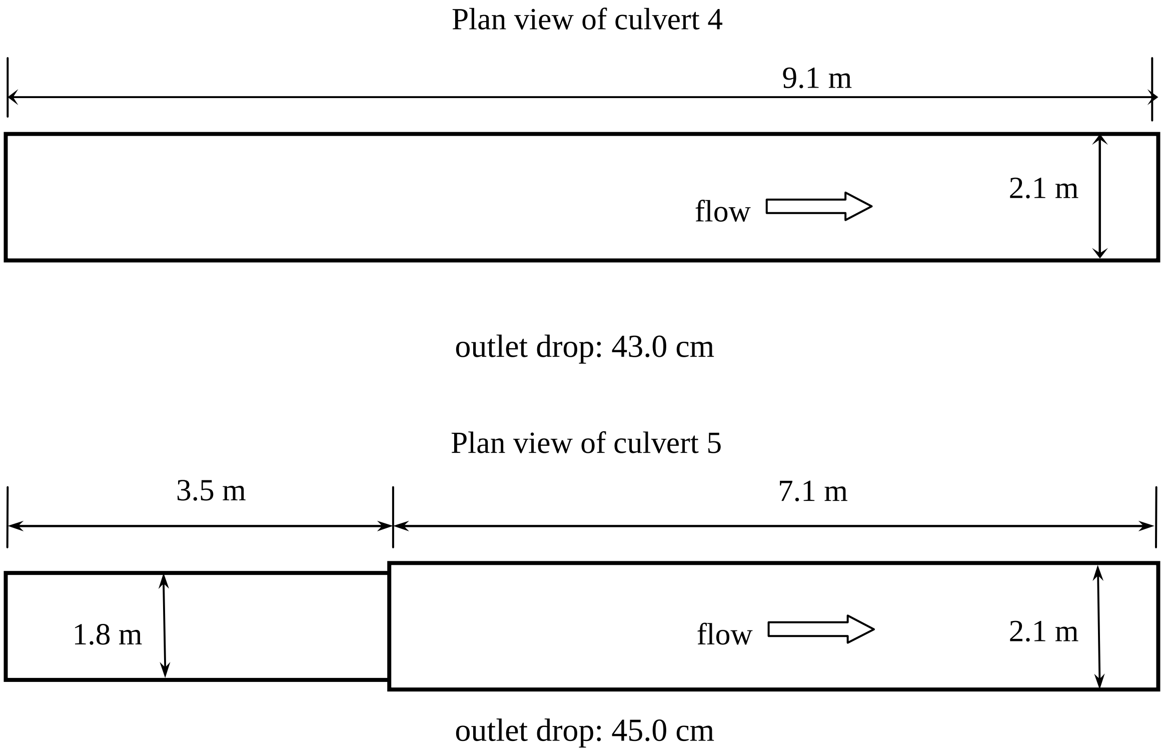


Figure 3. Plan view of circular steel pipe culverts 4 and 5.

Fish Trapping and Tagging

Fluvial-adfluvial YCT and RBT migrating upstream out of the Yellowstone River were captured using a weir and trap located 125 m upstream of the confluence of Mulherin Creek and the Yellowstone River (Figure 1). Fish were anesthetized with tricaine methanesulfonate (MS-222), and species, total length and sex (when apparent from appearance or expression of eggs or milt) were recorded. A half duplex (HDX) PIT tag was inserted into the abdominal cavity between the pyloric caeca and the pelvic girdle (Columbia Basin Fish and Wildlife Authority 1999) using a syringe style injector. HDX

PIT tags used in the study were 23 mm x 3.85 mm, weighed 0.6 g, and operated at a frequency of 132.2 kHz. Following recovery from anesthesia, fish were released into a backwater pool upstream of the weir. In both 2005 and 2006, trapping operations began in mid April and continued through late July. However, in 2006 trapping was not possible from 12 May to 18 June due to high flows. All trapped fish were tagged. Individuals that were sampled in 2006 were scanned for PIT tags from the previous year prior to tagging. If a PIT tag from 2005 was found, tag code and fish total length were recorded.

Because of the small number of individuals trapped and tagged in 2005, fish immediately below culverts 4 and 5 were collected on 27 April 2006 and displaced downstream directly below culvert 1 with the assumption that they would have sufficient motivation to return to their home location passing again through culverts 1 through 3 (Belford and Gould 1989; Halvorsen and Stabell 1990). Twelve fish were sampled from the junction of Mulherin Creek and Cinnabar Creek proceeding upstream to culvert four and culvert five (Figure 1) using a Smith-Root Model 15-D generator powered backpack electrofishing unit and a two person crew on 27 April 2006. Fish were anesthetized with tricaine methanesulfonate (MS-222) and species, total length (mm) and sex were recorded and a PIT tag was inserted. Fish were then transferred downstream in livewells, allowed to recover and released in the plunge pool below culvert 1, a total displacement distance of 1840 m.

Antenna Placement and Design

In 2005, PIT tag detecting antennas were installed on the upstream and downstream ends of each of the five culverts on Mulherin Creek. This design allowed us to determine (1) passage success or failure; (2) the number of passage attempts made at each culvert; and (3) the time required for passage through each culvert. In 2006, an additional antenna was installed below the plunge pool of each culvert (Figure 4) in order to better ascertain the (1) the travel time between culverts; (2) the number of fish that reached the plunge pool but did not attempt passage; and (3) the amount of time fish are delayed by each culvert. Additionally, the antenna located below the plunge pool of culvert 1 allowed us to determine the number of tagged individuals that moved from the weir trap to the first culvert. In 2006, a bridge located between culvert 2 and culvert 3 was also equipped with a three antenna array in order to act as a control of a road crossing with natural slope and substrate. However, this antenna array was destroyed by high flows on 19 May 2006 as was Antenna 3 on culvert 2. A substitute control reach consisting of a long glide simulating shallow, moderately fast water, was added to the antenna monitoring array on 29 June 2006 (Figure 1). Antenna arrays were operational throughout the period when YCT were migrating and spawning except for periods in 2006 when high water destroyed antennas and precluded repair. Table 1 summarizes the operational periods for each study culvert and control reach.

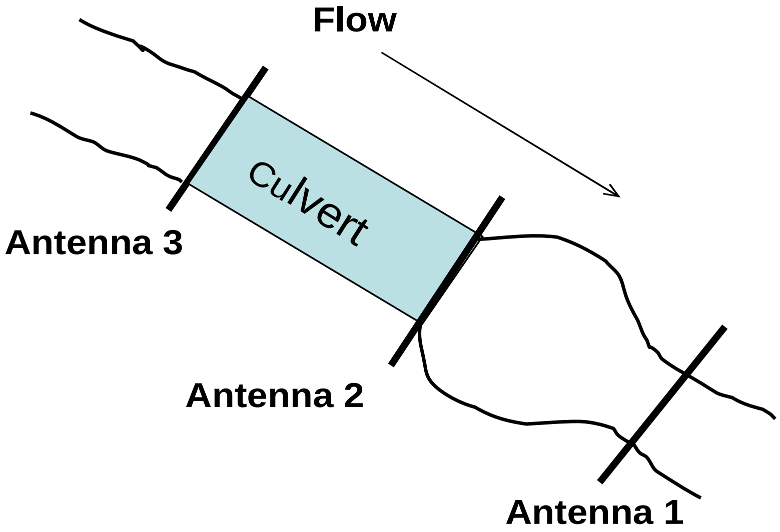


Figure 4. Typical antenna array configuration.

Table 1. Dates of culvert and control antenna array operation.

	2005	2006
Culvert 1	May 10 to September 17	April 9 to May 25 June 27 to September 30
Culvert 2	May 10 to September 17	April 8 to September 30[a]
Culvert 3	May 19 to September 17	April 15 to September 30
Culvert 4	May 19 to September 17	April 16 to May 19 June 28 to September 30
Culvert 5	May 19 to September 17	April 22 to May 19 June 24 to September 30
Control		June 29 to September 30

[a] Antenna 3 was washed out on May 19, 2006 and never repaired due to high flows. The other two antennas on culvert 2 remained operational.

Distances from antenna 1 to culvert outlet varied from 4.1 to 29.9 m. Antenna 2 was placed at the downstream end of the bridge and directly on the downstream outlet on culverts 1, 2, 4 and 5. Debris located near the outlet of culvert 3 prevented placement of antenna 2 on the downstream outlet of the culvert therefore it was placed 1.9 m upstream into the culvert where a 15 cm deep seam between segments allowed burial of the antenna wire. Similarly, the placement of antenna 3 varied because of debris and lack of anchor points on the upstream inlet of culverts (Table 2). The natural control reach was 9.9 m long, with antenna 2 positioned 4.4 m upstream of antenna 1 and antenna three 5.6 m above antenna 2.

Table 2. Antenna placement specifications for each culvert and the control reach.

	Antenna 1 distance below culvert outlet (m)	Antenna 2 distance from culvert outlet (m)[a]	Antenna 3 distance from culvert entrance (m)[b]
Culvert 1	29.9	0.0	2.1 downstream
Culvert 2	4.9	0.0	1.9 downstream
Bridge	4.1	0.0	0.0
Culvert 3	5.8	1.9 upstream	3.7 upstream
Control	4.4	0.0	0.0
Culvert 4	7.0	0.0	0.0
Culvert 5	12.3	0.0	1.9 upstream

[a] Antenna 2 on culvert 3 was placed in the culvert because debris prevented placement on the face of the culvert outlet.

[b] Antenna 3 was placed upstream, inside culverts 1 and 2 because of debris at the culvert's entrance. Antenna 3 was placed upstream of the inlet on culverts 3 and 5 because of debris at the culvert entrance and lack of anchor sites within the culvert.

Antennas were constructed of 8-gauge multi-strand copper wire loops with the lower portion of the loop either buried in the substrate or fastened under the lower lip of the culvert (Figure 5). The upper end of the culvert antennas was either attached using eye hooks or clamps to the culvert edges and supported by string attached to the culvert ceiling (Figure 5). The number of loops varied by location, antennas located in the control reach and below the plunge pools required a single loop while concrete box antennas required two loops and antennas located on the steel culverts required three loops to maximize their detection range and accuracy. Half duplex antennas are listed as having a read accuracy of up to 90% within a distance of 60 cm of the antenna (OregonRFID; Tranquilli 2005). This limited antenna size to a maximum of 1.2 m high. However, because of electrical interference antennas located on the steel pipe culverts were a maximum of 0.75 m high (Figure 5).

Figure 5. Antenna construction design for culverts where the antenna could be mounted directly on the downstream outlet of the culvert. Left: outlet of culvert 1. Right: outlet of culvert 4. Arrows indicate location of lower end of antenna loop.

Natural stream sections had the upper portion of antenna loops constructed by running a steel cable across the stream and attaching it to a post on either bank (Figure 6). The antenna wire was attached to the posts and fastened to the steel cable with plastic fasteners. The lower portion of the antenna wire was run through flexible electrical conduit that was attached to the posts and buried in the substrate. The conduit acted both to protect the wire and hold the wire loops together to maximize detection accuracy.

Antennas spanned the entire width of the channel so that fish passing underneath at any point in the channel could be detected.

Figure 6. Antenna construction design for the natural control reach and for culverts where the antenna could not be attached directly on the upstream end of the culvert or within the culvert. Left: inlet of culvert 3. Right: inlet of culvert 5. The lower portion of the antenna loop is encased in the plastic conduit and buried in the substrate.

Tag Detection Range and Accuracy

Half duplex antennas do not have inter-antenna interference (OregonRFID). However, electrical interference can still result from steel and other ferrous metals such as steel, which was used in the construction of concrete box culverts (i.e. rebar) and steel culverts. Therefore, in order to maximize detection range and accuracy, proper tuning of antennas is essential. Read range and accuracy for each antenna was maximized by adjusting the tuner modules using a tuning indicator provided by OregonRFID. The tuner was used in the initial construction of all antennas. Antennas were periodically tested to determine if they were still tuned correctly. An LED light indicated the antennas were properly tuned. Whenever an antennas position was changed due to either high water or debris they were retuned. Each antenna was attached directly to the tuner module and twinax cable consisting of two separate insulated wires was used to attach the tuner module to a central RFID multiplexer transceiver. The transceiver is capable of monitoring up to four antennas (OregonRFID specifications), but I limited use in my study to three antennas per transceiver as the increased cycling time of the detection field through the use of a fourth antenna would increase the likelihood of allowing fish to pass undetected.

The detection range of each antenna was measured to determine the size of the detection plane at each site in relation to culvert characteristics and antenna placement. Horizontal detection distance was determined by slowly moving a test tag attached to a measuring staff upstream and downstream of each antenna until the tag was detected by the transceiver. Because the vertical detection range was well within the 60-cm detection range for HDX tags, I only measured vertical detection range at culverts with outlet drops. This was done in order to determine if fish passing under a perched culvert would be detected by the outlet antenna 2 (Figure 5) and perhaps lead to overestimates of the number of attempts of fish entering the outlet.

