FISH PASSAGE IN MONTANA CULVERTS: *PHASE II - PASSAGE GOALS*

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June 2007

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16. Abstract

Culverts have been shown to disrupt fish mobility in high-gradient mountain streams, and are of concern to transportation system planners, designers, and managers. However, there is still some uncertainty concerning the cumulative impact that culverts can have on a fishery. In this project, passive integrated transponders (PIT tags) were used, primarily on Yellowstone cutthroat trout, to examine fish passage in the roaded drainage of a high-gradient stream system. This project focuses on fish passage in the upstream direction through successive culverts over all portions of the hydrograph, including the high flows that Yellowstone cutthroat encounter during spawning runs. Results are presented in probabilistic terms in addition to the traditional passage/no-passage format. The results show that water velocity is a good indicator of the probability of fish passing a culvert. The probability of a fish passing a series of culverts is best predicted by combining the probability that fish will, in general, pass individual culverts.

17. Key Words

culverts, fish passage, hydraulics

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Unit Conversion Factors

All numeric values having units are presented in SI (metric) units. The following factors can be used to convert to traditional (English) units:

1 mm = 0.03937 inch	1 inch = 25.4 mm
1 cm = 0.39370 inch	1 inch = 2.54 cm
1 m = 3.281 feet	1 foot = 0.3048 m
1 km = 0.6214 miles	1 mile = 1.6093 km
1 cms = 1 m^3/sec = 35.3198 ft^3/sec	1 ft^3/sec = 0.0283 cms

Introduction

Other Work

Fish passage through road culverts is a concern to engineers and biologists when designing new culverts, retrofitting culverts with baffles, weirs, or natural bedding, or when completely replacing culverts (Baker and Votapka 1990; Votapka 1991; Lang et al. 2004; Gibson et al. 2005). With an estimated 2,600 culverts that could block fish migrations on federal lands in Oregon and Washington (General Accounting Office 2001), and nearly 2,200 more on Oregon state and county property (Mirati 1999), limited fiscal budgets will make prioritizing culverts for replacement a monumental task (General Accounting Office 2001; Hanley and Tomberlin 2005). Many culverts were originally 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 diligence during installation can lead to the poor compliance with fisheries guidelines (Gibson et al. 2005).

Culverts at road crossings have the potential to restrict or prevent migration of fishes (Belford and Gould 1989; Warren and Pardew 1998). The increased velocity, decreased depth, lack of refuge from high velocity water, 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 system (Gibson et al. 2005) and isolate segments of populations. Isolation and fragmentation increase the risk of loss of genetic diversity and increase 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).

Both direct and indirect methods have been used in the past to examine fish passage. Direct methods, such as mark-and-recapture techniques, require individual fish to be captured, tagged, and placed 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; Cahoon et al 2005). Although this method is useful for determining if potential barriers are passable, the labor requirements can limit the number of culverts that can be monitored. Also, capturing fish on multiple occasions can increase stress levels and may bias results because of induced behavioral changes (Mesa and Schreck 1989; Clements et al. 2002). The use of radio telemetry eliminates the need for multiple trappings and can determine if passage is successful. Unfortunately, radio tags are large, limiting the size of fish tagged, and expensive, limiting the number of fish tagged. Battery life can also be limiting (Diana et al. 1990) and the exact time of passage of a radio tagged fish is difficult to determine, resulting in lost information about the hydraulic and physical conditions during passage.

Early methods for incorporating fish passage into the design or indirect assessment of fish passage in culverts relied primarily on coupling observations of fish swimming speed and jumping ability with contemporary models of culvert hydraulics (Tillinger and Stein 1996; Robison et al. 1999). Current methods use the same general approach, but with substantial automation of the superimposition of fish abilities on culvert hydraulics. The software FishXing (FishXing Development Team 1999) was initially developed in 1999, has been updated periodically since then, and is often used to assess passage restriction at culverts (Lang et al. 2004; Cahoon et al 2005; Castro-Santos 2006). This software program combines known fish swimming performance data (swimming speeds, swimming times, jumping ability, and fish length) and hydraulic computations based on gradually varied hydraulic computations (based on shape, length, slope, roughness, drop height, and flow rate) to predict barriers to fish passage. Although this method is less labor intensive than direct methods and makes it possible to assess many culverts, a review of the literature has revealed it is often conservative in the sense that fish have been observed to pass through culverts that FishXing analyses labeled as barriers (Cahoon et al 2005) even when calibrated to local hydraulic conditions (Karle 2005).

An alternative approach that is becoming more commonly used to examine fish movement is the use of passive integrated transponder (PIT) tags (Lucas et al. 1999; Olsson and Greenberg 2001; Aarestrup et al. 2003). PIT tags can provide more accurate information than traditional mark-recapture techniques because the chance 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, thus allowing passage monitoring over a wide range of conditions and at numerous sites.

A shortcoming of contemporary methods for classifying culverts with respect to fish passage is that structures are often rated as either barriers or non-barriers. However, the probability of passage likely varies markedly as a function of temperature, discharge, fish species, fish size, fish health, motivation, presence of predators, etc. These are all factors that, to some extent, influence whether or not a fish passes through a culvert. 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 or with healthier fish. Passibility 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 tags and PIT tag detecting antennas allows simultaneous monitoring of these factors for a variety of settings and environmental conditions (Lang et al. 2004).

Yellowstone cutthroat trout (YCT herein, *Oncorhynchus clarkii bouvieri* formally) are listed as a "species of special concern" and were petitioned for listing as a threatened species under the Endangered Species Act (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 overt time, 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 of stream length (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 spring snowmelt portion of the hydrograph (Clancy 1988; De Rito 2004). Non-native rainbow trout (RBT herein, *Oncorhynchus mykiss* formally) enter tributaries and spawn five to nine 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 and water temperatures can be very different while each species is migrating, thereby affecting passage of the two species in different ways.

This Study

Probabilistic approaches to passage are necessary to move forward from contemporary pass/no-pass approaches. Observing passage success and failure over a diverse range of conditions is necessary to begin to consider the issue on a probabilistic basis. The objectives of this study were to use both traditional and innovative tools to determine the biotic and abiotic factors that most influence the probability of fish passage through culverts, consider the timing issues that passage probability should be superimposed on, and to study the travel history of fish in a system that had the potential to limit overall mobility.

Study Area

Mulherin Creek is a high-gradient second-order tributary of the Yellowstone River located 12.9 km northwest (downstream) of Gardiner, Montana, as shown in aerial view in Figure 1. The average gradient from headwaters to mouth is 11.6% (Blank, 2005) and the 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 have a higher 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 baffled and unbaffled box culverts and unbaffled steel pipe culverts. The section is host to a known spawning run of fluvial-adfluvial YCT from the Yellowstone River. Spawning habitat was thought to be limited in the lower reaches of the stream, providing migrating fluvial-adfluvial YCT, RBT and hybrids with sufficient motivation for mobility.

The native species present in Mulherin Creek include YCT, and species not considered in this study: 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, not considered in this study, brown trout (*Salmo trutta*).

The five culverts in the study were on Mulherin Creek downstream of the confluence with Cinnabar Creek (culverts 1, 2 and 3), on Mulherin Creek upstream of the confluence with Cinnabar Creek (culvert 4) and on Cinnabar Creek upstream of the confluence (culvert 5). The graveled road system passes through both private land and portions of the Gallatin National Forest, and is maintained by Park County.

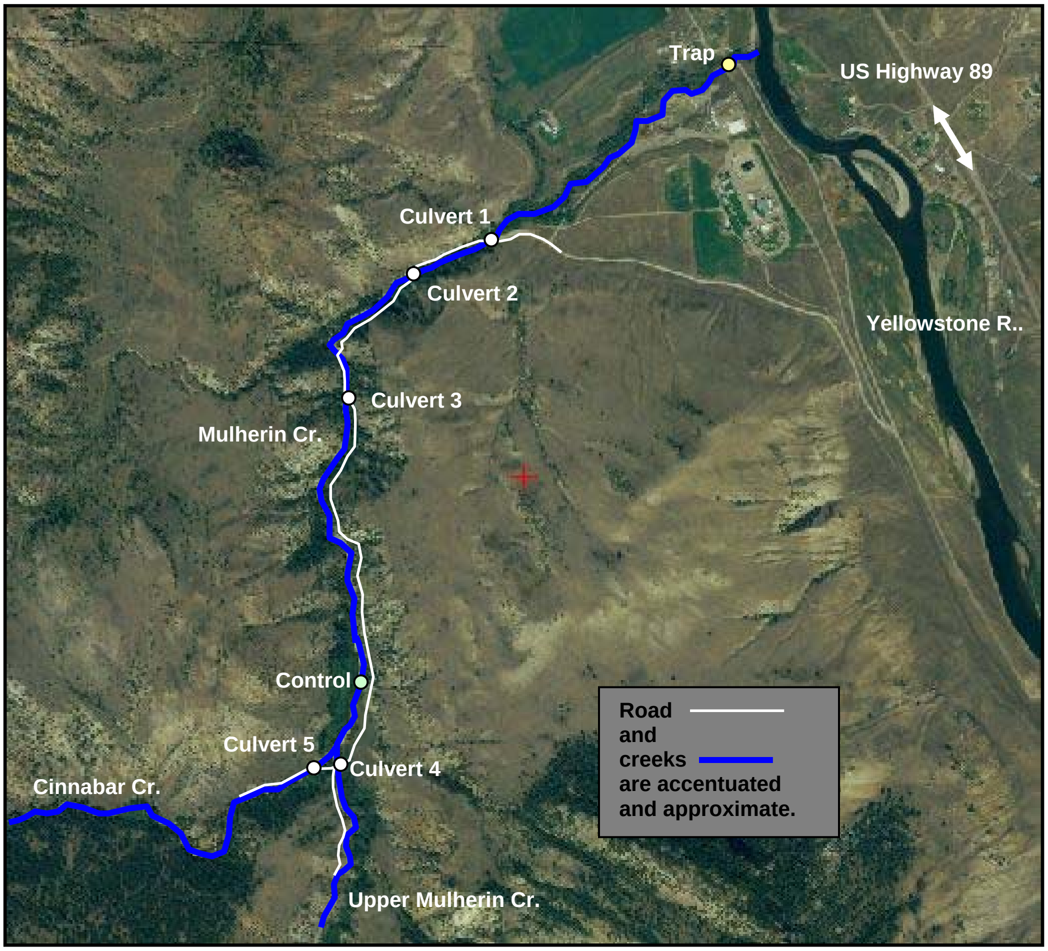

Figure 1. The study area on Mulherin Creek, Montana.

The culverts were of three different types as described by material, length, outlet drop height, and physical dimensions in Table 1. Figure 2 further describes the dimension details of the culverts and Appendix A shows some photos of the study culvers.

A control reach 10 m long with a bankfull width of 5 m in a segment of Mulherin Creek with 0.9% downstream slope was also established to compare PIT tag read-efficiency and water flow velocities to those observed in the culverts. Surveying equipment was used to measure each culvert, included length, height, width, baffle size and configuration (where applicable), plunge pool depth, outlet height, slope of the culvert, and slope of the channel upstream and downstream of the culvert.

Table 1. Physical attributes of the culverts in the study.

	Culvert 1	**Culvert 2**	**Culvert 3**	**Culvert 4**	**Culvert 5**
Material	concrete	concrete	concrete	steel	steel
Type	box	box	box	circular	circular
Length (m)	11.4	9.3	9.7	9.1	10.6
Width (m)	3.7	3.7	3.7	2.2	2.2
Height (m)	2.0	1.8	1.8	-	-
Diameter (m)	-	-	-	2.1	2.1 and 1.8[b]
Substrate	none	baffles [a]	baffles [a, c]	none	none
Slope (%)	1.1	0.8	1.0	1.1	6.6
Outlet drop (cm)	17.0	11.0	-	43.0	45.0

[a] Baffles are concrete slabs 2.13 m long, 0.24 m wide and 0.24 m high and are spaced 1.52 m apart.
[b] The upstream one-third of the culvert is a smaller diameter pipe nested inside a larger pipe.
[c] Culvert 3 was baffled and had a collection of gravel, rock, and debris in the barrel.