Tag detection was measured while moving the test probe horizontally through the center of the vertical antenna detection plane, mimicking that of a fish swimming upstream through the detection field. Detection was indicated by an audio signal sent from a speaker attached to the transceiver. Three passes were made with the probe during each reading, and detection accuracy was measured by recording the number of ‘hits’ during each test. Detection range and accuracy was measured weekly.

Culvert Hydraulics

Water height, water temperature, and air temperature were recorded with TruTrack (model WT-HR 1000, Christchurch, New Zealand) data loggers installed at three sites in the study area: the main stem of Mulherin Creek at culvert 1; in Mulherin Creek above its junction with Cinnabar Creek (hereby called Upper Mulherin); and in Cinnabar Creek upstream of culvert 5. In 2005, measurements were taken hourly from 13 May to 2 October. In 2006 measurements were taken every 15 minutes from 15 April to 2 September. To convert stage height to discharge, a stream transect was established directly downstream of each data logger and 10 discharge profiles were taken at each site during various discharges in 2005. Discharge measurements for each transect were taken with a pygmy meter and an aquacalc 5000 handheld computer using USGS flow measurement techniques (Rantz 1982). Data loggers were in the same locations in 2006. Spot checks of flow rate were used in 2006 to verify that the stage/discharge relationships were therefore assumed to be the same as in 2005. Stage-discharge rating curves were developed for each recorder using the model:

$$Q = a(y + h)^b$$

Where:

Q = discharge (m^3/sec)

a, ^{b} and h = regression coefficients

y = stage height (cm)

At various flows, the cross sectional flow area, *A* were measured. Then, the mean culvert velocity was calculated using the relationship $V = \frac{Q}{A}$ where:

V = velocity

A = wetted area

Q = flow rate from the data loggers and rating curves

Flow area, *A*, were measured at culvert outlets in 2005. For unbaffled culverts (1, 4, and 5), a single measurement of *A* was taken from the center of the outlet. Because water depth in baffled culverts was not uniform, two measurements of *A* were taken on either side of the outlet and averaged. V then regressed on Q so that velocity could be calculated at any time from recorded water depths.

FishXing Comparison

Observed passage success through the unbaffled box culvert (culvert 1) and the unbaffled steel culvert (culvert 4) on Upper Mulherin Creek was compared to passage success predicted by the FishXing culvert passage model in order to determine the model's accuracy. If the FishXing model accurately predicts passage, no successful passage should be observed above the maximum passable discharge predicted, although failed attempts could still be made. FishXing was not used to examine culverts 2 and 3 because the model cannot effectively model the hydraulics of baffled culverts (FishXing 1999). The model was not used to assess culvert 5 because FishXing cannot model double barrel culverts (FishXing 1999). FishXing model inputs included culvert length, slope, roughness, outlet plunge pool depth, and tailwater control cross section. Tailwater control refers to the plunge pool tailout that controls the depth of the plunge pool. These data were obtained from a culvert survey conducted by the USFS in 2002.

Passage success using the model was determined for all days during the upstream migration period. This period was defined as the period from 24 hours prior to the first fish trapped at the fish weir near the mouth of Mulherin Creek to 24 hours after the last recorded upstream movement. Because FishXing requires a fish length for the 'test fish' to determine which swimming velocity will be used in the model, the average fish length of 343.0 mm was used. A minimum water depth in the culvert is also needed by the FishXing model, therefore a minimum culvert depth of 9.1 cm for upstream passage was used based on recommendations in the literature for adult cutthroat trout (Fitch 1995). Culvert roughness was estimated by adjusting roughness coefficients until the observed culvert water depth was within 5 cm of that predicted by the model.

Tag Loss and Spawning Habitat Availability

Because the number of fish attempting to migrate upstream through culverts was a much lower fraction than expected based on the total number tagged at the trap, I examined the possibility that fish shed the PIT tag or else spawned below culvert 1. To assess tag loss, I scanned the 1,113 m-long reach between the trap and the first culvert with a portable PIT tag detector at the end of the study on 24 - 25 September 2006. The detector consisted of a Biomark Destron Fearing FS2001F-ISO PIT tag reader base unit and a 30.5-cm triangle antenna with 3 m pole and belt system. I walked upstream with the detector scanning the wetted stream area as well as any potential spawning gravel within the active stream channel. To test for detection accuracy, I placed a single PIT tag in the substrate at several different locations during the survey. Of the 10 tags tested, all were detected within approximately 0.5 m of the test tag.

To assess if fish were spawning below culvert 1 and to assess availability of spawning habitat above culverts 4 and 5, I measured spawning substrate availability within the study area. The study area was divided into six reaches: weir to culvert 1; culvert 1 to culvert 2; culvert 2 to culvert 3; and culvert 3 to Cinnabar Creek. Upper Mulherin Creek above the junction of Cinnabar Creek and culvert 4 had a single 1.5 km reach surveyed due to the presence of a cascade/waterfall migration barrier (De Rito 2004). Cinnabar Creek above culvert five extends 6.5 km and was divided into thirteen 0.5 km reaches and I randomly selected two reaches representing 15% of the total available habitat.

Based on examination of redds in Mulherin Creek, I chose substrate sizes ranging from 12 to 50 mm as the size range used to assess the amount of spawning habitat. As in Magee et al. (1996), only areas of gravel at least 0.25 m^2 were included in estimating the amount of available spawning habitat measured. Each reach was measured with a hip chain to determine reach length. The areal dimensions of patches of spawning-sized gravel at least 0.25 m^2 located in areas suitable for spawning (pool tailouts, below boulders and on the stream edge) were measured with a meter stick while walking upstream. Because surveys were conducted during low flow conditions, areas suitable for spawning that were dry but were within the bankfull width were included in measurements. Amounts of available spawning habitat were expressed as total area per reach and area per linear stream distance.

Data Analysis

Trapping and Tagging

Mann-Whiney U-tests were used to examine differences in mean trapping date, discharge at the time of trapping, and water temperature between study years 2005 and 2006. Nonparametric U-tests were used because tests for normality using a Shapiro-Wilk test for 2005 data ($N < 50$) and a Kolmogorov-Smirnov test for 2006 data ($N > 50$) indicated the data were not normally distributed. An alpha level of 0.05 was used to test for significance for all statistical tests.

Detection Range and Read Accuracy

Mean detection accuracy and detection range among the culverts and the natural control was compared using one-way ANOVA. Post-hoc comparisons of means were analyzed with Fisher's least significant difference (LSD) tests.

Fish passage

Because of the potentially large number of tag detections associated with HDX PIT tag equipment (3 scans per second per antenna), data filtering was necessary to eliminate redundant detections when fish remained stationary over an antenna for long periods. In these cases, I only retained detections recorded at 30 second intervals when assessing passage attempts. .In addition, there were several instances where individual fish made multiple upstream and downstream passes through an individual culvert. In those cases, I used only the first successful passage was used for analysis.

Daily time of attempts for both 2005 and 2006 were plotted against the mean time of sunrise and sunset for June and July 2006 in Livingston, MT in order to determine if movement occurred at a particular time of day. Attempts were also plotted against the temperature at the time of the attempt in order to ascertain patterns of when movement occurred.

Movement data from 2005 and 2006 were combined and Mann-Whitney U-tests were used for pairwise comparisons to test for significant differences in biotic factors (species, sex, fish length and number of attempts) and abiotic factors (temperature, velocity, drop height and culvert length) between individuals that passed or failed to pass through culverts. Factors that were found to be significant were used in a stepwise logistic regression to determine the best model for predicting the probability of successful passage. Differences in passage time among culverts and the control reach were assessed using a Kruskal-Wallis test non-parametric analysis of variance and Mann-Whitney U-tests for paired comparisons.

Culvert Hydraulics

In order to determine the influence of culvert type on velocity, velocities in culvert 1 (unbaffled box), culvert 2 (baffled box), culvert 3 (baffled box with 10% natural substrate) and the control (natural substrate) were examined with a Kruskal-Wallis test. A Kruskal-Wallis test was used to test for significant differences among the treatments because a Kolmogorov-Smirnov test indicated the data were not normally distributed.

Mann-Whitney U-tests were used for pair-wise comparisons to determine which treatments have significant differences in velocities.

FishXing Comparison

Upper and lower passage thresholds for each culvert identified in FishXing were compared to passage attempts and successful passes observed in the field. The range of flows within this passage window bounded by the upper and lower passage thresholds were compared to the range of flows that were passable in the field as a percentage of time passable under predicted and observed conditions. Additionally, discharge at each culvert during the spawning run was converted into velocity values with the use of equations derived from the culvert's stage-discharge rating curve. The velocity values predicted as barriers to upstream passage in the FishXing model were then plotted on the generated velocity profile and compared to the observed number of passage attempts and successes.

RESULTS

Trapping and Tagging

In 2005, trapping of fluvial-adfluvial YCT and RBT from 23 April to 30 August resulted in the capture and PIT tagging of 28 YCT, two RBT and four hybrids. In 2006, 90 YCT, 5 RBT, and two hybrids were trapped and PIT tagged from 18 June thru 13 July (Figure 7). Additionally in 2006, two YCT, seven RBT and three hybrids were electroshocked below culverts 4 and 5 and tagged and released below culvert 1. Relatively few RBT and hybrids were captured in both years because high flows and ice prevented effective trapping in March and April when upstream migration of rainbow trout primarily occurs (De Rito 2004; M. Blank, MSU Department of Civil Engineering, unpublished data).

Upstream migration of YCT occurred during a relatively short period of time during late June to early July as flows stabilized following peak discharge in mid June and as temperatures rose to 12^{o}C (Figure 7). Mean trapping date was significantly later in 2005 (July 5) than in 2006 (23 June) ($U = 0.00$ $P < 0.001$) and occurred at a significantly lower discharge in 2005 (1.41m^3/sec) than in 2006 (1.57 m^3/sec) ($U = 552.0$, $P < 0.001$). However, mean water temperature during upstream migration was similar between years (2005: 13.3ºC; 2006: 13.1ºC) ($U = 1314.0$, $P = 0.25$).

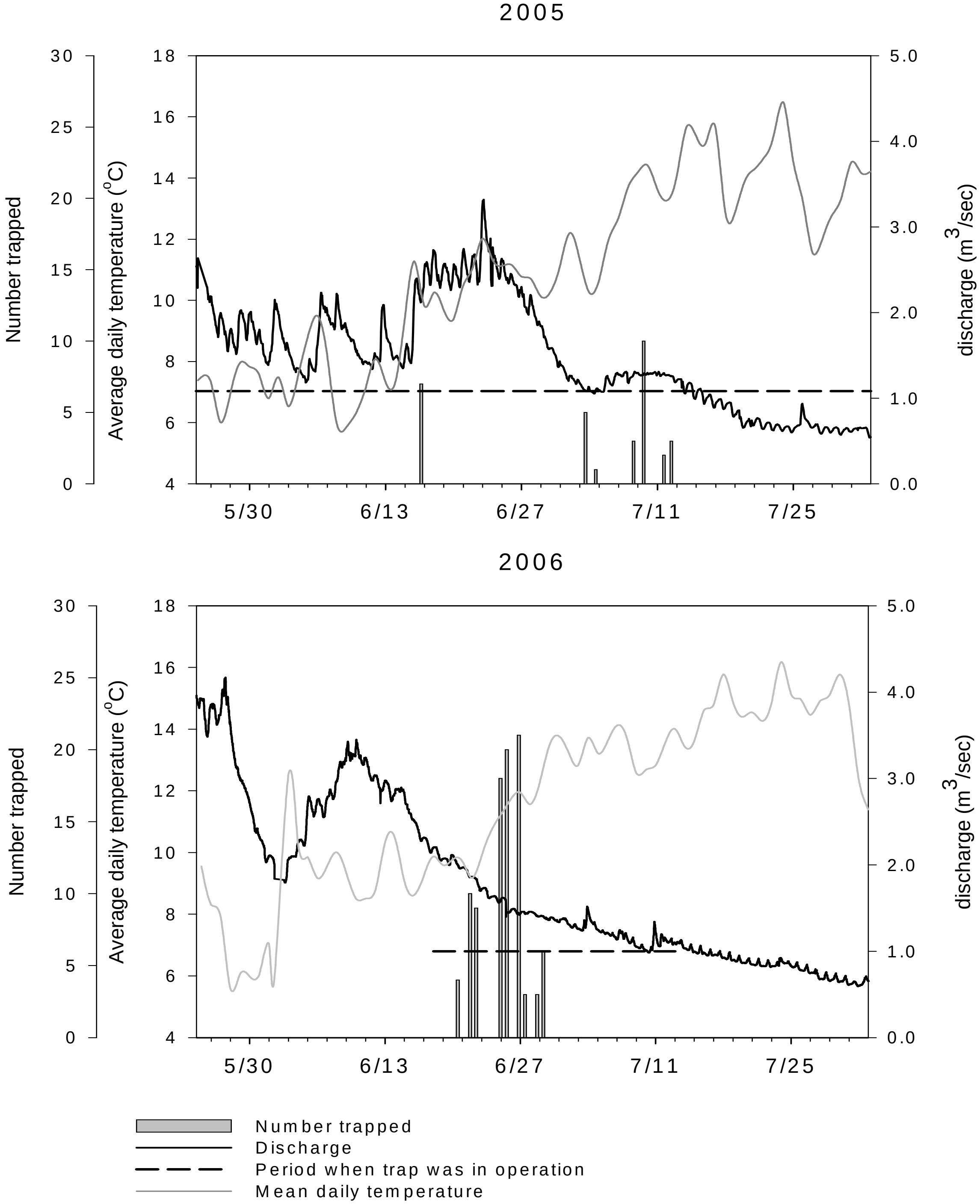


Figure 7. Numbers of migrant trout (YCT, RBT and hybrids) captured and PIT tagged in relation to discharge and mean daily temperature of Mulherin Creek, MT for 2005 and 2006.

Tag Detection Range and Accuracy

Detection range varied by the antenna attachment surface (natural substrate, concrete box culvert, or steel pipe culvert). The natural control reach had a mean detection distance of 28.2 cm both upstream and downstream of the antenna. Concrete box culverts and steel pipe culverts had significantly lower detection ranges of 18.8 and 6.0 cm, respectively (Table 3). Mean detection range varied significantly among all three attachment surfaces (ANOVA: F = 976.1, df = 2, $P < 0.001$). Fisher's least significant difference (LSD) tests showed significant differences in detection range between all possible pairwise comparisons of antenna locations.

Mean detection accuracy of test tags ranged from 74.7 to 94.5% (Table 3) and differed significantly among the natural reach and the two culvert types (ANOVA: F = 18.5, df = 3, $P < 0.001$). Fisher's LSD tests showed significant differences in detection accuracy between all possible pairwise comparisons of the natural control and both box and steel pipe culverts (Table 3). Antennas placed in the natural control reach had the highest detection accuracy at 94.7%, whereas the lowest accuracy (74.7%) occurred at antennas attached to steel pipe culverts. Culvert box culvert antennas had an intermediate detection accuracy of 80.6%.

Table 3. Mean (± 95% CI) PIT tag detection range and percent detection accuracy by antenna location. Underlined values are significantly different ($P < 0.05$). Sample size shown in parentheses.

	Control	Box culvert	Steel culvert
Detection range, cm	<u>28.2</u> ± 0.3 (75)	<u>18.8</u> ± 0.6 (167)	<u>6.0</u> ± 0.5 (84)
Detection accuracy, %	<u>94.5</u> ± 2.9 (75)	<u>80.6</u> ± 3.5 (167)	<u>74.7</u> ± 5.1 (84)

Fish Passage

Of the 143 fish tagged at the trap or released below culvert 1 in 2005 and 2006, 36 (25%) were detected at culvert 1. These 36 individuals resulted in a total of 6,763 tag detections at the tag-detecting antennas. Omitting multiple detections at a single antenna, missed detections, and multiple passes through a single culvert, resulted in a total of 46 successful passes and eight failed attempts.

Fish were observed successfully passing through all culverts except culvert 5. The percentage of fish that both attempted passage and successfully passed through each culvert ranged from 0% for culvert 5 to 100% for culvert 3. For all culverts, the number of attempts varied from 1 to 11 with a mean of three before successful passage (Table 4). Although no individuals successfully passed through culvert 5, two individuals were recorded attempting passage with 24 and 2 attempts. The majority of attempts (88.6%) occurred during daylight hours in the eight hour period between 12:00 and 20:00 hours; very few attempts were made at night (Figure 8). The majority of attempts (70.0%) occurred at water temperatures between 12 and 17°C (Figure 9).

Table 4. Summary of successful passage and failed attempts by culvert and through the natural control reach. Successful passage: *N* = 46, failed to pass: *N* = 8.

Culvert	Number of fish attempting passage	Pass (%)	Time to pass, min Mean	Time to pass, min Range	Attempts Passed Mean	Attempts Passed Range	Attempts Failed passage Mean	Attempts Failed passage Range
Culvert 1	30	90	0.6	(0.2 – 1.3)	5	(2 – 11)	3	(1 – 4)
Culvert 2	25	96	13.3	(4.1 – 46.0)	5	(1 – 10)	3	3
Culvert 3	22	100	3.8	(0.9 – 11.1)	2	(1 – 4)	–	–
Culvert 4	9	77.8	2.1	(0.2 – 11.9)	3	(1 – 6)	3	(1 – 4)[b]
Culvert 5	2	0	–	–	–	–	13	(2 – 24)[b]
Control	2	100	22.2	(3.2 – 41.2)[a]	2	2	–	–

[a] Only two individuals were recorded passing through the control reach.

[b] Only two individuals were recorded failing to pass culverts 4 and 5.

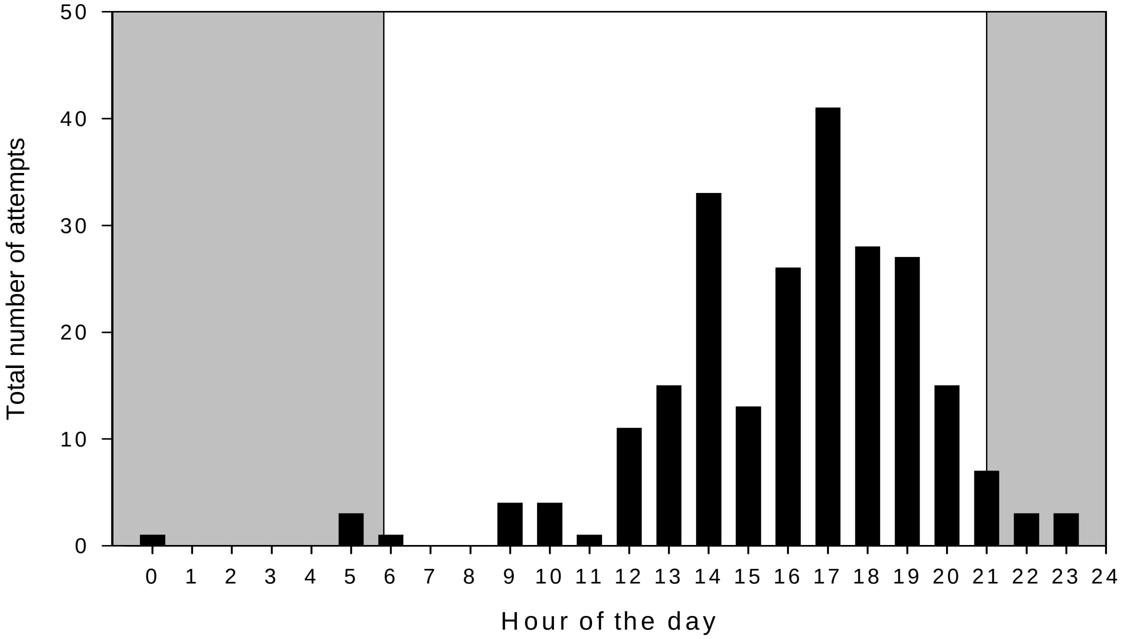


Figure 8. Total number of attempts by hour of the day for all culverts, shaded area indicates the mean time of darkness (between sunset and sunrise).

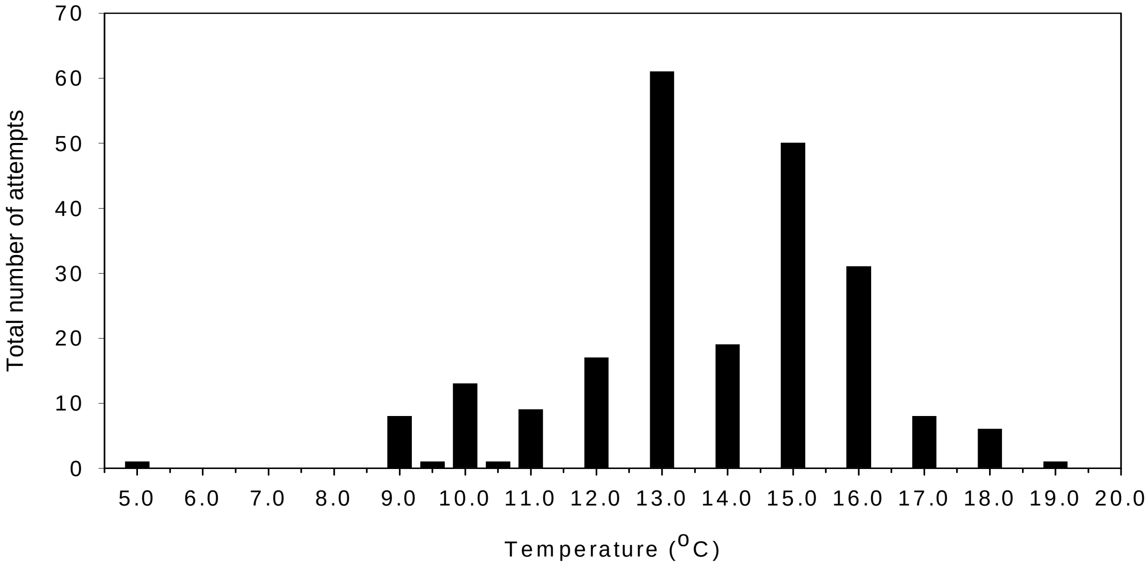


Figure 9. Total number of attempts of fish passage at all culverts in relation to water temperature on Mulherin Creek, MT. Temperatures at the time of attempts are rounded to the half of a degree.

Passage success varied significantly with fish size, water temperature, culvert velocity, and outlet drop. Fish that successfully passed through culverts were significantly smaller than fish that attempted to pass but were unsuccessful (362.5 versus 320.2 mm) ($U = 71.5$, $P = 0.005$) while the mean length of all fish tagged was 343.0 mm. The smallest individual that passed through any culvert was 300.0 mm while individuals as small as 230.0 mm were tagged and had the opportunity to attempt passage (Figure 10). Successful passage also occurred at significantly higher water temperatures than unsuccessful passage (13.6 versus 12.3 °C) ($U = 101.0$, $P = 0.043$). Passage success also occurred at significantly lower culvert velocities than unsuccessful attempts (1.6 versus 2.5 m/sec) ($U = 33.0$, $P < 0.001$). The highest velocity for successful passage was 2.71 m/sec, but I observed passage attempts at velocities as high as 2.97 m/sec. Passage success also occurred at significantly smaller outlet drops than unsuccessful attempts (11.9 versus 35.0 cm) ($U =62.5$, $P = 0.002$). Other factors examined (culvert slope, culvert length, number of attempts, sex, and species) showed no significant relationship with passage success (Figures 11 and 12).

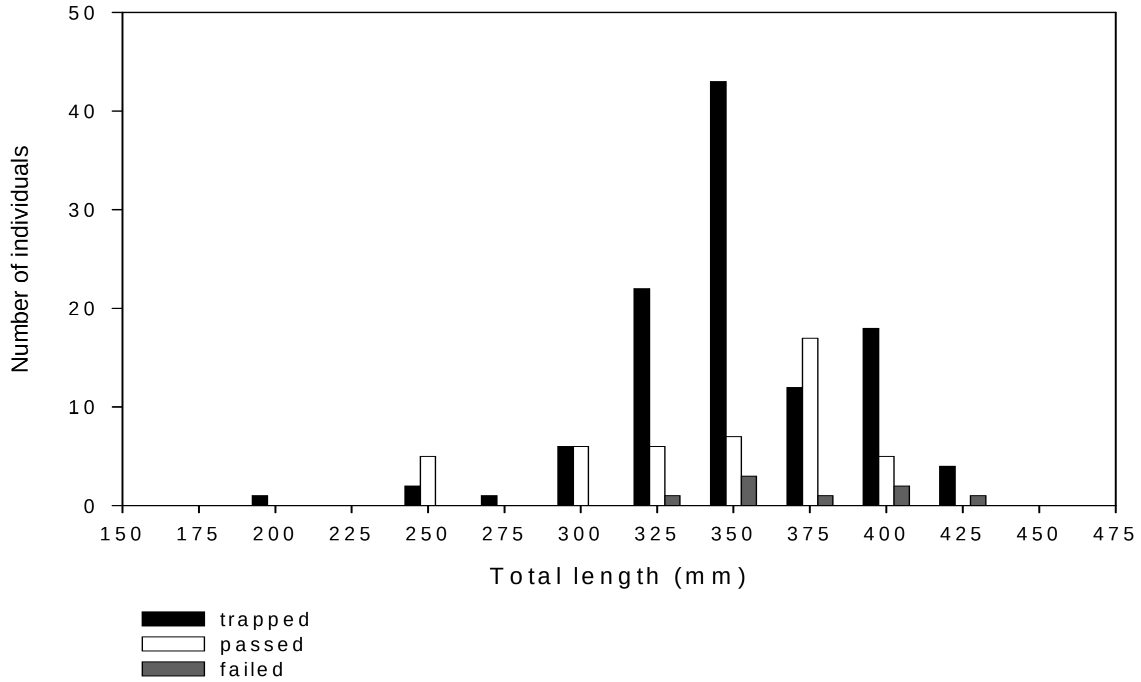


Figure 10. Length distribution of individuals that were trapped, successfully passed and failed to pass culverts on Mulherin Creek, MT in 2005 and 2006. Length values indicate the highest value in 25 mm increments.