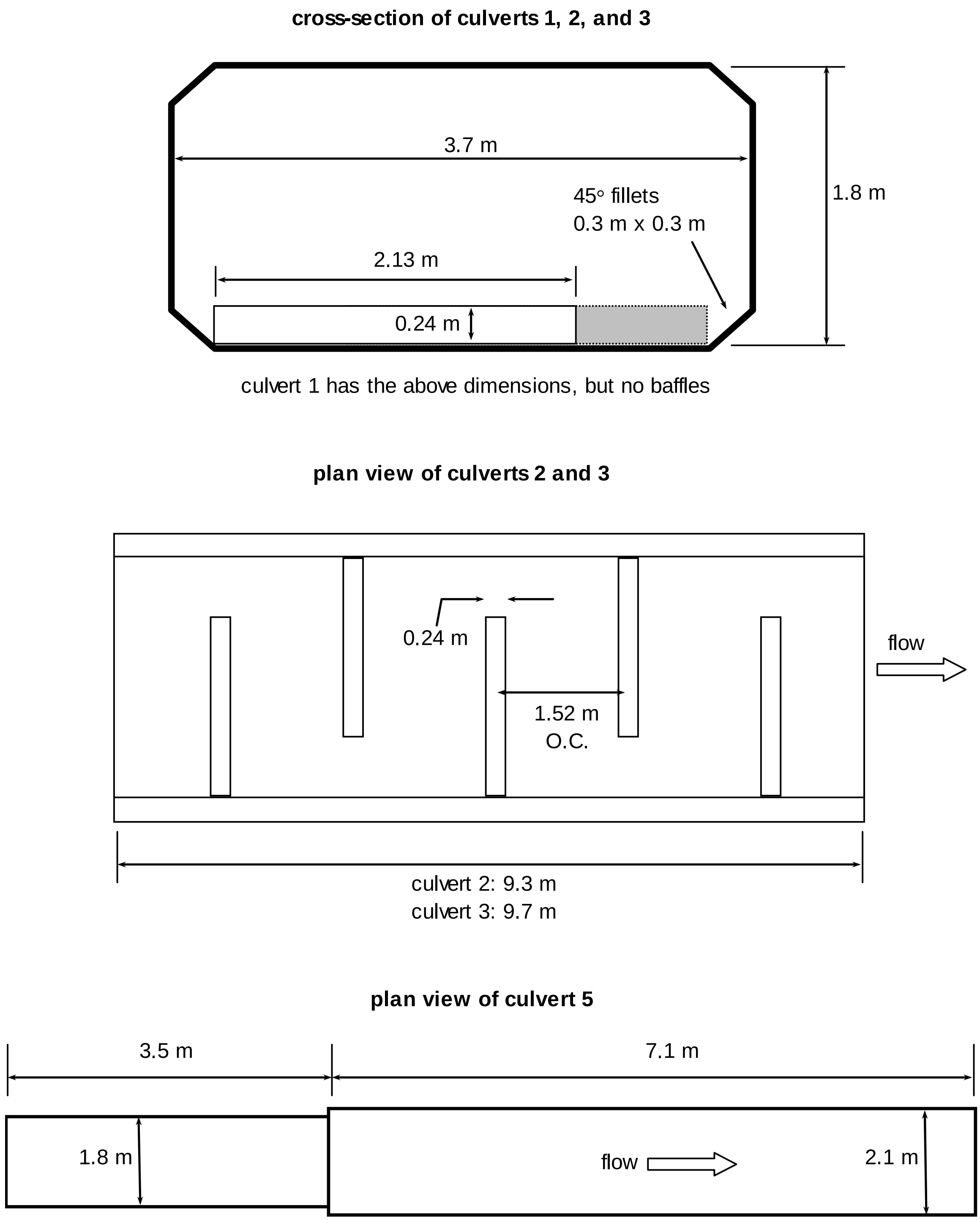

Figure 2. Overview of study culvert dimensions.

Methods

Trapping and Tagging

The success of experiments based on PIT tagging fish and detecting PIT tagged fish throughout the roaded stream system depend on having a large number of tagged fish. Two different capture locations and methods were used, although fish were always handled and tagged in the same manner. In either case, tagged fish were replaced in the stream system downstream of culvert 1, although at two locations.

Confluence Trap

Fluvial-adfluvial YCT, RBT, and hybrids migrating upstream in Mulherin Creek out of the Yellowstone River were captured using a temporary net and trap located 125 m upstream of the confluence of Mulherin Creek and the Yellowstone River. The net blocked the entire stream cross section and routed upstream-swimming fish into a one-way trap. Fish were anesthetized with tricaine methanesulfonate (MS-222) and species, total length and gender (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 long by 3.85 mm diameter, weighed 0.6 g, and operated at a frequency of 132.2 kHz. Following recovery from anesthesia, fish were released into a backwater pool just upstream of the trap. In both 2005 and 2006, trapping operations began in mid April and continued through late July. However, in 2006 trapping was not possible from May 12 to June 18 due to high flows. All trapped fish were tagged. Fish trapped 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.

Electrofishing

A lesser number of additional fish were collected just downstream of the junction of Mulherin Creek and Cinnabar Creek (just downstream of culverts 4 and 5) using a Smith-Root Model 15-D generator powered backpack electrofish unit and a two person crew on April 27, 2006. As with the fish caught in the confluence trap, these fish were treated and tagged as the rest, except that they were returned to the stream just downstream of culvert 1. Homing motivation has been discussed by Halvorsen and Stabell (1990).

Tag Shedding or Post-Tagging Mortality

To examine whether the fish had shed tags or had died in the stream system after being tagged, an experiment was conducted over the reach (1,113 m long) of stream between the confluence trap and culvert 1. The reach was scanned with a portable PIT tag detector at the conclusion of field work in late 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 a 3 m pole and belt system. The stream was scanned in the upstream direction, scanning over the wetted stream width and in any adjacent spawning gravel in or near the active stream channel. No shed tags or expired fish that had been tagged were detected. To ground-truth the readability of this method, PIT tags were placed in the substrate at arbitrary positions, and 100% (10 of 10) of the placed tags were detected.

Antenna Placement and Design

PIT tag detecting antennas were installed in 2005 just upstream and downstream of all the study culverts as diagramed in Figure 3. The antennas are connected to data loggers that recorded the time of detection and the tag detected whenever a tag (i.e. a tagged fish) was in proximity to the antenna. An additional antenna was installed downstream of the plunge pool of each culvert in 2006 to better clarify fish activity in the culvert vicinity.

An arbitrarily selected natural stream reach between culverts 3 and 4 was instrumented in 2006 with three antennas. This control was used primarily to compare tag read efficiencies away from the potentially interfering metal in and around the culverts with the read efficiencies at the culverts, and to contrast water velocity in the culverts with what may be found in a natural reach.

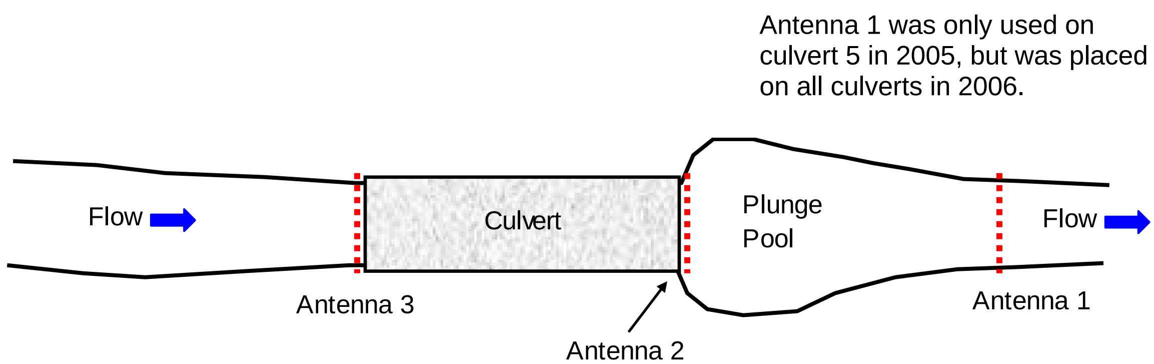

Figure 3. Diagram of the general antenna configurations for each culvert.

Antenna arrays were not always operational - debris or high flows would sometimes damage or displace an antenna (*operational* was defined as all three antennas in an array actively scanning PIT tags). Table 2 notes periods of operation throughout the study.

Table 2. Periods of operation of PIT tag detection antennas.

	Periods when Operational	
	2005	**2006**
		April 9 to May 25
Culvert 1	May 10 to September 17	June 27 to September 30
Culvert 2	May 10 to September 17	April 8 to September 30
Culvert 3	May 19 to September 17	April 15 to September 30 [a]
		April 16 to May 19
Culvert 4	May 19 to September 17	June 28 to September 30
		April 22 to May 19
Culvert 5	May 19 to September 17	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 3 remained operational.

Antenna placement varied by culvert because of specific characteristics as shown in Table 3. The distances from antenna 1 to the culvert outlet varied from 4.11 m to 29.87 m. Antenna 2 was placed directly on the downstream face of culverts 1, 2, 4, and 5. Debris located near the outlet of culvert 3 prevented the placement of antenna 2 on the downstream face of the culvert, so it was placed 1.94 m 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 end of culverts - sometimes it was placed just inside the culvert (culverts 1 and 2) or just upstream of the culvert (culverts 3 and 5). Antenna placement within the natural control reach was such that antenna 1 was 4.35 m downstream of antenna 2, which was 5.57 m downstream of antenna 3.

Table 3. Antenna placement by culvert.

	Distance downstream from the culvert outlet to antenna 1 (m).	Distance and direction from the culvert outlet to antenna 2 (m).	Distance and direction from culvert inlet to antenna 3 (m).
Culvert 1	29.87	0.00	2.10 downstream
Culvert 2	4.88	0.00	1.94 downstream
Culvert 3	5.76	1.94 upstream	3.68 upstream
Culvert 4	7.01	0.00	0.00
Culvert 5	12.25	0.00	1.97 upstream

Antennas were constructed of 8-gauge multi-strand copper wire with the lower wire either buried in the substrate or fastened under the lower lip of the culvert. As shown in Figure 4, the upper end of the antenna was either attached using eye hooks or clamps to the culvert edges or supported by cable attached to the culvert soffit. The distance between the lower and upper extent of the antennas was a maximum of 1.2 m but varied because of interference, particularly on steel culverts where the maximum distance between the lower and upper portions of the antenna loop was 0.75 m.

culvert 1 outlet

culvert 4 outlet

Figure 4. Antenna installation for culverts where the antenna could be mounted directly on the face of the culvert.

Natural stream sections had the upper end of antennas constructed by suspending steel cable across the stream and attaching it to a post on either bank as shown in Figure 5. The antenna wire was attached to the posts and suspended across the stream by attaching it to the steel cable with plastic fasteners. The distance between the lower and upper portions of the antenna loop installed in natural stream channels was 1.2 m. Antennas spanned the entire width of the channel so that fish passing underneath at any point in the channel could be detected.

culvert 3 inlet

culvert 5 inlet

Figure 5. Antenna construction design in cases where the antenna could not be attached directly to a culvert.

Tag Detection Range and Efficiency

The antennas used with the HDX tags do not tend to interfere with each other, but can have interference from ferrous metals such as the steel reinforcing bar in concrete box culverts or the material of the pipe itself in the case of metal culverts. Each antenna was tuned to maximize tag detection. Read range and efficiency for each antenna was adjusting until a tuning indicator provided by the manufacturer indicated that performance was optimized (OregonRFID 2005). Each antenna was attached directly to the tuner module. Twinax cable consisting of two separate insulated wires was used to attach the tuner module to a central RFID multiplexer transceiver that was capable of monitoring up to four antennas. HDX antennas have been shown to have a read efficiency of up to 90% within a distance of 60 cm of the antenna (OregonRFID 2005;

Tranquilli 2005). This maximum detection range limits antenna height to a maximum of approximately 120 cm.

The detection range and efficiency of each antenna was measured on a weekly basis during the 2006 season using a test PIT tag attached to a measuring staff . The test tag was moved toward the antenna until it was detected. Detection was signaled with an audio signal from a speaker attached to the transceiver. Horizontal detection distance was determined by measuring detection range both upstream and downstream of each antenna. Vertical detection range was measured with the same procedure but only for those culverts that had an outlet drop on their downstream end. This was done to determine if fish that are in the plunge pool could be detected when swimming under the antenna rather than through it. Detection efficiency was measured by moving the staff through the center of each antenna three times and recording the number of detection occurrences.

Mean detection efficiency and detection range for antennas near the culverts and in the control were compared using one-way ANOVA and Fisher's least significant differences (LSD) for pair-wise comparisons. This, and all statistical tests conducted in the course of this project that involve a confidence level, used α = 0.05 (the 95% confidence level) to establish significance.

Fish Movement

Fish movement data from 2005 and 2006 were combined and the Kruskal-Wallis test was used to test for significant differences in biotic factors (species, gender, fish length, and number of attempts) and abiotic factors (temperature, velocity, drop height, and culvert length) comparing fish that successfully passed through culverts with those that failed to pass. Mann-Whitney U tests were then used for pair-wise comparisons. Factors that were found to be significant were used in stepwise logistic regression to determine the best model for predicting the probability of successful passage. Differences in time-for-passage between 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.

The travel history of each individual fish was also recorded and mean travel times and the probability of passing successive points in the stream system were computed.

Culvert Hydraulics

Transducer-based stage-height data-loggers (TruTrack 2007) were installed in the main stem of Mulherin Creek, in Upper Mulherin Creek, and in Cinnabar Creek. These data loggers recorded water height, water temperature, and air temperature. In 2005 measurements were logged hourly from May 13 through October 2. In 2006 measurements were logged every 15 minutes from April 15 through September 2.

Stream transects were established just downstream of each data logger and 10 discharge measurements were taken at each site during the 2005 season. 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 installed in the same locations in 2006. A few ground-truths of the stage-discharge relationships were measured in 2006, and in all cases the 2005 stage-discharge relationships held. Stage-discharge relationships were modeled using:

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

Where Q is the stream discharge (m^3/s), y is the stage (from arbitrary datum) observed using the transducers, and a, b and h are regression coefficients.

For many components of this project, the flow rate was used primarily as a vehicle for arriving at a representative velocity. Once hydrographs were prepared, corollary graphs of velocity versus time for each of the culverts were arrived at by the following. First, flow depths at appropriate locations in the culvert were recorded over time and at a variety of flow rates. Then, the cross sectional flow area, A (m^2), was calculated for each flow depth based on the geometry of the cross section. A representative culvert velocity, V (m/s), was estimated using:

$$V = \frac{Q}{A}$$

Finally, the velocities were regressed against the flow rates using a power function so that at any point in time during the periods when stage was logged, discharge and velocity could both be estimated.

With this approach, it was important to determine where in the culvert the flow depths should be measured to arrive at a representative velocity for each culvert (a velocity that well represented the mean of cross-sectional velocities that fish encounter over the length of the culvert). Selecting the locations for depth measurements was based on observation. Culverts that had baffles had depth measurements taken at the upstream and downstream ends of the culvert, averaging the two depths to calculate representative velocities. Unbaffled culverts had a single depth measurement taken from the midpoint of the barrel length. For the control reach, the representative culvert velocities were developed from the HEC-RAS model calibrated to local conditions and used over the range of flows observed.

FishXing

Data were collected to facilitate the use of the FishXing model at culverts 1 and 4. Culverts 2 and 3 are baffled, and FishXing is not recommended for use with baffled culverts or culverts having natural substrate. Culvert 5 has two different pipe diameters (a smaller diameter pipe spilling into a larger diameter pipe) and the hydraulic model in FishXing is not appropriate for this system. Culvert surveys included culvert length, slope and roughness as well as plunge pool depth and tailwater channel cross sections.

The *test fish* used in the model was a YCT having the average length of YCT trapped (343 mm). The minimum passable flow depth prescribed was 9.1 cm, based on recommendations in the literature for adult cutthroat trout (Fitch 1995). The FishXing model was calibrated at each culvert, varying the Manning’s roughness coefficient until the culvert water depth predicted by FishXing was within 5 cm of the measured depth.

Results and Discussion

Trapping and Tagging

In 2005, a total of 34 adult trout were captured and tagged at the trap during the dates of operation from 23 April to 30 August. As shown in Figure 6, upstream migrants were comprised of 28 YCT, 3 RBT, and 3 hybrids (each symbol in Figure 6 represents an individual fish). In 2006, a total of 109 adult trout were captured and tagged (92 YCT, 12 RBT, and 5 hybrids) from 18 June thru 13 July. The open symbols in Figure 6 represent fish that were electrofished downstream of culverts 4 and 5, and the closed symbols represent fish trapped at the trap near the confluence of Mulherin Creek and the Yellowstone River.

The observation that RBT migrate at the onset of the rising limb of the snowmelt hydrograph and YCT spawn on the falling limb is supported by Figure 6. The decision was made early in the project to attempt to tag as many YCT (a native species) as possible, but to also include any RBT or hybrids (non-natives) when caught. Trapping and tagging intensity was intentionally highest on the falling limb of the hydrograph (coinciding with water temperatures of 9 to 10 degrees C) to maximize the YCT catch. This also reduced safety concerns as project personnel were not working in the stream during peak flows or when the stream was iced.

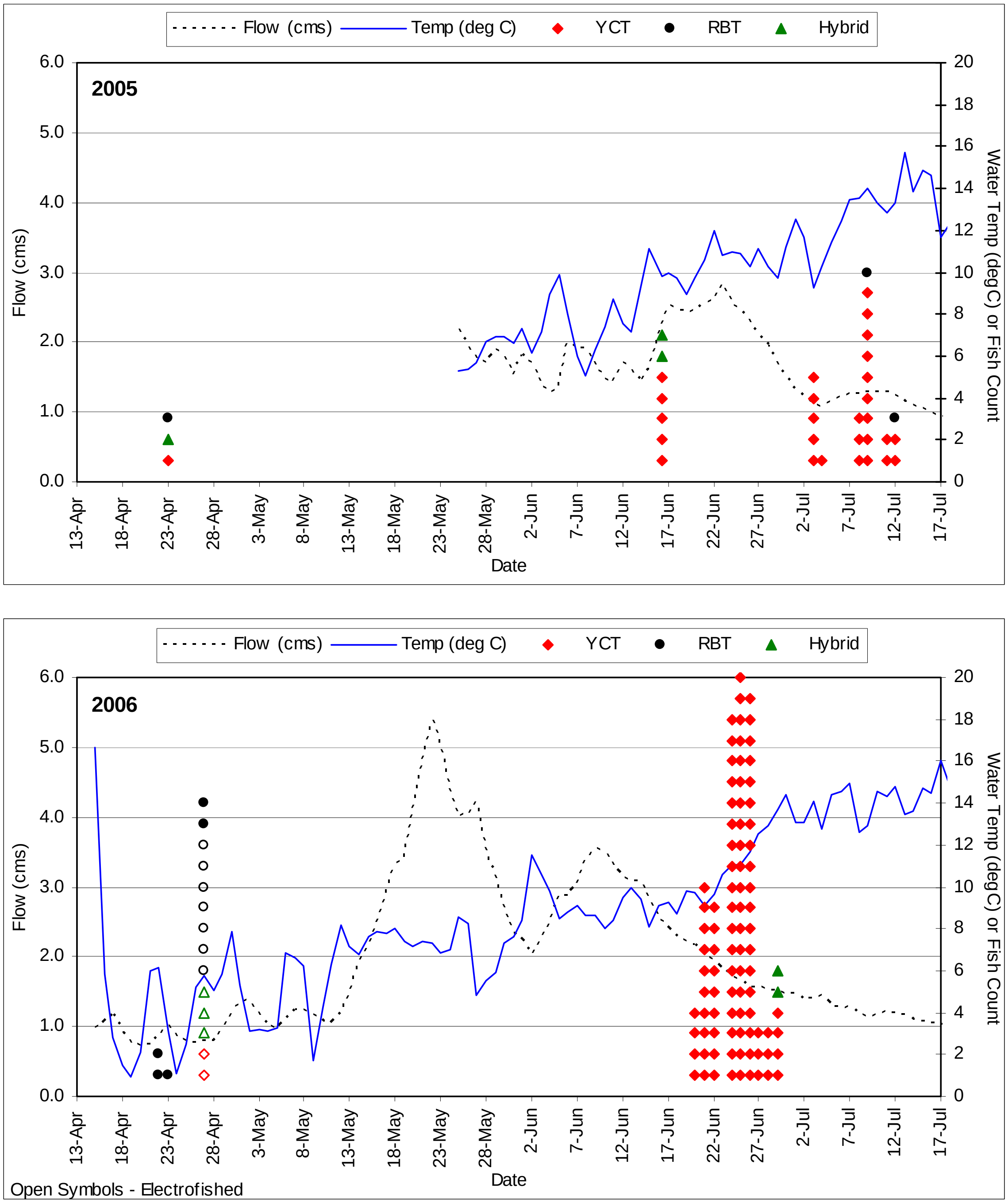

Figure 6. Numbers of migrant trout (YCT, RBT, and hybrids) captured and PIT tagged in relation to discharge and mean daily temperature of Mulherin Creek, MT for 2005 and 2006.

Tag Detection Range and Read Efficiency

Tests of detection efficiency used PIT tags that were manually moved through and around antennas. Mean detection efficiencies were 75% at the steel culverts, 81% at the concrete box culverts and 95% in the control reach. Mean detection efficiencies were significantly different in all possible pairwise comparisons of settings using Fisher's least significant difference (LSD) test as shown in Table 4. For example, reading Table 4 to the right from the antenna setting row label *Control* to the first *a* encountered in the column with the label *Concrete* shows that tags were detected with a significantly higher efficiency in the control reach than near the concrete culverts.

Table 4. PIT tag detection efficiency statistics.

Antenna Setting	Mean Detection Efficiency (%)	95% Confidence Interval (%)	Number of Samples	Fisher's LSD Test		
				Control	**Concrete**	**Steel**
Control	94.5	±2.9	75	-	a	a
Concrete	80.6	±3.5	167	b	-	a
Steel	74.7	±5.1	84	b	b	-

The letter *a* indicates detection efficiency is significantly higher when reading the table in ⟶↑ direction, the letter b indicates detection efficiency is significantly lower.

Detection range also varied by antenna setting. The control reach had a mean detection distance of 28 cm. That is, as a tag was moved horizontally through an antenna in the upstream direction, the average distance from the antenna where detection would first occur was 28 cm from the antenna. The antennas tend to be horizontally symmetric with respect to read range. Concrete culverts and steel pipe culverts had detection ranges of 19 cm and 6 cm respectively. Mean detection ranges were significantly different in all possible pairwise comparisons of settings using Fisher's least significant difference (LSD) test as shown in Table 5.

Table 5. PIT tag detection range statistics.

Antenna Setting	Mean Detection Range (cm)	95% Confidence Interval (cm)	Number of Samples	Fisher's LSD Test		
				Control	Concrete	Steel
Control	28.2	±0.3	75	-	a	a
Concrete	18.8	±0.6	167	b	-	a
Steel	6.0	±0.5	84	b	b	-

The letter *a* indicates detection efficiency is significantly higher when reading the table in ↑ direction, the letter b indicates detection efficiency is significantly lower.

The results of the tests to determine tag read range and efficiency were as expected. Ferrous metals interfere with the antennas. Steel pipes had more interference that concrete pipes (the concrete pipes have steel reinforcing bar imbedded in them). The control reach had only the steel t-posts and cable used to support the antennas. Overall, though the read ranges and efficiencies were acceptable. Having a read efficiency of less than 100% means that on occasion a fish may pass a culvert and not be registered. This may not represent a complete loss of data, however, because if that same fish is registered at a further upstream antenna later in time, it can be concluded that the fish did pass through the culvert where the tag was not logged, but at an unknown time. Incidentally, some fish were observed to exit the system (moving in the downstream direction) but rarely, and of not great interest to the project (culverts are not highly regarded as barriers to downstream mobility). In the course of the trials to determine tag read range and efficiency there were no occurrences of a false positive. In that regard, fish passage as measured by PIT tags may be thought of as being conservative by a magnitude indicated by the passage efficiency. Ideally, the read efficiency should be high (minimizing failed detections during passage through the antenna loop) and the read range should be low (minimizing the number of false positive readings as a fish hovers near an antenna without passing through it). This combination is unlikely, though, as read range appears to be positively correlated with detection efficiency.