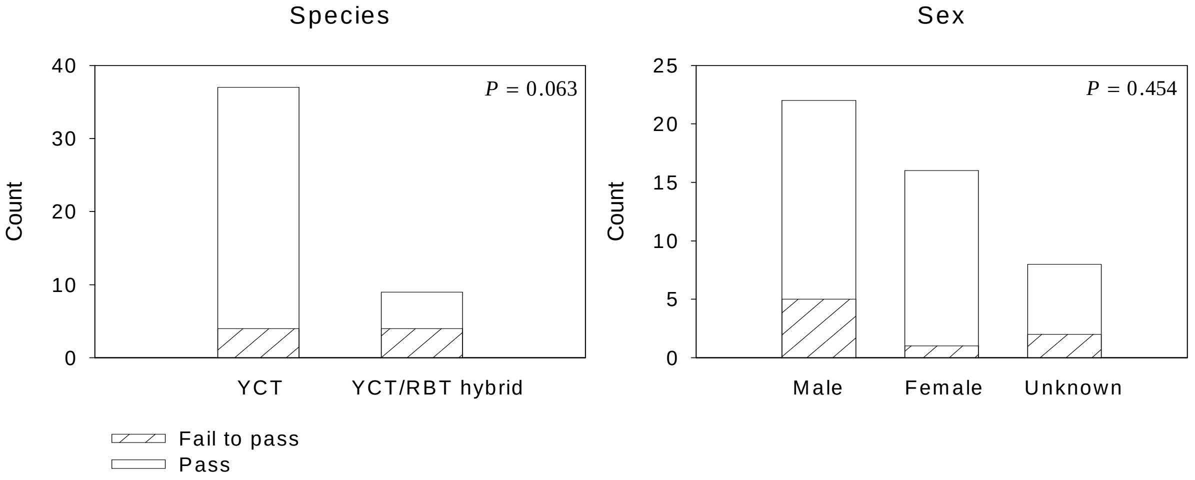


Figure 11. Differences in species and sex proportions between individuals that successfully passed through culverts and those that failed to pass; *P*-values determined using Chi square tests. Passed *N* = 46, failed to pass *N* = 8.

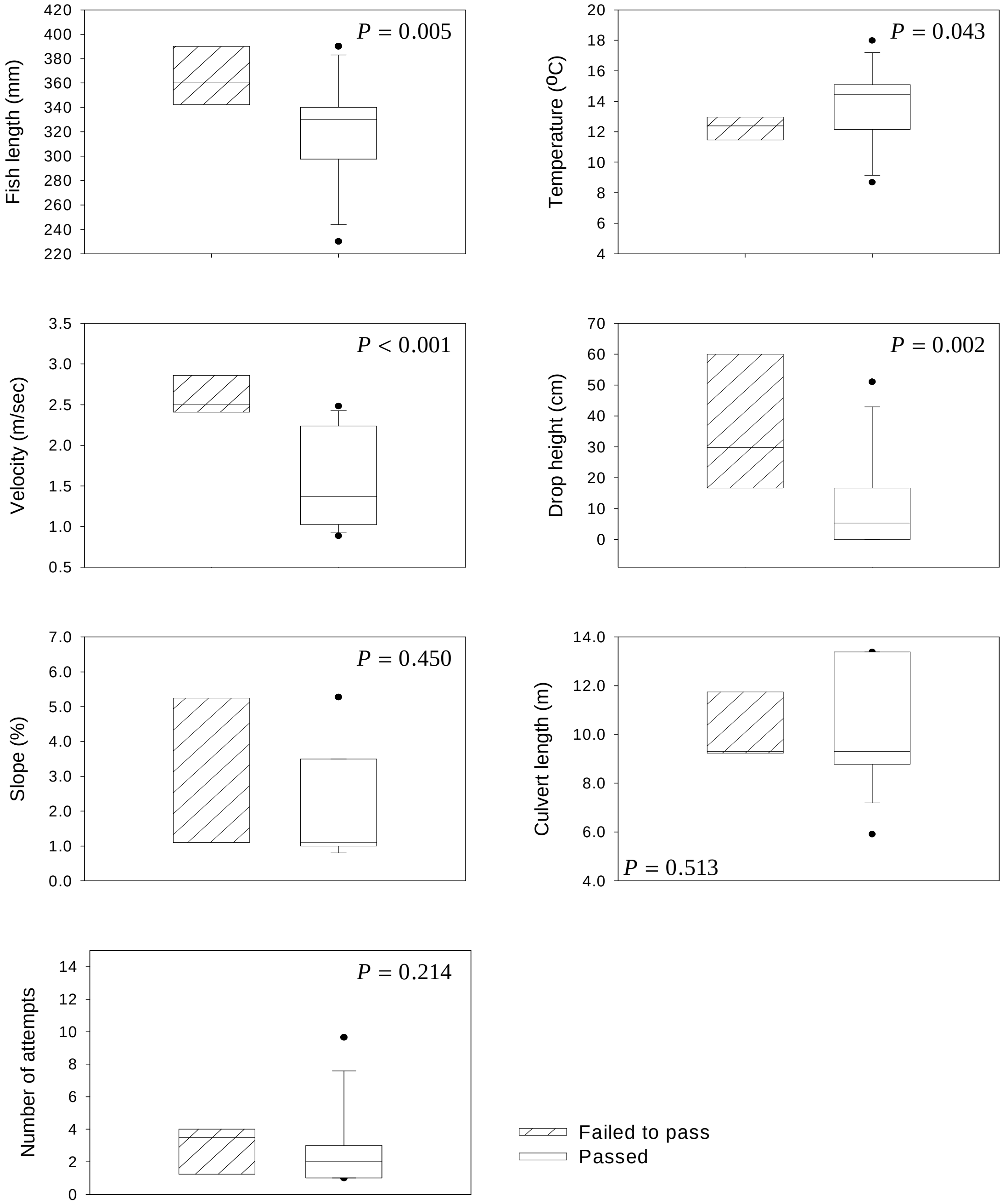


Figure 12. Box plots comparing differences in biotic and abiotic characteristics of culverts and test fish during passage successes and failures. *P*-values were determined using Mann-Whitney U tests. Passed N = 46, failed to pass N = 8. Vertical lines of box plots with horizontal dashes indicate minimum and maximum. The boxes represent the first and third quartiles (25th and 75th percentiles) of the distributions, and the horizontal solid lines in the boxes indicate medians.

Of the four factors found to be significant in the single factor analysis (fish length, water temperature, outlet drop, and velocity), the only regression model to predict the probability of passage that was significant was a single factor model containing velocity (Figure 13) represented by the equation:

$$p = \frac{1.0}{1 + e^{\left(\frac{v - 2.6086}{-0.2569}\right)}}$$

$p =$ Probability of successful passage

v = Velocity (m/sec)

This model correctly predicted passage success/failure in 88.9% of the cases. The model correctly predicted successful passage in 97.8% of cases but failed passage was correctly predicted in only 37.5% of cases.

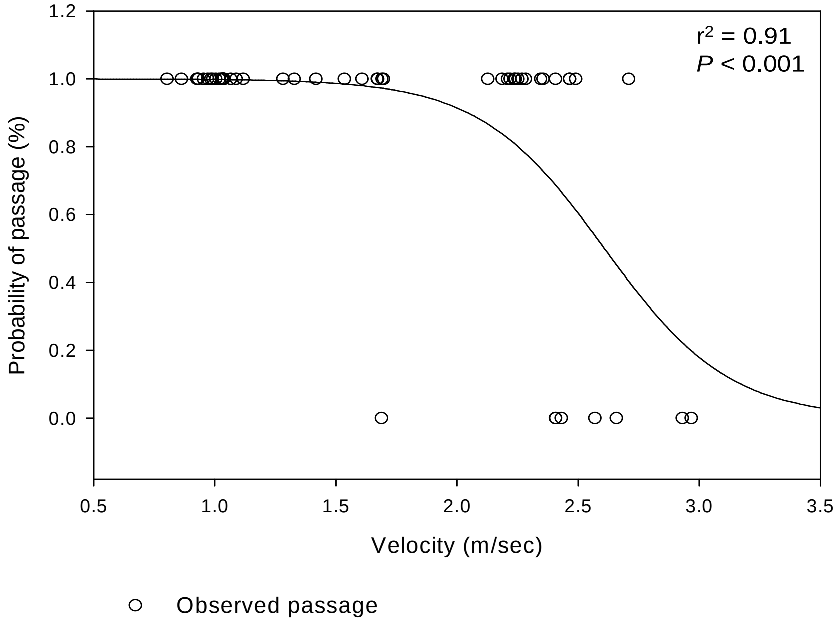


Figure 13. Logistic regression model of the probability of YCT passage in relation to culvert velocity. Data points indicate show observed passage success (1.0) and failure (0).

Time of Passage

The mean time of passage through culverts and the control ranged from 0.2 to 41.2 min and time required for passage varied significantly among culvert types (Kruskal-Wallis: H = 17.97, df = 2, $P < 0.001$). A single record of 17.3 hours required to pass through culvert 1 (unbaffled box) was an extreme outlier that was eliminated from the analysis.

Average passage time varied by culvert and the control (Table 5). Passage time through the baffled box culverts was 9.5 times slower than passage time through unbaffled box culvert (5.7 versus 0.6 min) (U = 2.0, $P = 0.001$) and baffled box culverts had seven times the variation in passage time. Passage time through the baffled box culverts was also significantly slower (2.7 times) than through the unbaffled steel culvert (2.1 min) (U = 23.00, $P = 0.003$). Passage times were not significantly different between the unbaffled box and unbaffled steel culverts (U = 14.5, $P = 0.626$) although the unbaffled steel culvert had eight times the variation in passage time. However, the mean time of passage through the control (22.2 minutes) was 37 times slower than through the unbaffled box culvert (W = 15.0, $P = 0.053$). Passage time was not significantly different between the control and either baffled box culverts (U = 15.0, $P = 0.39$) or the unbaffled steel culvert (U = 1.0, $P = 0.079$). Although passage time through the control ranged from 3.9 to 37 times slower than through any other culvert, statistical tests showed no significant differences in passage time. This is most likely due to lack of power due to the small sample size (N = 2) which can lead to type II error.

Table 5. Mean ± 95% CI passage time through unbaffled box, baffled box, and unbaffled steel culverts. Sample size shown in parentheses.

	Time to pass, min
Culvert type	Mean
Unbaffled box	0.6 ± 0.5 (5)
Baffled box	5.7 ± 3.8 (24)
Unbaffled steel	2.1 ± 4.0 (7)
Control	22.2 ± 241.2 (2)

Culvert Hydraulics

Hydraulic conditions varied among the unbaffled box culvert, the baffled box culvert, and the baffled box culvert with 10% natural substrate as well as between these culverts and the natural control reach in Lower Mulherin Creek. Although discharge was similar within this reach (no inflowing tributaries), culvert velocities varied significantly during the spawning period in 2006 (24 hours prior to the trapping of the first individual to 24 hours after the last recorded upstream PIT tag detection, 22 April to 14 August) (Kruskal-Wallis: H = 5693.2, df = 3, $P < 0.001$). Data from 2005 were not used in this comparison because of the lack of a control. Pair-wise comparisons using Mann-Whitney U-tests tests showed that velocities were significantly different between all culverts and between each culvert and the control ($P < 0.001$).

The unbaffled box culvert had the highest mean velocity of 2.5 m/sec which was 2.3 times greater than the control reach which had the lowest mean velocity of 1.1 m/sec. Velocity in the unbaffled box culvert was 1.5 times faster than in the baffled culvert which had a mean velocity of 1.7 m/sec and 2.1 times faster than the culvert that contained baffles and 10% natural substrate which had a mean velocity of 1.2 m/sec

(Table 6, Figure 14). Although the model that contained velocity alone was the best predictor of passage in the regression analysis, there appeared to be no direct linear relationship between velocity and time of passage when examining the three culverts on Lower Mulherin combined (Figure 15).

Table 6. Mean velocities ± 95% CI of different culvert types from 24 hours prior to the first trapping of a fluvial-adfluvial individual to 24 hours past the last recorded upstream movement. Underline indicates significant differences at an alpha of 0.05.