Fish Passage

Detection Summary

The use of HDX PIT tag equipment allowed for near-constant monitoring of all the culverts instrumented in the stream system overt the time period of interest, in this case the beginning of the spawning migration period for YCT until late summer. Of the 143 individual fish tagged in 2005 and 2006 combined, 36 fish (25%) were detected by at least one of the antennas in the upstream system. These 36 individuals resulted in a total of 6,763 tag detections at the antenna locations - many of these being redundant detections as a fish sat in proximity to a given antenna or moved very slowly through a given antenna for long enough to be detected multiple times. After manually cleaning the data to sweep out redundant detections, there were 46 individual cases where one or more attempt was made to pass an individual culvert with the fish eventually passing that culvert, and there were 8 cases where one or more attempt was made to pass a culvert and no evidence indicated that passage of that culvert was successful by that fish. One fish was tagged in 2005, not detected at an antenna in 2005, but was then detected in 2006 on a return spawning trip.

All 34 fish tagged in 2005 were replaced in the stream near the confluence of Mulherin Creek and the Yellowstone River, approximately 1 km downstream of the first antenna in the system. Of these, 9 fish (26%) were detected by at least one antenna in the system. Of the 97 fish tagged and released at the same location in 2006, 18 fish (19%) were detected by at least one antenna in the system. Of the 12 fish electroshocked near culverts 4 and 5, tagged, and placed just downstream of culvert 1, 5 fish (42%) were detected by at least one antenna in the system. This last group (the 12 fish electroshocked) did not have to traverse the 1 km of stream between their placement location and the first antenna in the system. The Fisher’s LSD test indicated that release location and year were significant factors in detection by an antenna in the system as shown in Table 6.

Table 6. Summary of detection rates by release point and year.

Year and Release Point	**Number of Fish Released**	**Number of Fish Detected**	**Detection Rate (%)**	**Fisher's LSD Test**		
				2005 Confluence	**2006 Confluence**	**2006 Culvert 1**
2005 Confluence	34	9	26.5	-	a	b
2006 Confluence	97	18	18.6	b	-	b
2006 Culvert 1	12	5	41.7	a	a	-

The letter *a* indicates detection efficiency is significantly higher when reading the table in ⎯⎯↑ direction, the letter b indicates detection efficiency is significantly lower.

Habitat surveys of the stream system indicated that the reach of stream between the confluence and the culvert 1 had the highest spawning bed intensity of any reach in the system including those upstream of the reaches studied. With a substantial length of stream (1.085 km) having a high spawning bed intensity (113.4 m^2/km) in the reach between placement and the first possible detection, it may be that many of the fish released at the confluence were not motivated to travel even to the first culvert, having found suitable spawning beds in between. In this light, the ratio of fish detected to fish placed at the confluence (21% overall for both years) is encouraging. This is especially the case when it is considered that the trap was in effect for most of the YCT spawning run, meaning that it is not likely that a large number of spawning-run YCT spawned in the stream that were not tagged.

Fish were observed to have successfully passed through all culverts except culvert 5. The percentage of fish that were detected while attempted passage and successfully passed through each culvert ranged from 0% for culvert 5 to 100% for culvert 3. The average number of attempts prior to successful passage varied from 2 to 11 as shown in Table 7. Although no individual fish successfully passed through culvert 5, two fish were detected to have attempting to pass culvert 5, one with 24 and the other with 2 attempts.

Table 7. Summary of fish detections at each culvert; all fish, all years.

Culvert	Percent of Fish Attempting a Culvert that Passed	Time to Pass Unit Length of Culvert (sec/m)		Number of Attempts Followed by a Pass		Number of Attempts Followed by a Fail to Pass	
		Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
Culvert 1	75	3.2	1 to 7	5	2 to 11	3	1 to 4
Culvert 2	88	85.5	26 to 297	5	1 to 10	3	3
Culvert 3	100	23.3	6 to 69	2	1 to 4	0	0
Culvert 4	78	13.9	1 to 78	3	1 to 6	3	1 to 4
Culvert 5	0	none	none	0	0	13	2 to 24

The mean time of day for attempts was near 5:00 pm at an average water temperature of 13.6°C. It is noteworthy that the water temperature is affected by diel variability as well as seasonal variability. The majority of attempts (88.6%) occurred in the eight hour period between noon and 8:00 pm as shown in Figure 7.

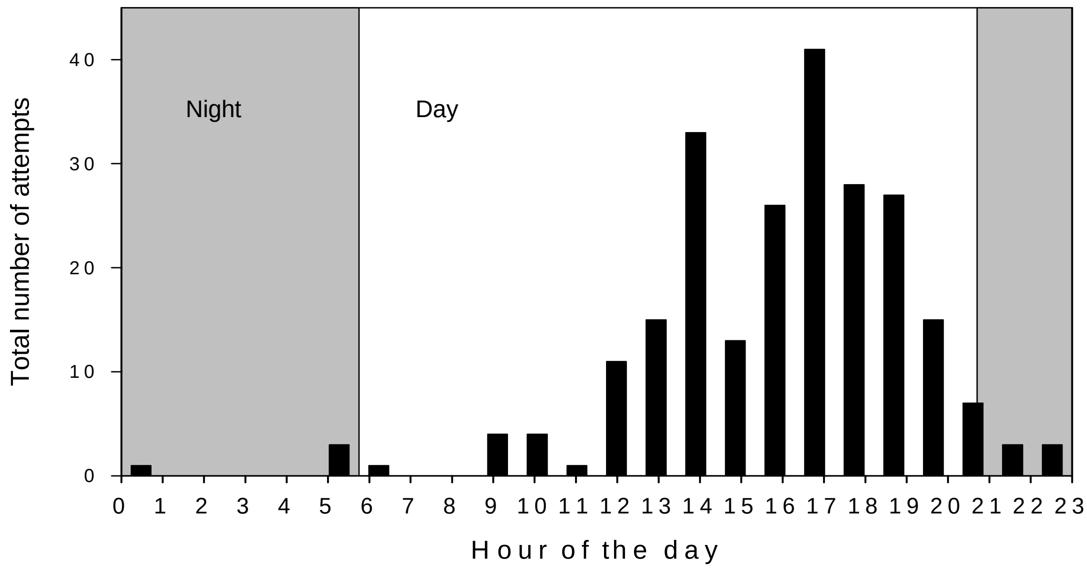

Figure 7. Total number of passage attempts by hour of the day for all culverts.

Passage Time

The time required for an individual fish to pass through a given culvert varied from 0.2 to 46.0 min. When examined by culvert type for all fish and years using the Kruskal-Wallis test, the time required for passage varied significantly between culvert types. One fish at one culvert was excluded from the analysis as an outlier, with 17.3 hours required to pass through culvert 1. In pairwise comparisons (Mann-Whitney), as shown in Figure 8, passage time was significantly different between smooth box and baffled box culverts with smooth box culverts having a mean passage time of 1.3 minutes while of the mean travel time through baffled box culverts was 46.0 minutes. Passage time between smooth steel and baffled box culverts was also significantly different with an average mean passage time through the smooth steel culvert of 2.11 minutes. Passage time was not significantly different between smooth box and smooth steel culverts. The increased travel time through the baffled culverts likely indicates the effect of rest areas where the baffles result in low velocities.

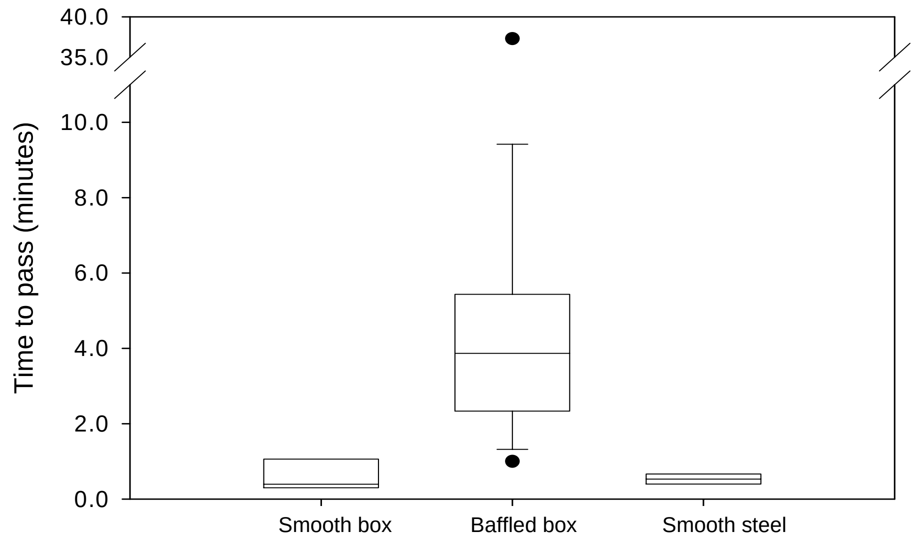

Figure 8. Box plots of passage time through smooth box, baffled box, and smooth steel culverts on the main stem of Mulherin Creek.

An analysis similar to the above, but considering cumulative passage time for fish detected in the system rather than individual passage time for a fish at a culvert is summarized in Figure 9. As seen in the figure, a fish that was detected in the system and passed through culverts 1, 2, 3, and 4 took more than 10 days to do so on the average, but with a large distribution about the mean. The dip in the curve from culvert 1 to 2 is because each culvert had a different pool of fish over which the time was averaged.

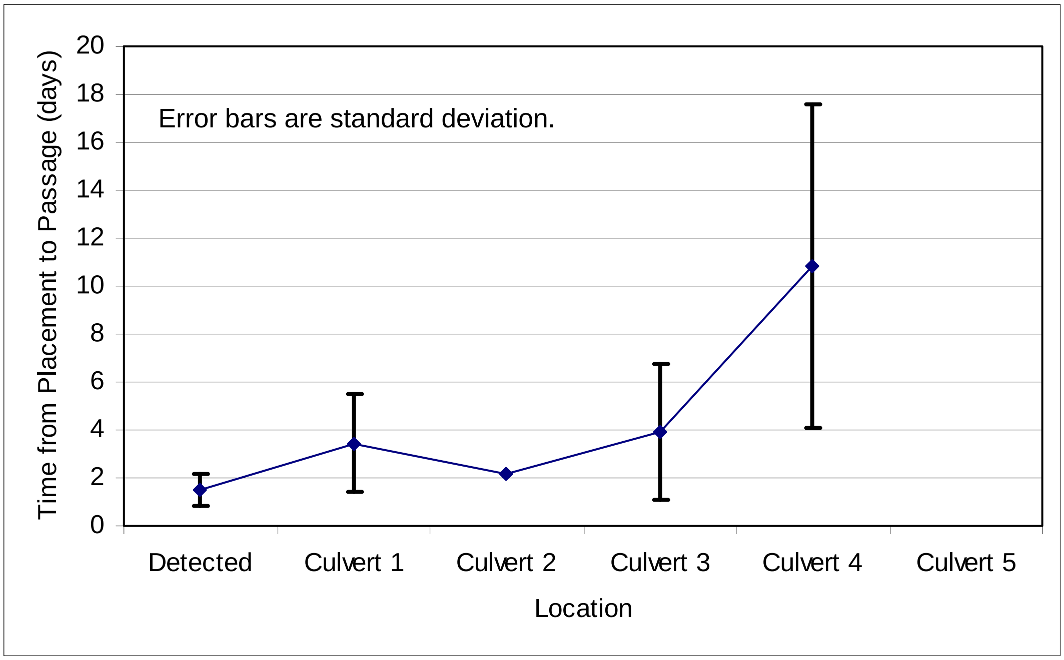

Figure 9. The cumulative time for passage of a fish detected in the system having passed up to and through a given culvert.

Factors Affecting Passage

In pair-wise comparisons (Chi-square), the success or failure of passage was examined by fish species over all years and culverts. There was no significant difference in pass rates by species as shown in Figure 10. Similarly, there was no significant difference in pass rates by fish gender, where RBT and hybrids were grouped together to arrive at adequate sample size.

Other features that occur on a continuous scale (fish length, for example) were examined using the Mann-Whitney U test to compare the distribution of the feature for fish that passed culverts against the distribution for fish that did not pass. In this comparison, the distribution of culvert slope, culvert length and number of attempts at passage were all not significantly different between fish that passed culverts and fish that did not pass as shown in Figure 11. Significant differences were detected for fish length, water temperature, outlet drop height, and water velocity in the culvert.