	Culvert 1 Unbaffled box	Culvert 2 Baffled box	Culvert 3 Baffled box + 10% natural	Control Natural
Mean Velocity (m/sec)	2.5 ± 0.02	1.7 ± 0.02	1.2 ± 0.02	1.1 ± 0.01

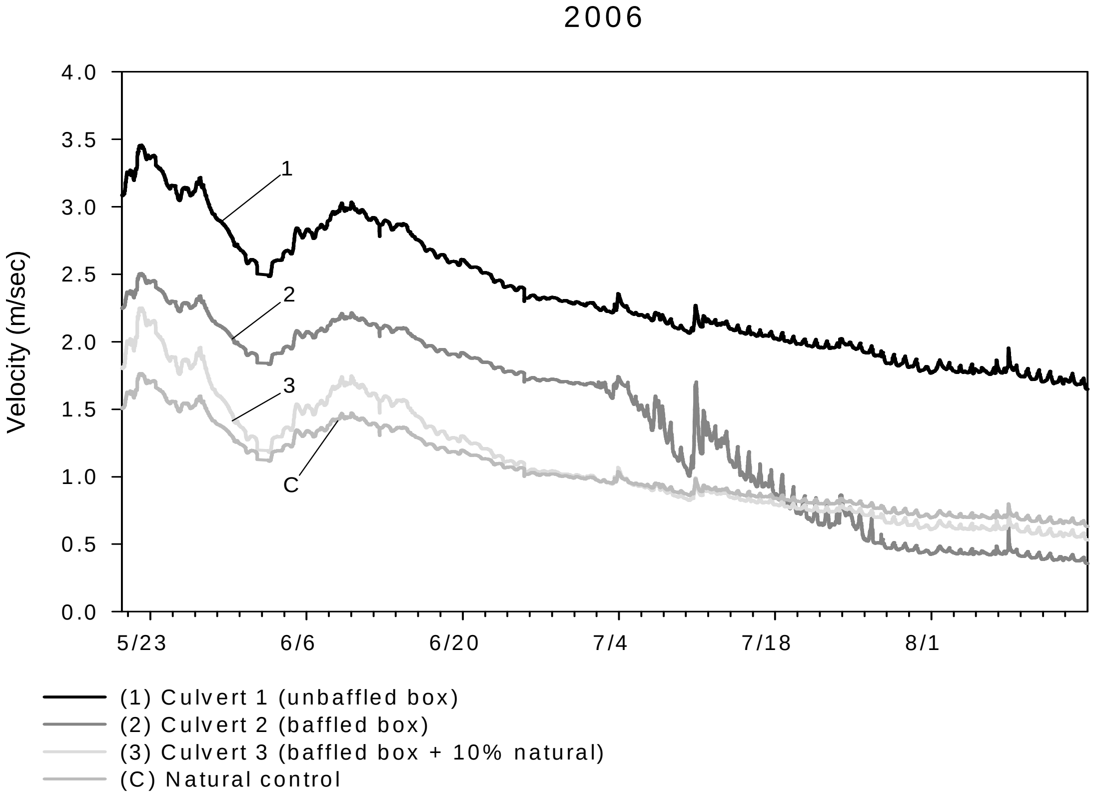


Figure 14. Velocity profiles of box culverts with and without baffles and the natural control reach over from 20 May 2006 through 14 August 2006.

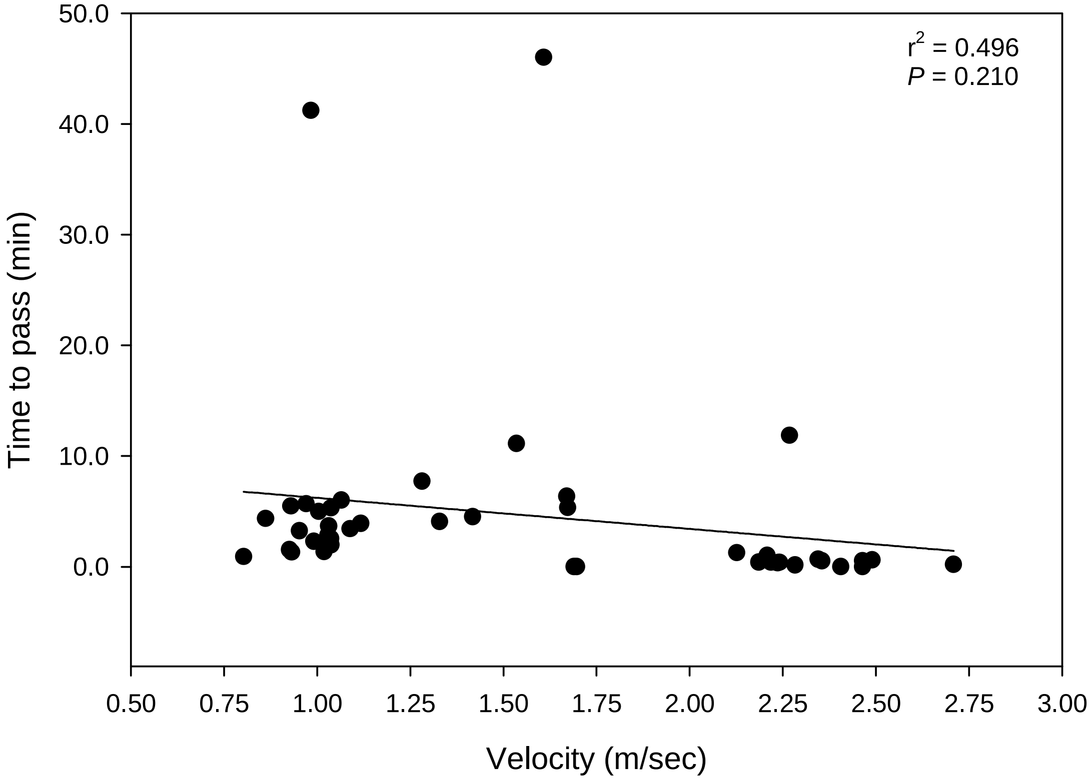


Figure 15. Relationship between velocity at time of passage and the length of time required for passage through culverts 1, 2 and 3 represented by the equation $t = 9.0169 - 1.3376v$.

FishXing Comparison

The results of the FishXing model indicate that the unbaffled box culvert poses a passage barrier at some flows while the steel pipe culverts are barriers under all flow conditions. FishXing predicted a passage window for the unbaffled box culvert from 0.7 to 1.5 m^3/sec resulting in 20.8% of the range of discharges being passable (Figure 16). At discharges greater than 1.5 m^3/sec the unbaffled box culvert posed a velocity barrier, while at discharges greater than 2.5 m^3/sec it also posed a leap barrier. FishXing indicated that the steel pipe culvert on Upper Mulherin Creek posed a velocity, leap, and pool depth barrier at all discharges and no passage was possible.

Field results showed that successful passage of the unbaffled box culvert only occurred within the passage window indicated by the FishXing model (Figure 16). Of all attempts, 28.1% occurred at discharges greater than 1.5 m^3/sec. The maximum discharge when passage was attempted was 1.8 m^3/sec. Field results showed that the steel pipe culvert on Upper Mulherin Creek was passable while FishXing indicated no passage was possible under any flow conditions. Fish were recorded successfully passing through the Upper Mulherin Creek steel pipe culvert at discharges from 0.6 to 1.7 m^3/sec (Figure 16).

When the passable discharge windows indicated by FishXing were converted into velocities, a passage window from 1.9 to 2.3 m/sec was indicated for the unbaffled box culvert while the steel pipe culvert was considered to be a barrier at all velocities. Field observations showed that fish successfully passed through the unbaffled box culvert at velocities from 2.1 to 2.3 m/sec which was within the range indicated by the converted FishXing results (Figure 17). Fish were observed passing through the steel pipe culvert on Upper Mulherin Creek at velocities from 2.2 to 2.7 m/sec although FishXing characterized it as impassable under all velocities (Figure 17).

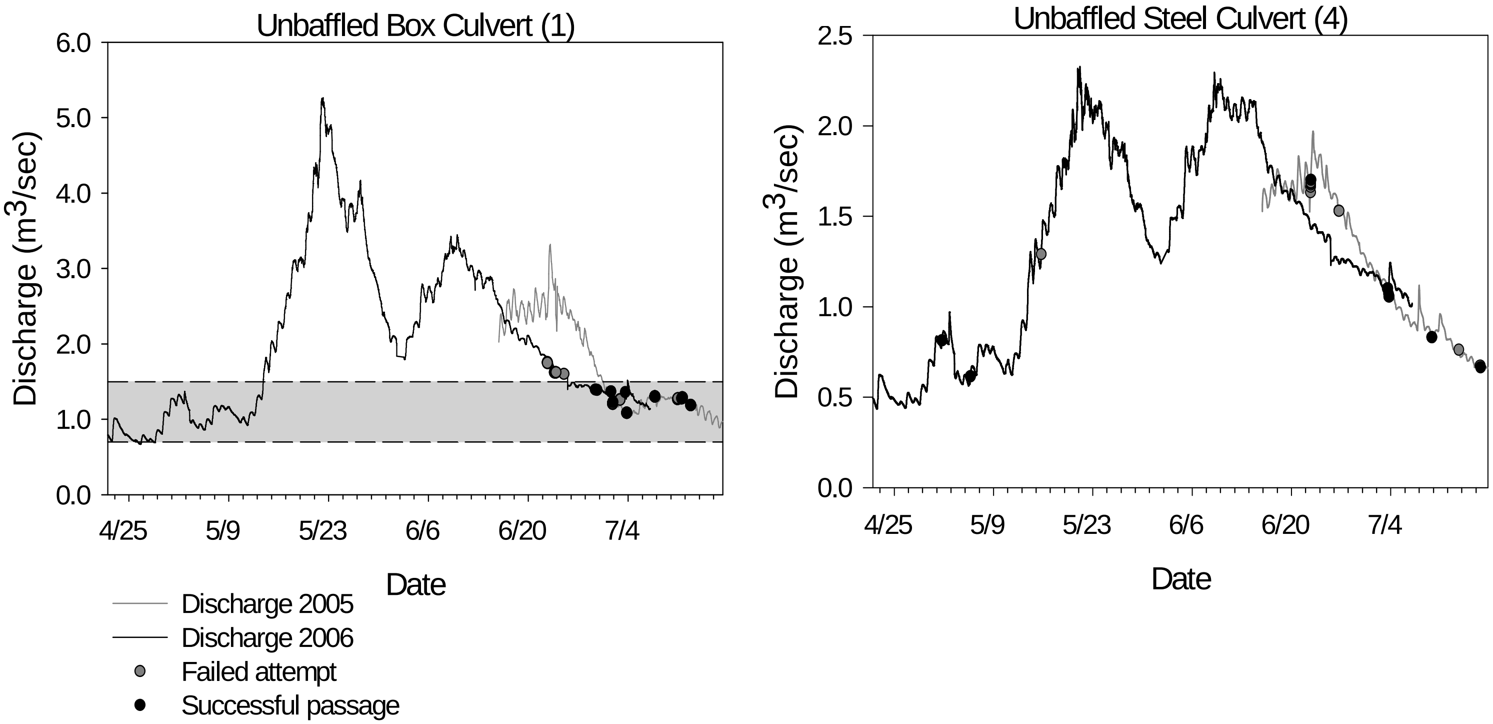


Figure 16. Observed passage and failed attempts of YCT in relation to discharge through culverts 1, 4 and 5 and the passage window calculated with the FishXing model indicated by gray shading.

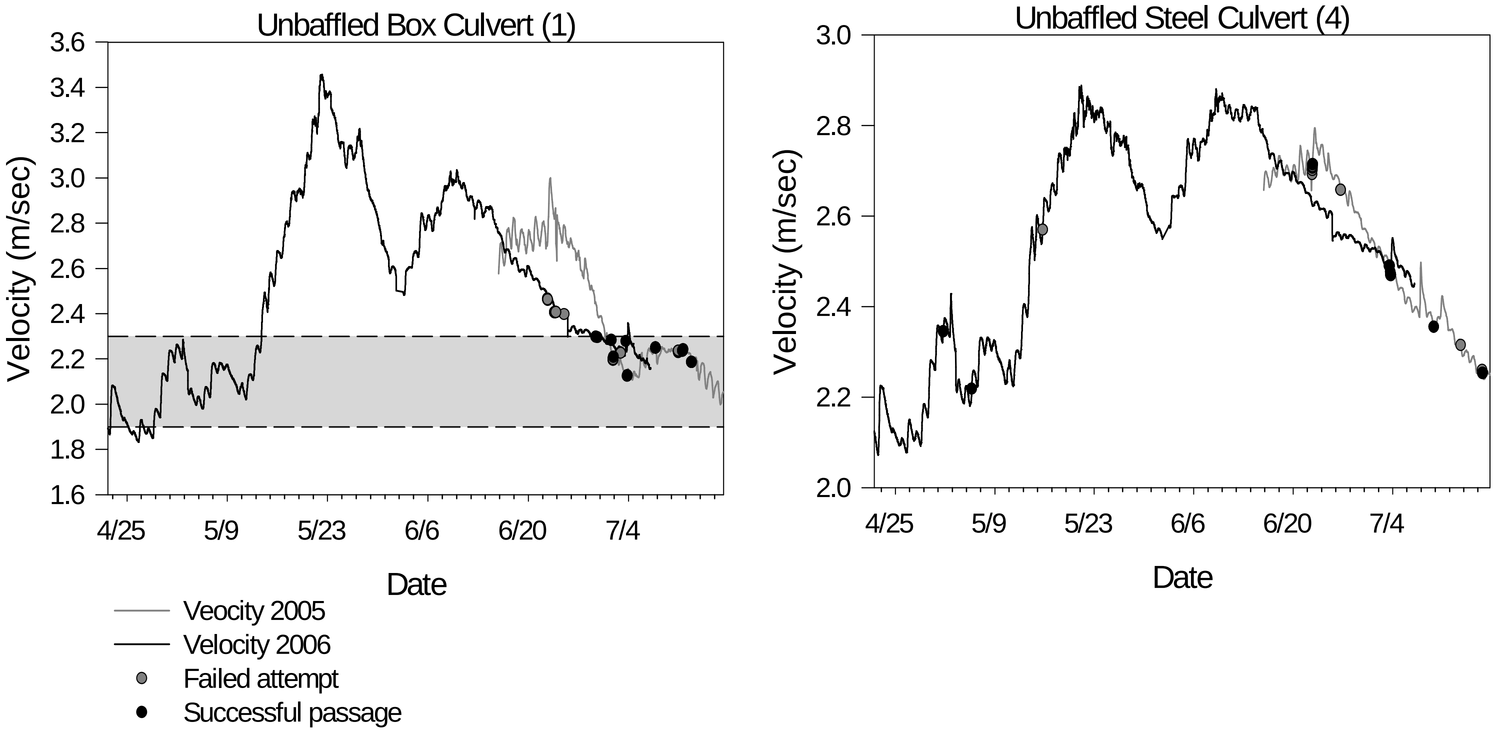


Figure 17. Successful passes and failed attempts of migrating individuals at culverts 1, 4 and 5. Gray shading indicates passable velocities calculated from the FishXing model indicated by gray shading.

Tag Loss and Spawning Habitat Availability

I found no shed tags while surveying the stream from the trap to culvert 1 despite detection accuracy of the PIT tag detector of 100% within 31.0 cm of test tags (*N* = 10). This suggests that the large numbers (75%) of tagged fish that were not detected at culvert 1 did not ascend the creek. This same reach also contained the most spawning gravel with 12.0 m^2/km and a total amount of 124.68 m^2 (Table 7). Cinnabar Creek above culvert 5 through which we observed no successful passage had the second highest concentration of spawning gravel with 104.70 m^2/km and a total of 680.54 m^2 (Table 7).

Table 7. Amount of spawning gravel available per reach.

Reach	Surveyed Length (km)	Spawning gravel total (m^2)	density (m^2/km)
1-Trap to culvert 1	1.1	124.7	113.4
2-culvert 1 to culvert 2	0.3	4.9	15.8
3-culvert 2 to culvert 3	0.7	17.5	25.4
4-culvert 3 to Cinnabar Cr.	0.8	38	45.8
Upper Mulherin (above culvert 4)	1.6	136.4	85.3
Cinnabar Cr. (above culvert 5)	6.5	680.5	104.7

DISCUSSION

Previous culvert fish passage evaluations have primarily relied upon application of laboratory-derived fish swimming and jumping capabilities to designate a culvert as passable or impassable to upstream passage. In this study, I applied new HDX PIT tag technology to provide real-time monitoring of fish passage through culverts in order to directly assess the probability of success or failure of passage over a range of biotic and abiotic conditions including fish size, culvert type, and the presence or absence of baffles. I then compared observations of passage success over a range of hydraulic conditions with passage status predicted by the FishXing model, a widely used tool to evaluate fish passage status of road culverts.

Upstream Migration of Rainbow Trout and Yellowstone Cutthroat Trout

I captured unexpectedly low numbers or RBT and YCT compared to preliminary work in 2004 when 23 RBT, 339 YCT and 21 hybrids were trapped (M. Blank, MSU Department of Civil Engineering, unpublished data). I believe this is primarily due to high runoff which precluded trapping and tagging of RBT shortly after the ice melted and to fish spawning below the weir trap where altered water flows exposed suitable spawning gravel. In both years of my study fish were observed spawning below the weir trap throughout the spawning season.

Results indicated that spawning migration timing of fluvial-adfluvial YCT may be influenced more by temperature than by discharge. Both discharge and mean date of trapping of YCT varied significantly by year. The mean trapping date of YCT in 2005 was 5 July while in 2006 it was 23 June which was similar to De Rito (2004) who found that the mean start date of the YCT spawning migration in the Yellowstone River was 10 June and M. Blank (unpublished data) who observed a mean trapping date of 22 June for YCT. Mean water temperature at the time of trapping was similar for both years. During both 2005 and 2006, individuals were observed moving upstream out of the Yellowstone River and staging downstream of the weir trap when the temperature first reached 12°C. At temperatures below 12°C no fish were visible below the weir and were assumed to have returned to the Yellowstone River as a temperature refuge because no suitable staging habitat was available between the trap and the river.

Application of PIT Tag Technology

Tag detection range and accuracy of the PIT tag detecting antennas varied greatly depending on the antenna attachment surface. While testing for detection range and accuracy, I observed both reduced detection range and accuracy due to increased signal interference as the amount of ferrous metal located in the vicinity of antennas increased. At sites with little or no metal nearby (natural control reach, cross section below plunge pools), tags were detectable an average of 28.2 cm upstream and downstream of an antenna and had a high detection accuracy (94.5%). When antennas were attached directly to steel culverts (culverts 4 and 5), detection range decreased to only 6.0 cm and detection accuracy similarly decreased to 74.7%. I found no other studies in the literature that had reported detection ranges for PIT tag antennas. However, reported detection accuracies for HDX PIT tag antennas are highly variable and have ranged from 62 – 93% (Tranquilli 2005) when measured in natural stream reaches. Antennas that were attached to box culverts and steel pipe culverts in my study had detection accuracies within the 62

– 93% range while antennas in the control and in the cross sections below plunge pools had detection accuracies higher than either of these studies. This may be the result of the method used for measuring detection accuracy. Although Tranquilli (2005) does not state how detection accuracy was measured, Adams et al. (2006) used tagged fish to measure accuracy. My method of measuring detection accuracy was to pass a ‘test tag’ through the antenna. This may have overestimated the actual accuracy because the tag always entered the detection field perpendicular to the field, which maximizes the likelihood of detection (Zydlewski et al. 2001).

Although detection range and accuracy was relatively high, any detection accuracy less than 100% means that, on occasion, a fish may pass through a culvert without detection resulting in underestimation of passage success. However, if the fish is detected upstream at another antenna, passage can be assumed. I documented 39 occasions where successful passage was not recorded although the fish passed through the culvert. Thirty-seven of these missed detections were due to the antennas at the upstream end of the culverts 1 and 2 being destroyed by debris during high flows. In order to reduce the possibility of antennas being destroyed, antennas may be laid horizontally on the bottom of the culvert (Hill et al. 2006). Antennas below the plunge pools were also damaged when high flows moved boulders anchoring them in the substrate. Improved detection accuracy could be achieved by anchoring antennas to the stream bed by burying PVC pipe deeper into the substrate, or using rebar anchors sunken into the substrate to hold the antenna in place.

Antenna design varied by location in order to maximize detection range and accuracy. The number of wire loops used to construct antennas varied by antenna location in order to obtain an inductance level that facilitated efficient tuning. In the natural control reach a single loop of 8-gauge multi-strand wire was sufficient to obtain a detection accuracy of 94.5%. Similarly, Adams et al. (2006) utilized 6-gauge wire with a single loop for an antenna with a width of 8.0 m and a height of 0.5 m resulting in a detection accuracy of 67%. Box culverts with steel reinforcement required two loops of antenna wire to obtain a detection accuracy of 80.6% while three loops were needed on the steel culverts to achieve a detection accuracy of 74.4%. While the natural control antennas, antennas below plunge pools, and box culvert antennas had a maximum height of 1.2 m, the height of antennas attached to steel pipe culverts also had to be smaller with a maximum height of 0.75 m due to increased interference caused by ferrous metal.

Detection accuracy can also be reduced by inherent characteristics of HDX PIT tag technology. If a tag enters the detection field in an orientation other than perpendicular to the antenna plane, the tag may not be detected. However, situating antennas where fish are most likely to pass through them perpendicular to their plane will maximize the likelihood of tag detection. I also observed that if multiple tags were in the detection field simultaneously, one or both tags are not read. These limitations were also observed by Zydlewski et al. (2001). However, because relatively few fish migrated up Mulherin Creek, the likelihood of multiple fish passing through the same antenna simultaneously was low.

Other factors that had the potential to reduce detection accuracy are the loss of battery power and corrosion. This study used a single 12 volt deep cycle marine battery to power each of the six PIT tag transceivers which required replacement every five days. During the 2006 field season, these batteries began failing in their ability to maintain a charge and had to be recharged more frequently. As a result of this phenomenon, batteries should be replaced every field season. Also, near the end of the study in 2006, data loggers began to shutdown. I believe this was primarily due to corrosion on electrical connections between the transceiver and the data logger caused by humidity in the data logger container and the loss of battery capacity. New transceiver models by OregonRFID have an internal data logger which will likely eliminate possible corrosion issues. Because these problems with batteries and data loggers began late in the season, I believe that no upstream culvert passes were missed. However, some fish descending the creek to return to the Yellowstone River in 2006 were not detected. In 2005, 44.4% of individuals were recorded descending the creek while in 2006, I recorded only 22.2%.

Fish Passage

Passage was significantly more successful at higher temperatures, lower outlet drop heights, smaller fish lengths, and lower water velocities. Successful passage occurred over a larger range of temperatures than failures. Successful passage occurred at temperatures from 5.2 to 18.3ºC while failed attempts occurred from 10.8 to 13.6ºC. However, only 21.7% of successful passes occurred at temperatures below 12ºC. Higher temperatures decrease water viscosity and allow for more efficient muscle movement by exerting more force per contraction (Moyle and Cech 2004). Webb (1978) also noted that trout benefit from warmer temperatures within their scope for activity by increased acceleration rates and hence burst swimming capability, which, in turn, likely translates into increased leaping ability for navigating culvert outlet drops.

The inverse relationship between fish size and passage success was unexpected. While the mean length of fish that were trapped and tagged was 341.5 mm, the mean length of individuals that successfully passed culverts was 320 mm and 363 mm for those that failed. This may have been the result of smaller individuals having the ability to use lower velocity zones along the sides or near the bottom of culverts that are not available to larger individuals as suggested by Belford and Gould (1989) or perhaps that smaller fish are typically capable of faster tail beat frequencies which can increase burst swimming velocities (Wardle 1975). However, the majority of studies have found a positive relationship between fish length and swimming ability for a variety of species: flannelmouth sucker *Catostomus latipinnis* (Ward et al. 2002), smallmouth bass *Micropterus dolomieu* (Peake 2004), and anadromous salmonids *Oncorhynchus* spp. (Reiser et al. 2006). Other studies have found no relationship between body length and swimming ability: spotted galaxias *Galaxias truttaceus* (Macdonald and Davies 2007), rainbow trout, brown trout *Salmo trutta*, and Yellowstone cutthroat trout (Belford and Gould 1989) who tested fish of similar size to this study. I observed no fish less than 300 mm attempting passage, however, only 9 individuals less than 300 mm were tagged. Failure to detect these fish attempting passage was most likely a result of them spawning below culvert 1. It must be noted that the small number of fish that failed to successfully pass culverts (*N* = 8) may not be representative of the portion of the population that failed to pass culverts and may have skewed results.

Fish were able to successfully pass through all culverts except the unbaffled steel culvert on Cinnabar Creek (culvert 5) which had the highest velocities and the largest outlet drop as well as the shallowest plunge pool. Thus, Cinnabar Creek upstream of this culvert which had the highest spawning gravel density among sampled reaches (680.5 m^2), appears inaccessible to spawning migrant YCT and RBT from the Yellowstone River. I recorded 26 unsuccessful passage attempts at this culvert as well as visually observed fish that were attempting passage but were unable to leap against the force of the culvert outflow with enough force to be detected by the antenna located on the downstream end of the culvert. I observed this phenomenon in 2005 which resulted in the installation of an additional antenna below the plunge pool of each culvert.

Culvert passage rates and times of YCT in baffled culverts closely paralleled that observed in a natural stream reach. Similar behavior of fish in baffled culverts and natural stream reaches was also evidenced by individual fish making repeated upstream and downstream passes through both, behavior not observed in other culvert types. The similarity in passage rates, fish behavior, and hydraulic conditions supports recently adopted guidelines for new culvert installations and retrofits which require culverts to simulate natural channel geometry (Katopodis 1992; Bates 2003; Lang et al. 2004; Karle 2005).

Detections of unsuccessful attempts at the culvert outlets may have underestimated the true number of fish that were actually attempting passage. Successful passage through culverts and other fishways depends on two factors, behavioral (motivation) and physiological ability (i.e. leaping ability) (Lang et al. 2004). Individuals that were detected at the antennas below the plunge pool of each culvert could be assumed to be showing motivation to continue their upstream migration because the antennas were generally in close proximity the culvert outlet. However, some of those individuals may not have had the physical ability to leap far enough to be detected attempting passage although the motivation was there. The unbaffled box culvert (culvert 1) and both unbaffled steel pipe culverts (culverts 4 and 5) which had both high velocities and outlet drops, had 60.0%, 28.6% and 71.4% respectively of fish that were detected entering the plunge pools not detected attempting passage. Alternately, the baffled box culverts (culverts 2 and 3) which had lower velocity and outlet drops had only 20.0% and 0.0% respectively of approaching fish detected below their plunge pools and not at the culvert outlet. If attempted passage was defined as a fish approaching the culvert, the percentage of individuals that failed to pass would be higher. This demonstrates a benefit of utilizing PIT tag technology to examine fish passage. Traditional mark-recapture studies simply show whether or not passage was successful. They cannot be used to show motivation of individuals that failed to pass but may have attempted passage.