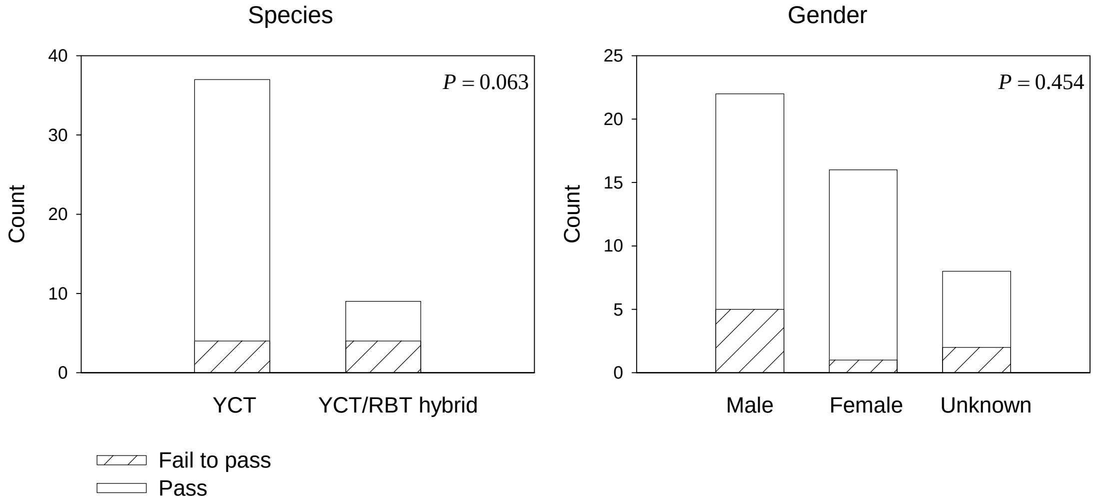

Figure 10. Differences in species and gender proportions between individuals that successfully passed through culverts and those that failed to pass.

The mean length of fish that passed culverts was 320 mm while those that failed to pass had a mean length of 363 mm. The smallest fish observed to have passed through any culvert was 300 mm while individuals as small as 230 mm were tagged and had the opportunity to attempt passage.

Mean water temperature was 13.6°C for successful passage and 12.3°C for failed attempts. Again, water temperature is affected by time of day and by day of season.

Mean water velocity for successful passes was 1.57 m/sec while for failed attempts it was 2.51 m/sec. The maximum observed passable velocity at any culvert was 2.71 m/sec while individuals were detected attempting to pass at velocities up to 2.97 m/sec.

The mean outlet drop height for individuals that passed was 11.92cm and 35.04 for those that failed to pass.

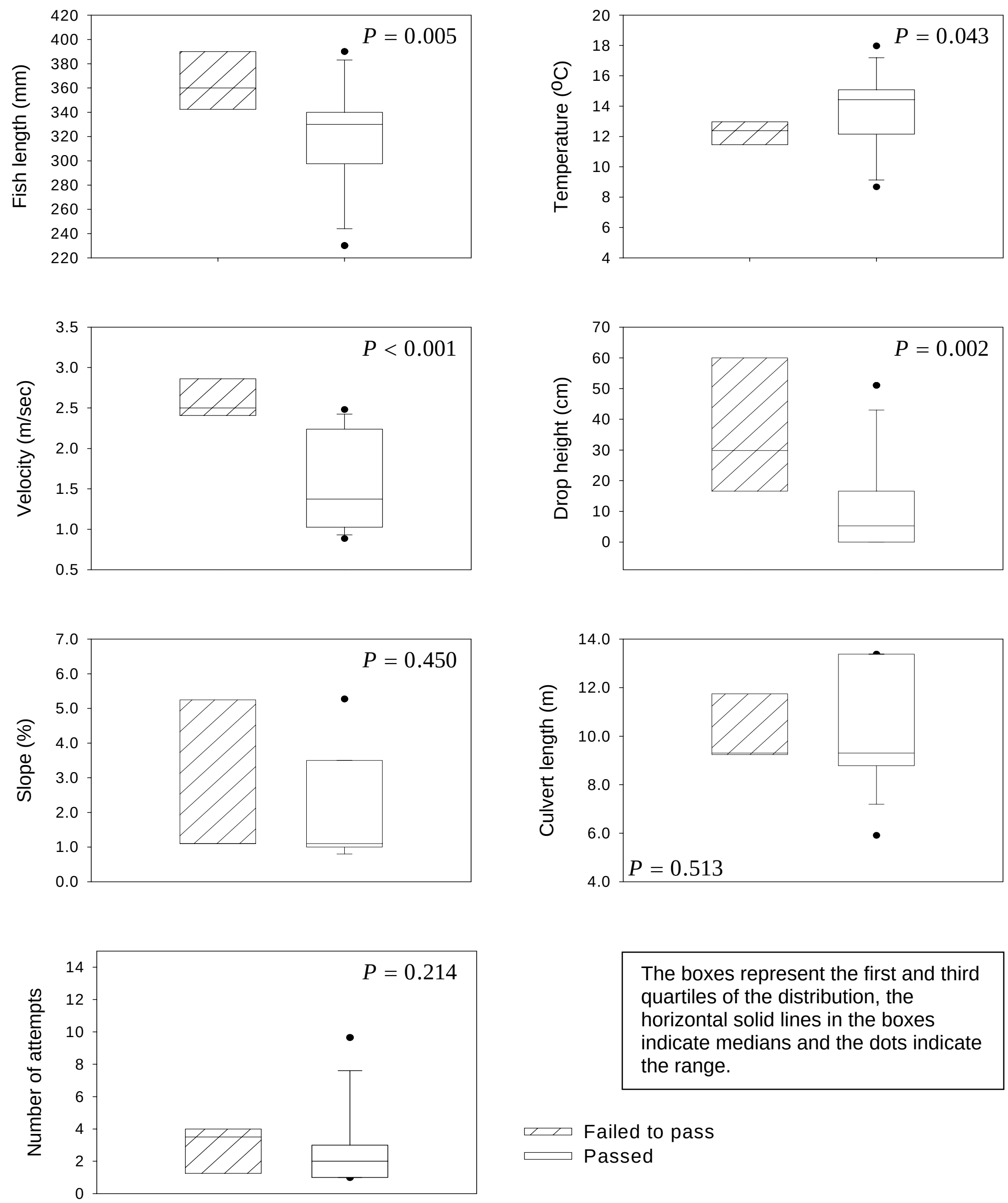

Figure 11. Box plots of fish that successfully passed through culverts and those that failed to pass.

A summarized above and shown in Figure 11, four factors were found to be significantly correlated to fish passage using the Mann-Whitney single factor analysis; fish length, water temperature, outlet drop height, and water velocity. These factors were then used as independent variables in multiple logistic regression modeling to determine which, if any, had significant predictive capability. The only model that, at a significant level, predicted the probability of passage was a single factor model based on water velocity as shown in Figure 12. The model was:

$$P = 1.0 - 0.00469\ V^{\ 4.7957}$$

relating the probability of successful passage (P) to the representative water velocity in the culvert (V, m/sec). This model correctly predicted passage/failure in 89% of the cases. The model correctly predicted successful passage in 98% of cases and failure to pass was correctly predicted in 38% of cases. The model coefficient of determination (R^2) was 0.988, and the velocity at which the model predicts no probability of passage was 3.06 m/sec. Recall that in the field experiments, no fish was detected passing a culvert with a velocity of greater than 2.71 m/sec.

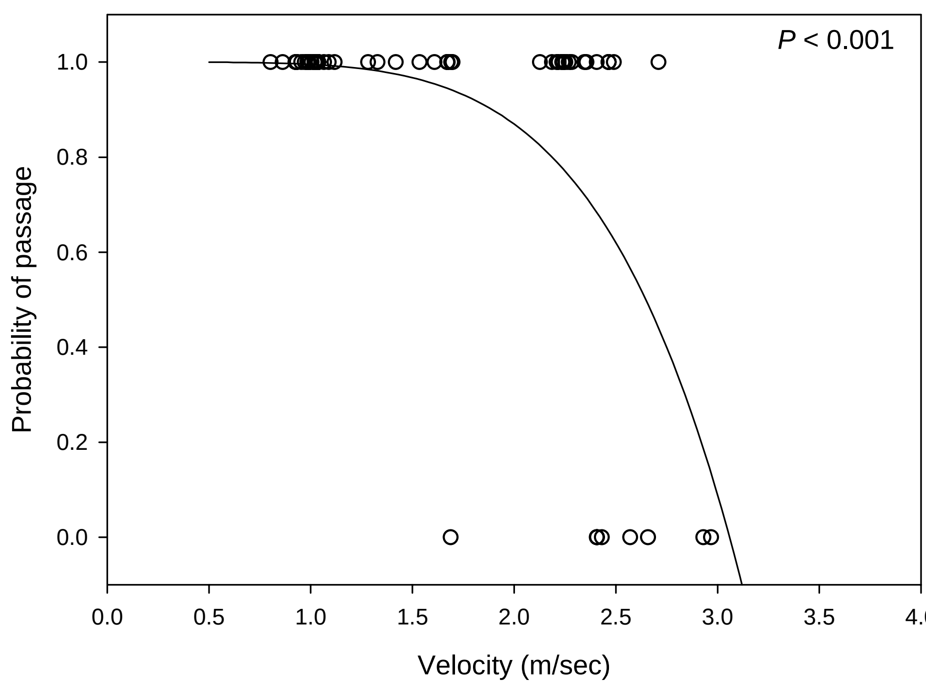

Figure 12. Predicted probability of YCT passing a culvert in the system age based on water velocity in the culvert, superimposed on observed data.

Effect of Baffles

Questions often arise concerning the effect of using baffles to hydraulically roughen a smooth culvert. To illustrate this at a point in time, velocities were compared between culverts 1, 2, 3, and the control reach. Culvert 1 is smooth, culvert 2 has baffles, and culvert 3 has baffles with some infill of natural stream cobble and rock. The spot in time chosen for the comparison was 24 hours prior to trapping the first fish (April 21, 2006). In this comparison, the representative velocities in the four settings were significantly different using ANOVA. Furthermore, pair-wise comparisons using Fisher's LSD tests showed that velocities were significantly different between all culverts and between each culvert and the natural control. Short of repeating the analysis at all points in time, the effect of baffling smooth culverts on water velocity over the season is illustrated in Figure 13.

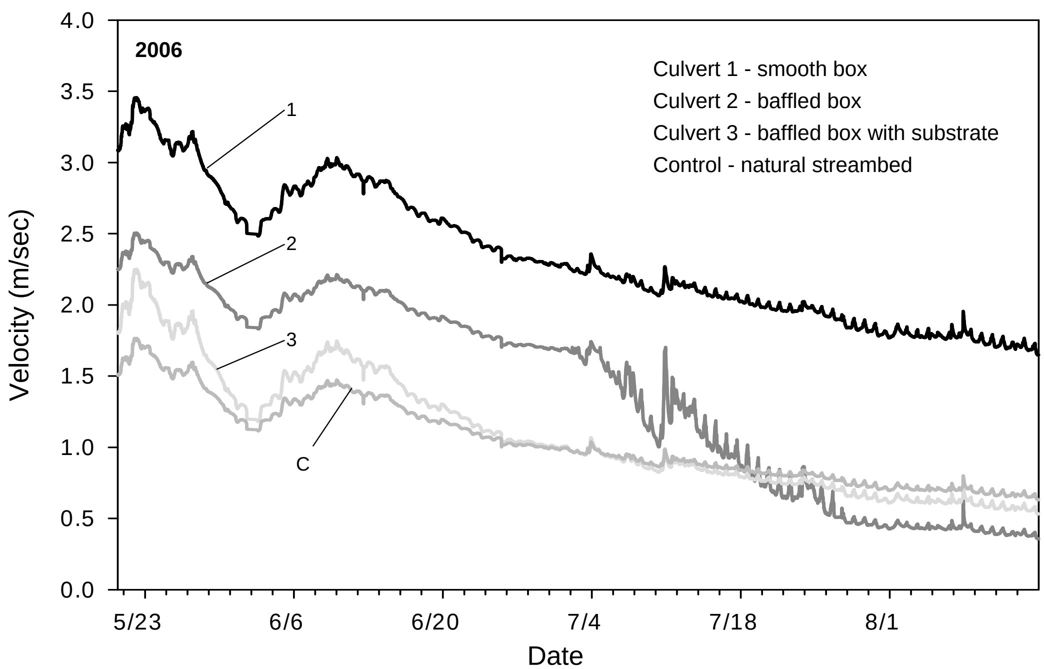

Figure 13. Representative water velocities in concrete box culverts with and without baffles and in the natural control reach in 2006.