By changing the definition of an attempt to any fish that approaches the culvert is attempting passage, the true “passability” of culverts may better ascertained. By defining an attempt as fish being detected leaping past the culvert’s outlet, the “passability” of culverts may be exaggerated. This is because individuals that are predisposed to have greater leaping and swimming abilities are more likely to be detected attempting passage. Those individuals also have a higher probability of passing successfully. Individuals that lack the leaping and swimming ability to reach the culvert outlet and are not recorded can also result in an underestimation of failed attempts. This phenomenon may be exaggerated at culverts with large outlet drops, high velocities, or culverts with low detection range due to electrical interference. In order to account for lack of leaping and swimming ability, antennas may be better placed immediately below the culvert’s outlet.

The amount of spawning gravel may also have some influence on passage motivation. The reach from the weir trap to culvert 1 had 124.7 m^2 of the most accessible spawning gravel and 75% of tagged fish are assumed to have spawned there because they were not detected at culvert 1 and no shed tags were detected from the weir to culvert 1. This is in agreement with De Rito (2004) who observed 65% of radiotagged fish spawning below culvert 1. Relatively little gravel is found between culvert 1 and culvert 3 and 80.8% of individuals passed through these reaches. There are large amounts of spawning gravels above culverts 4 (136.4 m^2), and 26.9% of individuals passed through culvert 4 which is greater than the 12.5% found by De Rito (2004). The steel pipe culvert (culvert 5) which has 680.5 m^2 of spawning gravel above it had no successful passage; and similar results were observed by De Rito (2004). Because there is no passage through culvert 5, the individuals that were observed attempting passage may be the result of individuals from a resident population above the culvert attempting to return after being washed downstream.

The addition of baffles in concrete box culverts both greatly reduced water velocity and influenced passage time and rates of successful passage. In lower Mulherin Creek where discharges were similar through culverts 1 through 3 and the natural control reach, the unbaffled box culvert (culvert 1) had an average water velocity 47% greater than the baffled box culvert (culvert 2). Water velocities in culvert 1 were 108% greater than culvert 3 which has baffles and 10% natural substrate. This is in agreement with other studies which found water velocities decreased while water depth, turbulence, and flow obstruction increased with the addition of baffles (Slawski and Ehlinger 1998; Lang et al. 2004). Macdonald and Davies (2007) found that fish tend to rest directly behind, above, or adjacent to baffles which supports my results of fish taking a longer amount of time to pass through baffled culverts. Gore (1994) found that the effective placement of baffles can create hydrological conditions similar to natural stream channels, this may help explain why fish took up to 9.5 times more time to pass through the baffled culverts than the unbaffled box culvert. Because velocities are low and baffles act as velocity refuges, similar to boulders in a natural stream, fish may not see these culverts as obstacles. This is supported by the observation of three individuals passing through the baffled box culvert a total of eight times. Multiple passes were not observed at any other culvert, although one fish passed through the control eight times, further supporting the idea that baffles simulate natural stream reaches.

The type of swimming behavior (i.e., sustained, prolonged, or burst swimming) utilized to pass through culverts may differ depending on conditions within the culvert. Fish were observed successfully passing through culverts with lengths from 9.1 to 11.4 m at mean water velocities of up to 2.8 m/sec which is within the burst swimming speed range for cutthroat trout (Bell 1991). Belford and Gould (1989) suggested fish swimming distances greater than 10 m utilized prolonged swimming speeds rather than burst and found that mean bottom velocities greater than 1.0 m/sec produced ‘strenuous passage conditions’ for YCT. I observed fish passing at mean velocities greater than 1.8 m/sec which is above the maximum prolonged swimming speed reported by Bell (1991). This is most likely the result of velocity refuges created by baffles and natural substrate as well as lower velocity zones created by non-uniform flows in the culverts where fish may use sustained swimming to maintain their position in low velocity areas and use burst or prolonged swimming to move between baffles. This is demonstrated by a 380 mm YCT that remained stationary over antenna 2 in culvert 1 for 18.4 minutes at a mean velocity of 2.24 m/sec. Because water entered the culvert at an angle, the opposite side of the culvert had an area of low velocity where fish could recover from burst swimming. Belford and Gould (1989) observed YCT passing through a 45.0 m culvert at mean bottom velocities up to 1.4 m/sec only after resting areas were added. Unbaffled box culverts had passage times 9.5 faster than baffled box culverts and 2.7 times faster than the unbaffled steel culverts. This also likely is the result of the increased resting areas created by baffles. The range of velocities observed to be passable in this study may be higher than other studies because of differences in data collection. Belford and Gould (1989) compared mean bottom velocities to passage which will be lower than my culvert mean velocity measurements and Bell (1991) did not state how swimming speeds were collected.

Although factors that were found to be significantly different between fish that successfully passed and fish that failed to pass included fish length, water temperature, velocity, and outlet drop, the model that was found to be the best predictor of the probability of successful passage contained velocity alone. Other passage models have been developed to assess swimming ability and passage (Katopodis and Gervais 1991; Castro-Santos 2004; Haro et al. 2004). However, these models were created under laboratory conditions with uniform flow. Application of these models to field conditions is limited because culverts often have roughness elements, baffles, or weirs that disrupt flow (Haro et al. 2004). The effects of the other significant factors on passage may have been masked by fish being able to utilize areas of low velocity.

FishXing Comparison

A shortcoming of current methods of fish passage assessment such as FishXing is that structures are typically rated as either barriers or non-barriers to movement. By comparing successful passage and failed attempts I was able to assess what factors most strongly affected the probability of passage and found that the probability of passage is primarily a function of water velocity. My logistic model predicted a 90% probability of passage at a velocity of 1.9 m/sec. In contrast, Belford and Gould (1989) observed no passage of spawning YCT at velocities greater than 1.4 m/sec. At this velocity, my model predicted a 97.8% probability of passage. In part, the differences could be a result of different culvert lengths. In their study the culvert they examined was 45.0 m long compared to an average of 9.7 m in my study. The method of determining velocity may also be responsible for these differences. Belford and Gould (1989) measured water velocity 5 cm above the culvert bottom where the culvert's roughness can reduce velocity. I calculated the mean water velocity in the culvert using culvert geometry and water depth measured at the center of the outlet for unbaffled culverts and averaging depths taken on either side of the outlet for the baffled culvert. Fish swimming through culverts are most likely utilizing lower velocity zones near the bottom and edges (Belford and Gould 1989) which were not accounted for in my study. In order for FishXing to correctly simulate culvert water velocities, calibration with on-site field measurements is needed (Karle 2005). Although FishXing correctly represented unbaffled steel (culverts 4 and 5) without the need of calibration, when examining culvert 1, the percentage of passable flows increased 6.9% in 2005 and 18.4% in 2006 because velocity was reduced when using the calibrated model compared to the non-calibrated model.

Although the FishXing model is widely utilized, it has not been sufficiently field tested (Karle 2005). The model classified the unbaffled box culvert (culvert 1) as a velocity barrier at discharges greater than 1.5 m^3/sec and a leap barrier at discharges greater than 2.5 m^3/sec. This was confirmed with field data as I recorded no successful passage at discharges greater than 1.4 m^3/sec. It also correctly identified an unbaffled steel culvert (culvert 5) as impassable under all discharge conditions because it posed a depth, leap, and velocity barrier. The plunge pool was also rated as too shallow for fish to leap into the culvert under all discharges. However, two fish were recorded reaching the culvert outlet indicating that water velocity rather then plunge pool depth was restricting passage. FishXing classified an unbaffled steel culvert (culvert 4) as impassable at all discharges as it posed a leap and plunge pool barriers. Observations of passage revealed that the culvert posed a velocity barrier at discharges greater than 0.7 m^3/sec. However, seven individuals (77.8%) passed successfully at discharges from 0.6 to 1.7 m^3/sec. I believe this discrepancy is due to assumptions made in the model for calculations regarding leaping ability such as a fish leaps out of the water at a 45° angle and exactly where the plunge pool depth was measured. FishXing assumes a fish jumps from the location where the culverts outflow impacts the outlet pool. This area below culvert 4 was relatively shallow, however, a pool immediately downstream of this area had a maximum depth of 1.1 m. Fish may have been able to swim at an angle out of the pool and leap from further downstream than accounted for in the model. FishXing cannot effectively model the hydraulics of baffled culverts due to the complex hydraulic conditions associated with baffles. Therefore I could not compare observed and predicted passage success for these study culverts. Similarly, the double barrel design of the steel pipe culvert on Cinnabar Creek was not able to be modeled with FishXing because of complex hydraulics. The FishXing model correctly rated culverts as passable or impassable for one of the two culverts examined. This gives the model an overall prediction success of 50%.

Conclusions and Management Implications

The culverts on Mulherin Creek appear to be more passable than initially thought. Although the unbaffled concrete box culvert (culvert 1) has relatively shallow water levels during much of the year, during the spawning seasons of RBT and YCT there is sufficient water for passage and velocities do not preclude all passage. FishXing predicted discharges less than 0.5 m^3/sec create a depth barrier in culvert 1. However, this discharge was reached on 24 September 2005 and 30 August 2006 well after the upstream spawning migration had finished but may result in restricted passage of fall spawners such as brown trout. An area of low velocity within the culvert likely aids in passage, serving as an apparent rest area as indicated by the long period of time some individuals spent at that location. The baffled box culverts (culverts 2 and 3) were expected to have little problem passing fish due to the low velocity caused by baffles and their small outlet drops. However, culvert 2, which had a drop height of 11 cm, had a 12.5% lower passage success rate than culvert 3 which had no outlet drop. The 77.8% successful passage rate of the smooth steel pipe culvert on Upper Mulherin Creek (culvert 4) was an unexpected finding. Fish were observed passing culvert 4 at velocities greater than those that prevented passage through culvert 1. This may be the result of culvert 4 being 2.6 m shorter than culvert 1.

My logistic model predicting the probability of passage indicated that fish attempting passage of the studied culverts at velocities greater 2.6 m/sec have a 50% probability of successful passage. Retrofitting culverts that have velocities greater than 2.6 m/sec during spawning migration could be an effective method of improving fish passage. In this study, box culverts with baffles had water velocities up to 2.1 times slower than the unbaffled box culvert. However, the addition of baffles decreases hydraulic capacity and may catch debris which may lead to culvert blockage and roadway damage (Bates et al. 2003). Therefore baffles may only be a temporary solution to fish passage while more permanent solutions are designed.

By using the velocity value of 2.7 m/sec as the limit for the passable velocity of RBT and YCT, managers could use stage height recorders in conjunction with field measurements of velocity in order to determine periods when culverts along migration routes are passable and make the appropriate retro fittings or replace culverts that pose barriers during migration periods. This may be more useful than utilizing the FishXing model alone given its low percentage of prediction success in this study.

This study has proven the usefulness of HDX PIT tag technology. By recording fish approaching culverts as well as attempts and successful passage, much more information on motivation and effort (i.e., number of attempts) is gathered than through traditional mark-recapture studies. However, improvements to my techniques could improve results of future studies. Although no shed tags were detected during surveys, the potential for tags to be shed during spawning is still possible. In order to minimize the chance the potential for fish to shed tags, the dorsal sinus is better tagging site (Tranquilli et al. 2003).

In order to better characterize the number of attempts and the percentage of fish that passed a culvert, the antenna located on the culvert outlet should be moved to directly below the culvert. This would aid in the detection of fish that are attempting to pass but do not have the swimming and leaping ability to reach the culvert outlet. Alternatively, any fish that is detected by the antenna below the plunge pool could be assumed to have the motivation to attempt passage.

I used mean water velocity determined at the culvert outlet to estimate culvert passage velocity. However, the relationship of mean velocity to the velocities followed by the fish in actual passage remains uncertain. Observations of fish passage in culverts have shown that fish follow low velocity zones near culvert bottoms and edges when navigating through culverts (Kane et al. 2000). Mean velocities may be 1.4 times greater than bottom and edge velocities (Belford and Gould 1989). More accurate representation of velocity conditions within culverts and paths that fish follow when passing upstream is needed to more accurately predict velocity conditions and fish passage behavior under various flows.

Yellowstone cutthroat trout in Mulherin Creek are considered to be at extreme risk of hybridization (Frazer et al. 2000). Because this study showed culvert 5 to be a complete barrier to all tagged fish, the upstream population of YCT (if present) should be examined for genetic purity before any effort is made at culvert replacement. If the resident population above culvert 5 is shown to be genetically pure, efforts should be taken to ensure maintenance of genetic integrity before passage improvements are made.

LITERATURE CITED

Aarestrup, K., M. C. Lucas, and J. A. Hansen. 2003. Accuracy of a nature-like bypass channel for sea trout (*Salmo trutta*) ascending a small Danish stream studied by PIT telemetry. Ecology of Freshwater Fish12:160-168.