As seen in Figure 13, early in the season the culverts rank 1-2-3-control, from high velocity to low. Mid-season, the control and culvert 3 begin to behave similarly. This is expected, as culvert 3 is not only baffled, but has over time accumulated some natural infilling of streambed rocks and cobble. Late in the season the velocity in culvert 2 is the lowest. This is because at low flow the baffles are no longer submerged and essentially provide flow path sinuosity. However, regardless of flow the baffled culverts have much lower velocities than the unbaffled culvert, with culvert 1 maintaining high velocities throughout the season.

Probability of Passage

The probability of fish passage success can be examined in three ways, as shown in Figure 14. First, the diagonally hatched bars in Figure 14 show the results of applying the overall probability of passage success at each culvert in series (multiplicatively). That is, if the probability that fish, in general, pass culvert 1 is 0.75 (from Table 7) and the probability that fish, in general, pass culvert 2 is 0.88, then the probability of fish generally passing both culverts is 0.77 x 0.88 = 0.66 or 66%. This is then repeated successively as each culvert is added to the calculation in the upstream direction. A second way of examining the probability of passage success is to consider that if a specific fish is detected in the system, it had to have passed the culverts downstream of the detection point. For example, a fish detected at the inlet to culvert 4 had clearly passed through culverts 1, 2, and 3, but at unknown times. With this information at hand, the probability that a certain fish that was detected somewhere in the system passed all culverts up to and including any given culvert can be computed directly from PIT tag detection data. The results are shown as the dotted pattern bars in Figure 14. The third method would be to repeat the analysis for a detected fish but to modify these probabilities by a) the probability that a fish tagged and placed at the confluence was ever detected at all (multiply by 0.206), and b) the probability that PIT tags pass through culverts undetected (divide by 0.786). The result (the open bars in Figure 14) is the probability that a fish that enters Mulherin creek from the Yellowstone River passes through each successive culvert. It's important to note that both of the latter two analyses (represented by the dotted and open bars of Figure 14) show the effect of culverts in addition to many things that are not culverts - motivation, habitat availability, predation, mortality, etc. Only the series analysis of the probability of fish in general passing individual culverts (the first approach, shown by the diagonal hatched bars) isolates the effect of the culverts.

Also evident in Figure 14 is that regardless of the method of analysis used, fish were never predicted to have had a chance (0% probability) of passing through culverts 1, 2, 3, and then 5, but some did pass through culverts 1, 2, 3, and 4. Recall that culverts 4 and 5 are on different stream branches, and no fish was observed to pass through culvert 5.

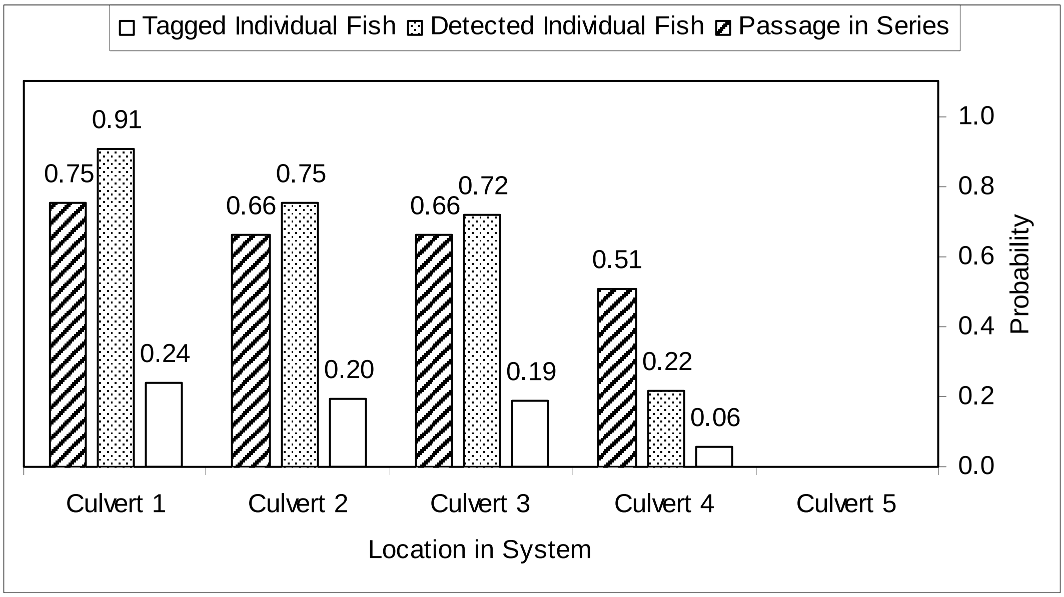

Figure 14. The probability of a fish detected in the system having passed up to and through a given culvert.

Travel History

The travel history of any given tagged fish may be plotted to show where the fish was detected and at what cumulative time since replacement, what culverts were passed and at what times, the time lags between culverts, skips in detection, time spent in the plunge pool of a culverts, and so on. These have been examined for each fish, but only a few samples are shown here in Figures 15 through 18 to avoid redundancy. In Figure 15 through 18, the approximate locations of each antenna and the control (for 2006 fish) are noted near the horizontal axis. Each triangular symbol represents a tag detection (after sweeping the data for redundancies). The line connecting the triangles (detections) is only present in cases where an antenna was not *skipped*.

Figure 15 shows the travel history of a YCT male trapped and tagged in 2005. The connecting line is solid throughout - this is a fish that was detected at every antenna as it traveled upstream. It took approximately 8 days for this fish to clear culvert 4 into the Upper Mulherin. There was a 3 day lag between the first attempt at the outlet to culvert 4 and the last attempt at the inlet (clearing the culvert).

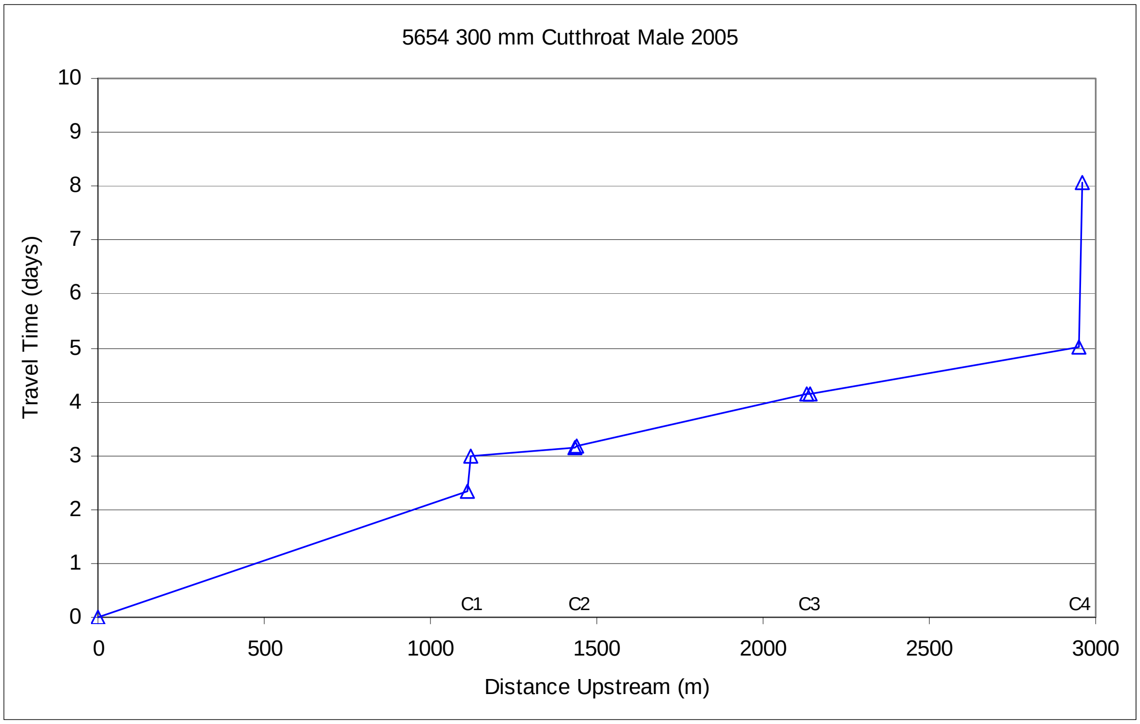

Figure 15. Travel history of a YCT male trapped and tagged in 2005.

Figure 16 shows the travel history of a hybrid of unknown gender trapped and tagged in 2006. This fish cleared culverts 1 and 2 but were not detected there as indicated by a detection at culvert 3 later in time. The fish was then detected at antennas 1 and 2 but not antenna 3 on culvert 3. At approximately 8 days after tagging and again at approximately 17 days after tagging, the fish attempted to enter culvert 5, but was never detected at the upstream end of the culvert (a failed attempt). Then, at approximately 18 days after tagging, the fish abandoned attempts to pass culvert 5, went back downstream to the confluence of Cinnabar and Upper Mulherin Creeks, traveled upstream in Upper Mulherin Creek, and attempted to pass culvert 4. The fish was never detected successfully passing culvert 4 either, and likely washed out downstream. This was the only fish detected at both culverts 4 and 5. The fish of Figure 16 is also one of the fish electrofished and placed just downstream of culvert 1, as evident by the position of the triangular symbol on the horizontal axis indicating the travel history started just downstream of culvert 1.

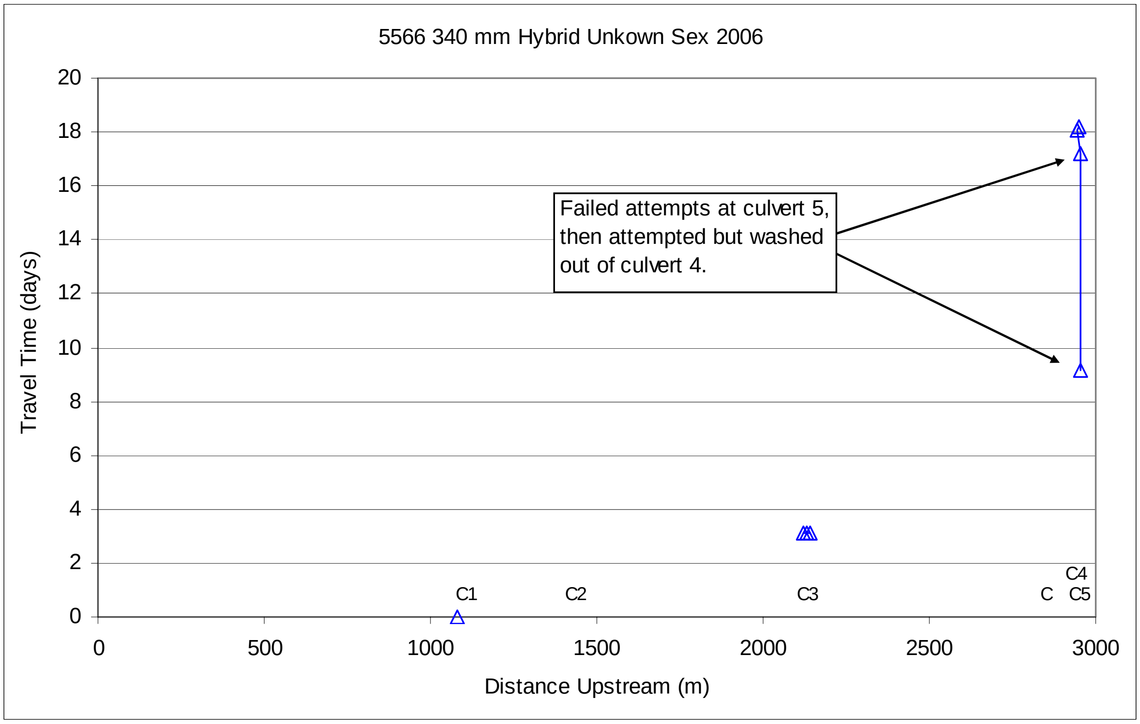

Figure 16. The travel history of a hybrid of unknown gender trapped and tagged in 2006.

Figure 17 shows the travel history of a female YCT trapped and tagged in 2006. This fish entered the plunge pool of culvert 1 approximately one day after being tagged. The fish was then detected attempting to enter the outlet of culvert 1 approximately 2.5 days later. This is a failed attempt to pass through culvert 1.

Figure 18 shows a less robust travel history, that of a female YCT trapped and tagged in 2006. This fish was detected at all three antennas at culvert 3, approximately 3 days after being tagged. This example provided more data to the probability analysis previously discussed than would perhaps be evident at first glance. While the non-detects at culverts 1 and 2 fail to provide as detailed information as detections would have, the fact that the fish was detected at culvert 3 verifies that the fish passed culverts 1 and 2. Furthermore the cumulative time from tagging until detection at culvert 3 is still valid.

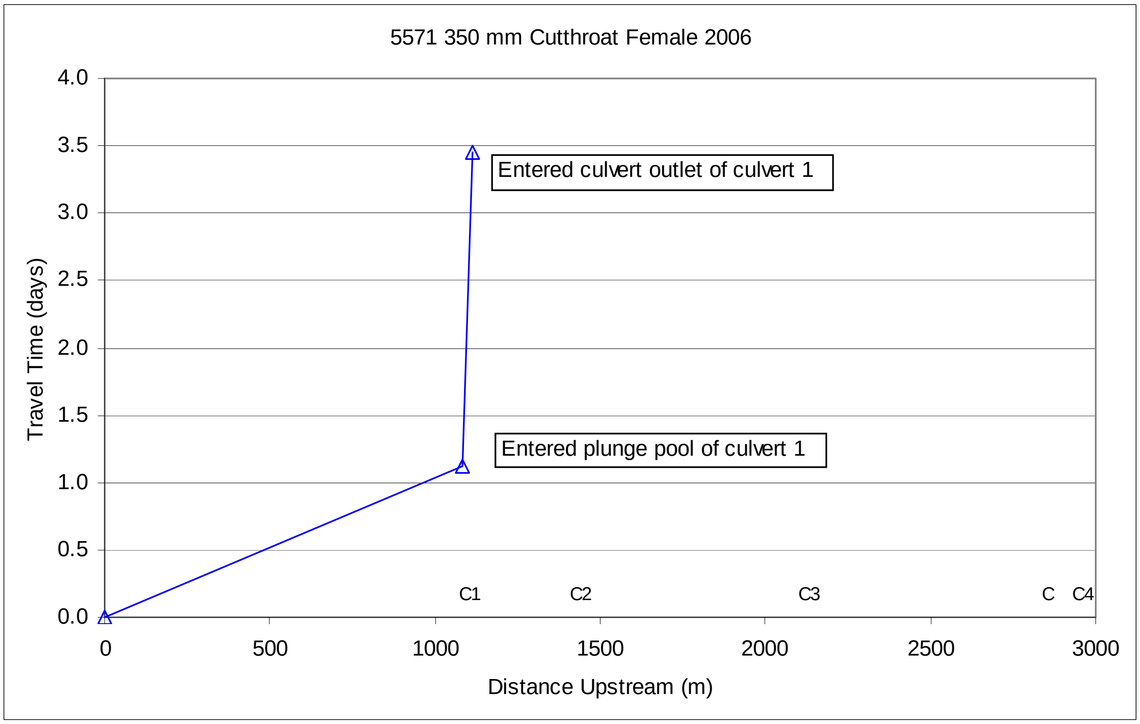

Figure 17. The travel history of a female YCT trapped and tagged in 2006.

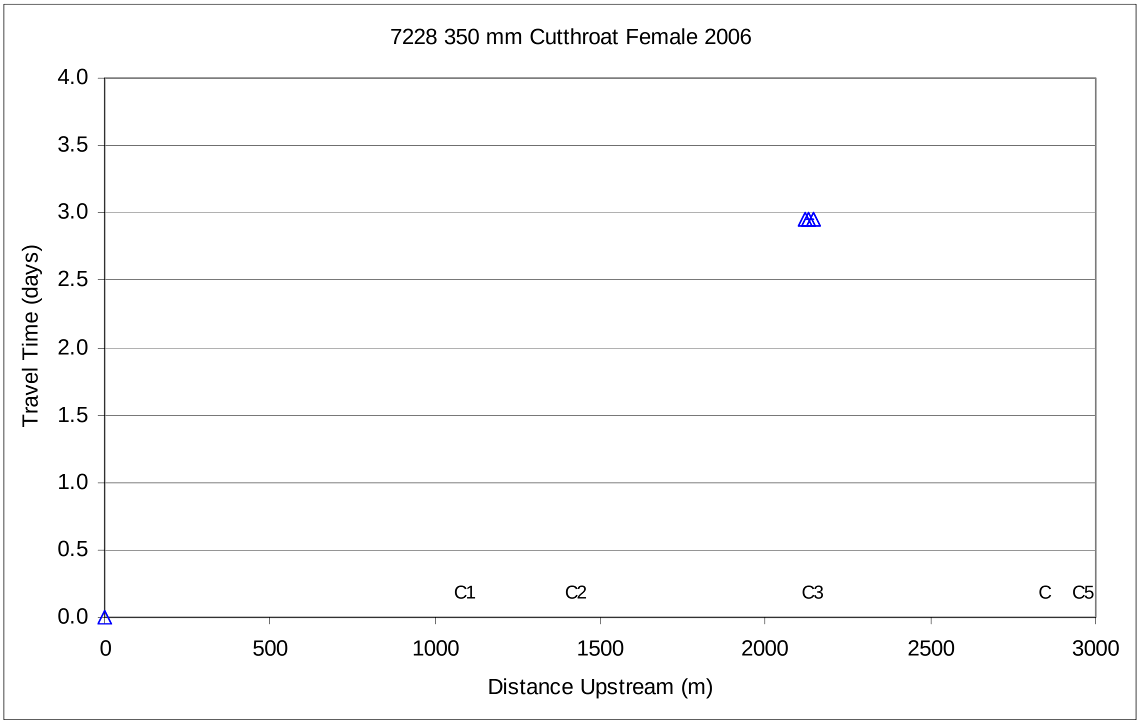

Figure 18. The travel history of another female YCT trapped and tagged in 2006.

FishXing

The FishXing model was used on culverts 1 and 4. Culverts 2 and 3 are baffled and culvert 5 has two pipe diameters, making the hydraulic model of FishXing inappropriate in these three cases. FishXing indicated that culvert 1 acts as barrier to YCT passage at some flows and that culvert 4 acts as a barrier at all flows. When the model predicts that a culvert is a barrier, it also indicates the hydraulic or physical reason for being a barrier. At low flow rates, barrier status for culvert 1 was predicted as the result of insufficient water depth. At high flows, culvert 1 was predicted to have excessive water velocity. Culvert 4 had combinations of barrier status at some flows and at all flows was predicted to have a leap height barrier.

Passage windows are a convenient way to superimpose culvert hydraulics, fish capabilities, hydrology and the results of fish passage experiments into one clear picture. Figure 19 shows the passage window predicted by FishXing for YCT at culvert 1 and Figure 20 shows that there was no passage window predicted (predicted to be a barrier at all flows) at culvert 4.

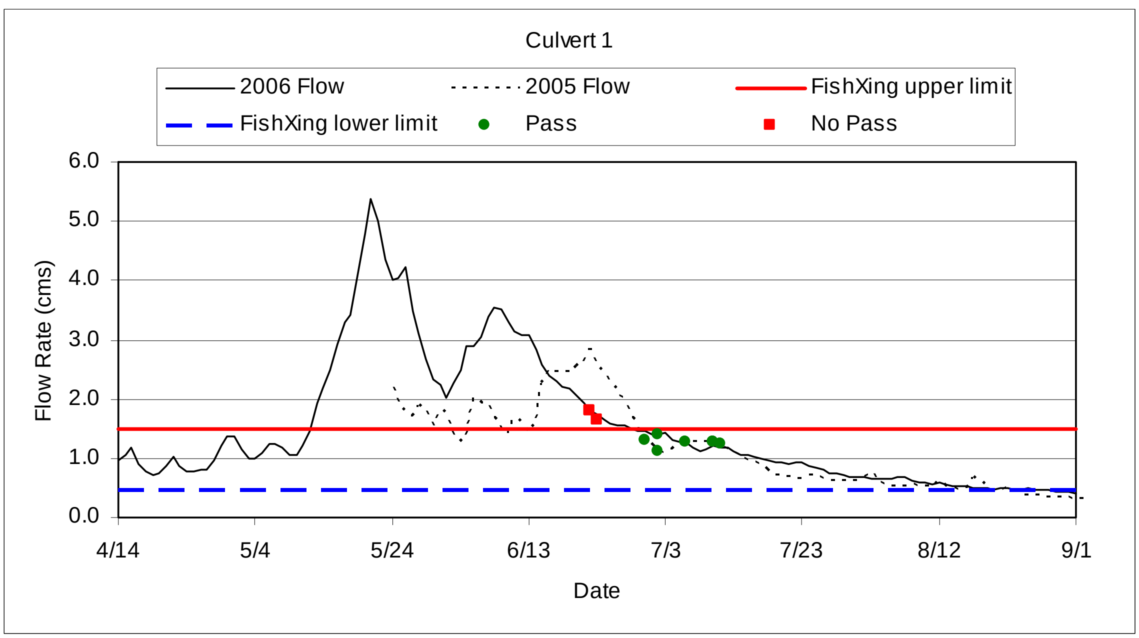

Figure 19. Passage windows for YCT on culvert 1.

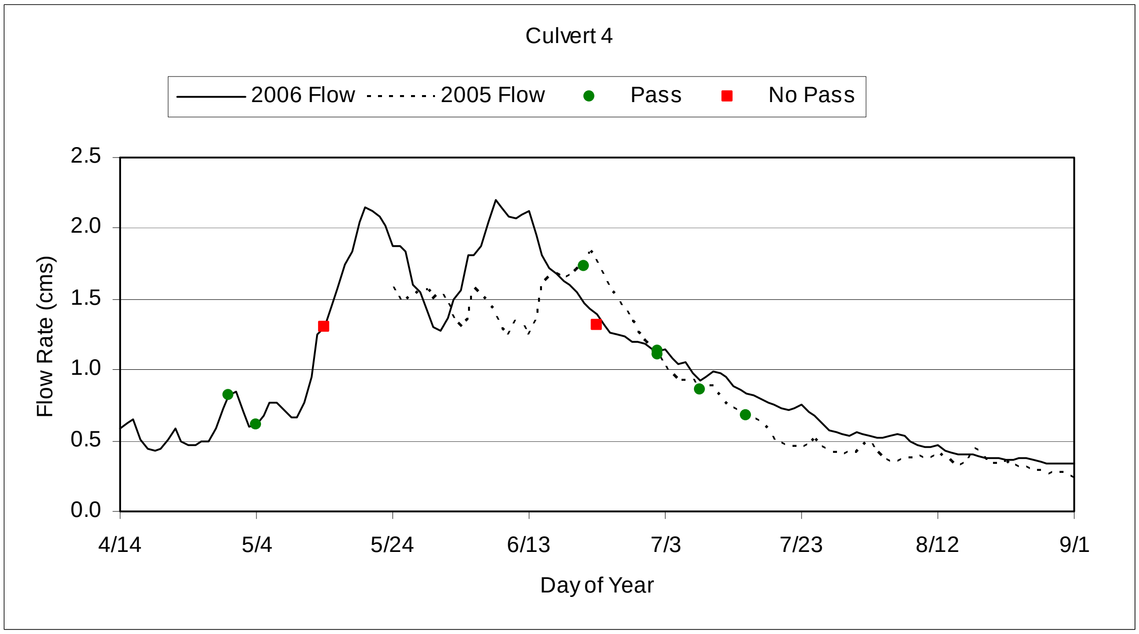

Figure 20. Passage windows for YCT on culvert 4.

Some important features of Figures 19 and 20 are:

1. The dashed blue horizontal line shows the lowest flow at which FishXing predicted that the culvert was not a barrier. Any flow less than this would have some sort of barrier issue according to FishXing.

2. The solid red horizontal line shows the highest flow at which FishXing predicted that the culvert was not a barrier. Any flow greater than this would have some sort of barrier issue according to FishXing.

3. The range between the two horizontal lines is the passage window. Any flow rate in this range would not have barrier issues according to FishXing. The absence of the two horizontal lines indicates that FishXing predicted barrier status at all flow rates.

4. The dotted line is the observed hydrograph for 2005 and the solid line is the observed hydrograph for 2006 sharing a common time scale. Whenever a hydrograph lies within the passage window, FishXing indicated no barrier issues at that flow rate.