Adams, J. A., R. K. Wolfe, W. E. Pine III, and B. L. Thornton. 2006. Efficacy of PIT tags and an autonomous antenna system to study the juvenile life stage of an estuarine-dependent fish. Estuarios and Coasts 29:311-317.

Baker, C. O., and F. E. Votapka. 1990. Fish passage through culverts. FHWA-FL-09-006. USDA Forest Service-Technology and Development Center. San Dimas, CA

Bates, K. B., B. Barnard, B. Heiner, J. P. Klavas, and P. D. Powers. 2003. Design of road culverts for fish passage. Washington Department of Fish and Wildlife. Olympia, Washington.

Beamish, F. W. H. 1978. Swimming capacity. Pages 101-187 *in* W. S. Hoar, and D. J. Randall editors. Fish Physiology. Vol. VII. Locomotion. Academic Press, London, UK.

Beamish, R. J. and T. G. Northcote. 1989. Extinction of a population of anadromous parasitic lamprey, *Lampetra tridentata*, upstream of an impassable dam. Canadian Journal of Fisheries and Aquatic Sciences 46:420-425.

Behnke, R. J. 1992. Native trout of western North America. American Fisheries Society, Monograph 6, Bethesda, Maryland.

Belford, D. A., and W. R. Gould. 1989. An evaluation of trout passage through six highway culverts in Montana. North American Journal of Fisheries Management 9:437-445.

Bell, M. C. 1991. Fisheries handbook of engineering requirements and biological criteria. Fish Passage Development and Evaluation Program, U. S. Army Corps of Engineers, North Pacific Division. Portland, OR.

Blank, M. Mulherin Creek 2004 Summary. Montana State University, Department of Civil Engineering, Unpublished report.

Burford, D. D. 2005. An assessment of fish culvert passage barriers in a Montana drainage using a multi-tiered approach. Master’s thesis, Montana State University, Bozeman, Montana.

Cahoon, J. T. McMahon, O. Stein, D. Burford, and M. Blank. 2005. Fish passage at road crossings in a Montana watershed. FHWA/MT-05-002/8160. Montana Department of Transportation, Helena, MT.

Carlander, K. D. 1969. Handbook of freshwater fishery biology, volume 1, 3rd edition, Iowa State University Press, Ames, Iowa.

Castro-Santos, T. 2004. Quantifying the combined effects of attempt rate and swimming capacity on passage through velocity barriers. Canadian Journal of Fisheries and Aquatic Sciences 61:1602-1615.

Castro-Santos, T. 2006. Modeling the effect of varying swim speeds on fish passage through velocity barriers. Transactions of the American Fisheries Society 135:1230-1237.

Clancy, C. G. 1988. Effects of dewatering on spawning by Yellowstone cutthroat trout in tributaries to the Yellowstone River, Montana. American Fisheries Society Symposium 4:37-41.

Clements, S. P., B. J. Hicks, J. F. Carragher, and M. Dedual. 2002. The effects of a trapping procedure on the stress response of wild rainbow trout. North American Journal of Fisheries Management 22:907-916.

Columbia Basin Fish and Wildlife Authority. 1999. PIT tag marking procedures manual. PIT tag steering committee, Portland, OR.

De Rito, J. N. 2004. Assessment of reproductive isolation between cutthroat trout and rainbow trout in the Yellowstone River. Master's thesis, Montana State University, Bozeman, Montana.

Diana, J. S., D. F. Clapp, E. M. Hay-Chmielewski, G. S. Del Siler, W. Ziegler, and R. D. Clark Jr. 1990. Relative success of telemetry studies in Michigan. American Fisheries Society Symposium 7:346-352.

FishXing Development Team. 1999. Fishxing software: version 3.0. USDA Foreset Service, Six Rivers National Forest. Eureka, CA. Available: http://www.stream.fs.fed.us/fishxing/ (October 2006).

Fitch, G. M. 1995. Nonanadromous fish passage in highway culverts. VTRC 96-R6. Virginia Transportation Research Council. Charlottesville, Virginia.

Frazer, K., R. Wagner, B. May, and J. Darling. 2000. Yellowstone cutthroat trout management program within the state of Montana. Lower Yellowstone River Conservation Unit. Helena, Montana.

General Accounting Office. 2001. Restoring fish passage through culverts on Forest Service and BLM lands in Oregon and Washington could take decades. GA0-01-136. November 2001.

Gibson, J. R., R. L. Haedrich and M. C. Wernerheim. 2005. Loss of fish habitat as a consequence of inappropriately constructed stream crossings. Fisheries 30(1):10-17.

Gore, J. A. 1994. Hydrological change. 33-54 *in* Calow and G. E. Petts, editors. The rivers handbook; hydrological and ecological principles, volume 2. Blackwell Scientific Publications, Cambridge, Massachusetts.

Halvorsen, M., and O. B. Stabell. 1990. Homing behavior of displaced stream-dwelling brown trout. Animal Behavior 39:1089-1097.

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

Henderson, R., J. L. Kershner, and C. A. Toline. 2000. Timing and location of spawning by nonnative wild rainbow trout and native cutthroat trout in the South Fork Snake River, Idaho, with implications for hybridization. North American Journal of Fisheries Management 20:584-596.

Hill, M. S., G. B. Zydlewski, J. D. Zydlewski, and J. M. Gasvoda. 2006. Development and evaluation of portable PIT tag detection units: PITpacks. Fisheries Research 77:102-109.

Kane, D. L., C. E. Belke, R. E. Gieck, and R. F. McLean. 2000. Juvenile fish passage through culverts in Alaska: A field study. Alaska Department of Transportation FHWA-AK-RD-00-03, Juneau, Alaska.

Karle, K. 2005. Analysis of an efficient fish barrier assessment protocol for highway culverts. FHWA-AK-RD-05-02. Alaska Department of Transportation, Juneau, Alaska.

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

Katopodis, C., and R. Gervais. 1991. Ichthyomechanics. Working document. Freshwater Institute, Central and Arctic Region, Department of Fisheries and Oceans. Winnipeg, Manitoba, Canada.

Klingeman, P. C. 2000. Streams and stream simulation for culvert fish passage. Culverts 2000: Oregon State University, Civil Engineering Department. Corvallis, Oregon.

Kondratieff, M. C., and C. A. Myrick. 2005. Two adjustable waterfalls for evaluating fish jumping performance. Transactions of the American Fisheries Society 134:503-508.

Lang, M., M. Love, and W. Trush. 2004. Improving stream crossings for fish passage. National Marine Fisheries Service, Report Number 50ABNF800082, Arcata, California.

Lucas, M. C., T. Mercer, J. D. Armstrong, S. McGinty, and P. Rycroft. 1999. Use of a flat-bed passive integrated transponder antenna array to study the migration and behaviour of lowland river fishes at a fish pass. Fisheries Research 44:183-191.

Macdonald, J. I., and P. E. Davies. 2007. Improving the upstream passage of two galaxiid fish species through pipe culverts. Fisheries Management and Ecology 14:221-230.

Magee, J. P., and T. E. McMahon, and .and R. F. Thurow 1996. Spatial variation in spawning habitat of cutthroat trout in a sediment-rich stream basin. Transactions of the American Fisheries Society 125:768-779.

May, B. E., W. Urie, B. B. Shepard, S. Yundt, C. Corsi, K. McDonald, B. Snyder, S. Yekel, and K. Walker. 2003. Range-wide status of Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*): 2001. U.S. Forest Service, Bozeman, Montana.

Mesa, M. G., and C. B. Schreck. 1989. Electrofishing mark-recapture and depletion methodologies evoke behavioral and physiological changes in cutthroat trout. Transactions of the American Fisheries Society 118:664-658.

Mesa, M. G., L. K. Weiland, and G. B. Zydlewski. 2004. Critical swimming speeds of wild bull trout. Northwest Science 78:59-65.

Mirati, A. H. 1999. Assessment of road culverts for fish passage on state and county owned roads. Oregon Dept. of Fish and Wildlife. Available: http://www.dfw.state.or.us/ODFWhtml/InfoCntrFish/Management/culvert_survey.pdf (October 2006).

Montana Fisheries Information System. 2005. Montana Dept. of Fish Wildlife and Parks, Helena, MT. Available: http://maps2.nris.state.mt.us/scripts/esrimap.dll?name=MFISH&Cmd=INST

Morhardt, J. E., D. Bishir, C. Handlin, and S. D. Mulder. 2000. A portable system for reading large passive integrated transponder tags from wild trout. North American Journal of Fisheries Management 20:276-283.

Morita, K. and S. Yamamoto. 2002. Effects of habitat fragmentation by damming on the persistence of stream-dwelling charr populations. Conservation Biology 16:1318-1323.

Moyle, P. B. and J. J. Cech Jr. 2004. Fisheries: an introduction to ichthyology, 5th edition. Prentice-Hall, Inc., New Jersey.

O'Hanley, J. R., and D. Tomberlin. 2005. Optimizing the removal of small fish passage barriers. Environmental Modeling and Assessment 10:85-98.

Olsson, I. C., and L. A. Greenberg. 2001. Effect of an artificial pond on migrating brown trout smolts. North American Journal of Fisheries Management 21:498-506.

OregonRFID. http://www.oregonrfid.com/. (February 2005).

Peake, S. 2004. An evaluation of the use of critical swimming speed for determination of culvert water velocity criteria for smallmouth bass. Transactions of the American Fisheries Society 133:1472-1479.

Rantz, S. E. 1982. Measurement and computation of streamflow: volume 2. Computation of discharge, U.S. Geological Survey Water-Supply Paper 2175.

Reiser, D. W., H. Chi-Ming, S. Beck, M. Gagner, and E. Jeanes. 2006. Defining flow windows for upstream passage of adult anadromous salmonids at cascades and falls. Transactions of the American Fisheries Society 135:668-679.

Robison, E. G., A. Mirati, and M. Allen. 1999. Oregon road/stream crossing restoration guide. Advanced Fish Passage Training Version. Oregon Dept. of Forestry, Salem, OR.

Schmetterling, D. A., R. W. Pierce, and B. W. Liermann. 2002. Efficacy of three denil fish ladders for low-flow fish passage in two tributaries to the Blackfoot River, Montana. North American Journal of Fisheries Management 22:929-933.

Sheer, M. B., and E. A. Steel. 2006. Lost watersheds: barriers, aquatic habitat connectivity, and salmon persistence in the Willamette and lower Columbia River basins. Transactions of the American Fisheries Society 135:1654-1669.

Slawski, T. M. and T. J. Ehlinger. 1998. Fish habitat improvement in box culverts: management in the dark? North American Journal of Fisheries Management 18:676-685.

Tranquilli, J. V. 2005. Tracking bull trout with stream-width half-duplex passive interrogation. Oregon Dept. of Fish and Wildlife, Salem, OR. http://www.dfw.state.or.us/ODFWhtml/springfield/PIT_tag_Presentations.html (February 2005).

Tranquilli, J. V., M. G. Wade, and C. K. Helms. 2003. Minimizing risks and mitigation of impacts to bull trout *Salvelinus confluentus* from construction of temperature control facilities at Cougar Reservoir, Oregon. Oregon Department of Fish and Wildlife, W66QKZ13186766, Annual Report, Salem, Oregon.

United States Department of the Interior. 2006. Endangered and threatened wildlife and plants; 12-month finding for a petition to list the Yellowstone cutthroat trout as threatened. Federal Register 71:34(21 February 2006):8818-8830.

Varley, J. D., and R. E. Gresswell. 1988. Ecology, status, and management of the Yellowstone cutthroat trout. American Fisheries Society Symposium 4:13-24.

Votapka, F. E. 1991. Considerations for fish passage through culverts. Transportation Research Record 1291:347-353.

Ward, D. L., O. E. Maughan, S. A. Bonar, and W. J. Matter. 2002. Effects of temperature, fish length, and exercise on swimming performance of age-0 flannelmouth sucker. Transactions of the American Fisheries Society 131:492-497.

Wardle, C. S. 1975. Limits of fish swimming. Nature 255:725-727.

Warren, M. L., and M. G. Pardew. 1998. Road crossings as barriers to small-stream fish movement. Transactions of the American Fisheries Society 127:637-644.

Webb, P. W. 1978. Temperature effects on acceleration of rainbow trout, *Salmo gairdneri*. Journal of the Fisheries Research Board of Canada 35:1417-1422.

Winston, M. R., C. M. Taylor, and J. Pigg. 1991. Upstream extirpation of four minnow species due to damming of a prairie stream. Transactions of the American Fisheries Society 120:98-105.

Wofford, J. E. B., R. E. Gresswell, and M. A. Banks. 2005. Influence of barriers to movement on within-watershed genetic variation of coastal cutthroat trout. Ecological Applications 15: 628-637.

Zydlewski, G., C. Winter, D. McClannahan, J. Johnson, J. Zydlewski, and S. Casey. 2002. Evaluation of fish movement, migration patterns, and population abundance with streamwidth PIT tag interrogation systems. BPA Report DOE/BP-00005461-1.