5. Green circles indicate cases where in field experiments fish were observed to pass through the culvert. When the green circle is in the passage window, the field experiment coincided with the FishXing results. When the green circle is outside the passage

window, fish were observed to have passed through the culvert at a flow that FishXing indicated should have been a barrier.

6. Red squares indicate cases where in field experiments fish were observed to not pass through the culvert. When the red square is in the passage window, FishXing indicated that there was no barrier, but field experiments indicated restriction to passage. When the red square is outside the passage window, FishXing results coincided with field observations that the culvert was restrictive to passage.

7. The *percent of time passable* is a way of considering the passage capability of a culvert over a season, year, or other period. The value is arrived at by dividing the total amount of time that the hydrograph lies in the passage window by the total duration of the hydrograph.

The passage window predicted by FishXing can be extended vertically in cases where field observations indicated that passage did indeed occur at a flow outside of the FishXing passage window. Or, the passage window could be reduced vertically if the opposite were observed. That is, the vertical limits of the passage window can be reset to the more extreme of the FishXing results or the field experiments results. Including the field observations generates a percent of time passable that is more representative of the entire study. At culvert 1, the percent of time passable was 55% based on FishXing alone, and was 52% when reduced to include the results of field observations.

Passage Goals

Passage goals can be separated into two categories, those for assessing the replacement or repair priority of existing culverts and those incorporated into the design of new or replacement culverts. Contemporary tools and information should be used in either case, but the way that information is used may differ between the two cases.

Passage Goals for Repair/Replacement Prioritization

Some agencies or organizations have used flowchart based screening tools (discussed in Cahoon et al. 2005) or the FishXing model to rapidly assess many culverts for fish passage status. The merits of these approaches are discussed in detail in Cahoon et al. (2007). Additional considerations having to do with passage goals rather than the appropriateness of the model selection can be drawn from Figures 12 and 14.

Figure 12 provides an important departure from traditional pass/no-pass approaches. In pass/no-pass approaches, such as those presented in Katopodis (1994), a critical swimming speed and a duration for sustaining that speed are established from observations for a fish species and size class. Then the maximum relative velocity is calculated for a given culvert length. Any combination of water velocity and culvert length that is above the critical line is considered a no-pass and combinations below the line are considered passes. However, the results shown in Figure 12 indicate that rather than a pass/no-pass threshold, the process should be thought of in terms of probabilities, as incorporated into Figure 21.

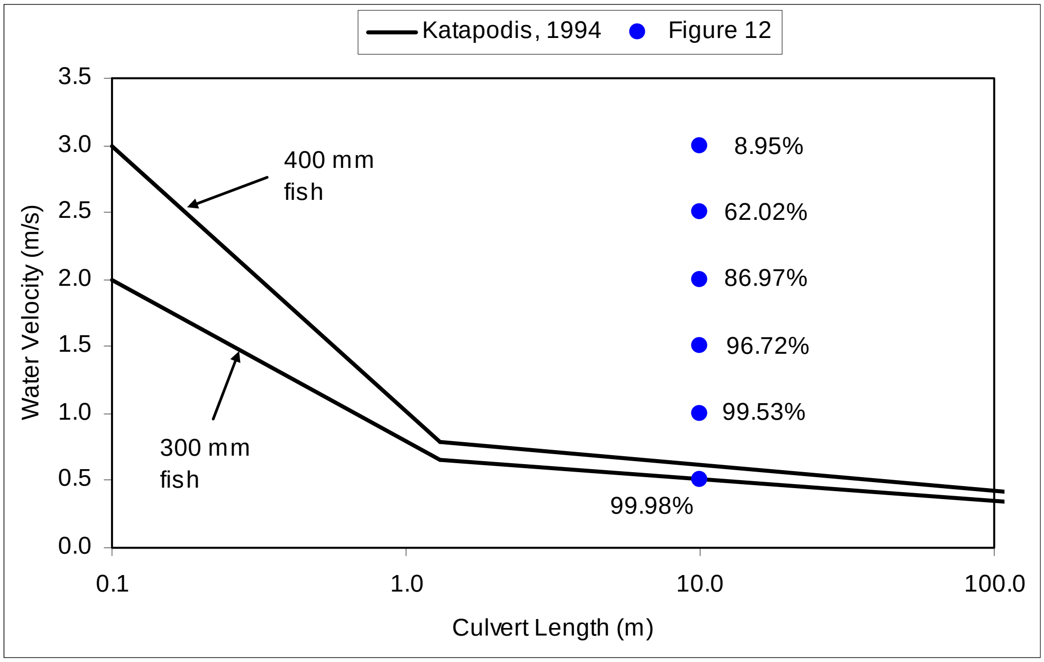

Figure 21. A pass/no-pass threshold with passage probabilities superimposed.

Figure 21 shows the pass/no-pass threshold for adult rainbow or brook trout having lengths of 300 and 400 mm. In this study the mean YCT tagged was 343 mm long, or approximately half way between the lines shown. Rainbow and brook trout have been used before as surrogates for YCT, as in Cahoon et al. (2005), and this study did not have much variation in culvert length, so the mean culvert length (10 m) was used in Figure 21. The pass/no-pass velocity in Figure 21 for the average YCT of this study is slightly more than 0.5 m/sec. While this value (0.5 m/sec) does correspond to the water velocity that in this study had virtually 100% passage probability, it is noteworthy that at velocities substantially greater than 0.5 m/sec fish still passed the culvert with probabilities in excess of 80% or even 90% (the blue circular symbols in Figure 21). It is not until water velocities between 2.5 and 3.0 m/sec were encountered that the probability of successful passage dipped as low as 50%. This issue and others, for example the 3-dimensional velocity variation discussed by Blank et al. (2005), make the pass/no-pass approach very conservative (more fish pass the culvert than the pass/no-pass approach would suggest). This conservatism is also discussed in Cahoon et al. (2007). Because of this conservatism, care should be taken when any method other than direct observation of fish passage is used to assess existing culverts.

The information in Figure 14 also raises questions concerning the effectiveness of traditional culvert assessment procedures. In traditional approaches to assessing the priority of culvert replacement for fish passage, the length of stream upstream of the barrier culvert may have been considered. If two culverts that were otherwise identical were compared for replacement priority, the one that *opened up* the most upstream length might be considered of higher priority. This process would typically have considered natural barriers or other barrier culverts upstream of the culvert in question. Another approach would be to consider the total amount of desirable habitat that is available, rather than just the stream length. For example, the area of potential spawning beds was observed in the reaches of the study culverts as shown in Table 8. Opening up the 6.5 km of stream above culvert 5 (a culvert that no fish were observed to pass in the study) would make available 680.5 m^2 of additional spawning bed, or 3.7 times the spawning area available in the entire length of stream from the confluence with the Yellowstone upstream to culvert 5. However, Figure 14 shows that 76% of the fish tagged and placed near the confluence of Mulherin Creek and the Yellowstone River were never detected anywhere in the system from culvert 1 upstream. So, when examined based on only stream length, one could argue that removing the barrier at culvert 5 triples the fish-navigable stream length. If habitat area were considered rather than stream length, one could say that removing the barrier at culvert 5 increases the spawning habitat area by a factor of nearly 5. However, both of these arguments assume uniform distribution of fish over the stream length or spawning area. If 76% of fish tagged were not motivated to move within detection of culvert 1, then clearly the distribution of fish in the system is not uniform and removing the culvert 5 barrier would not likely be as effective as anticipated.

Table 8. Spawning habitat survey results in the project vicinity.

Reach	Length (km)	Spawning Gravel total m²	Spawning Gravel m²/km
trap to culvert 1	1.1	124.7	113.4
culvert 1 to culvert 2	0.3	4.9	15.8
culvert 2 to culvert 3	0.7	17.5	25.4
culvert 3 to culverts 4 and 5	0.8	38.0	45.8
Upper Mulherin	1.6	136.4	85.3
Cinnabar	6.5	680.5	104.7

Passage Goals for New Culvert Design

The pitfalls of overly conservative fish passage assessment approaches have been discussed herein and in Cahoon et al. (2007). Also, an example of the potential effect of overly optimistic estimates of the benefits of barrier removal on the assessment process has been given. On the other hand, conservative models of fish passage, such as FishXing, can be a valuable component of the design process once it is decided that a culvert will be used for a road crossing, either a replacement or a new installation. That design process is detailed in Cahoon et al. (2007) and is included in Appendix B. The differences between figures 19 and 20 are consistent with the design approach of Appendix B. There is no passage window on Figure 20 because FishXing labeled this culvert a barrier at all flows. From a design standpoint, the fact that fish were observed to pass this culvert is inconsequential. If the culvert were in the design process, traditional culvert hydraulic design procedures could be used iteratively with FishXing until a design was arrived at that passed fish at the desired probability and at the desired flows and times. This is the basis of the procedure outlined in detail in Cahoon et al. (2007) and summarized in Appendix B.

Conclusions

The use of PIT tags to track fish mobility in and near culverts, while less efficient near culverts than in natural reaches, proved to be an effective tool for tracking the mobility of fish. Using the PIT tags over the duration of a spawning season with detection antennas at points near each culvert (plunge pool, outlet, and inlet) and in a natural control reach illuminated many of the characteristics of fish mobility in this system. In general, YCT tended to be much more mobile in the afternoon daylight hours than otherwise, and fish gender was not a good predictor of passage success. The culvert length, culvert slope, and number of attempts prior to successful passage were also not significant indicators of passage success.

Correlation analyses showed that fish length (negative correlation), water temperature, outlet drop height, and water velocity (positive correlations) were all significantly correlated with passage success. However, when subjected to multiple logistic regression analyses, the only significant predictive model related passage success to water velocity. This model showed that fish had a 90% probability of passing culverts in the system at a culvert water velocity of 1.9 m/sec, a 75% probability of passing at a velocity of 2.3 m/sec, a 50% probability of passage at a velocity of 2.7 m/sec, and a 25% probability of passage at 2.9 m/sec. The average length of fish passing the culverts was 320 mm.

Smooth concrete pipes that had been hydraulically roughened using baffles were more hospitable to fish passage than smooth concrete or steel pipes. This was evident not only in a higher degree of successful fish passage in the baffled culverts, but in lower observed water velocities and in much larger travel times through the culvert barrel.

The probability of a fish entering Mulherin Creek from the Yellowstone River and successfully passing all culverts in the system was low. Also, the probability of an individual fish entering and passing through all culverts was substantially lower than the estimate that would be arrived at by combining, in series, the probabilities of fish passing through individual culverts. Of course, the probability of a fish successfully passing all culverts in the system is impacted by not only the presence of culverts, but motivation, access to spawning locations, predation, mortality and a host of other issues.

The use of the FishXing model resulted in a conservative indication of fish passage at one culvert, but predicted passage success very well at another culvert. The most powerful predictive approach for assessing the design of a new culvert or a retrofit to an existing culvert may be to use FishXing with all local information available superimposed. This is consistent with the results of Cahoon et al. (2007) and with the design procedure summarized in Appendix B.

Recommendations and Implementation

While the reader should exercise caution when transferring certain specifics of the results of this project to other settings, there are some general recommendations for implementation that result. Prior to this study, fisheries researchers were hesitant to use PIT tag technology to study fish passage through culverts because of the contention that PIT tag antennas were not very functional near culverts due to interference. This project showed that the antennas are suitably efficient even near large structural steel culverts. The PIT technology is such that, in settings where fisheries are valued but the characteristics of the fishery are unknown, some pre-construction PIT tag-based research is recommended.

Placing baffles in culverts to enhance fish passage is not a new idea, and in fact has fallen out of favor for new culverts as more progressive design procedures have evolved. However, baffles remain an inexpensive tool for retrofitting existing high velocity culverts. This project showed the baffles are effective and it is recommended that baffles be considered in cases where a hydraulically functional culvert may be inexpensively converted to one that remains hydraulically functional while providing an increased probability of fish passage success.

Water velocity in the culvert barrel proved to be a good predictor of fish passage success. In this project the water velocity was related to the *probability* of passage success, rather than identifying a single value that when exceeded results in no fish passage. This approach shows that a high probability of passage is attainable with what would have previously been considered very high water velocities. It is recommended that appropriate levels of passage success probability are used in design rather than single-value thresholds. Results from this project concur with those of Cahoon et al. (2007) that conservative models of fish passage can be very desirable components of the design procedure as summarized in Appendix B, but should be used with caution in assessing existing culverts.

This project reported a very low probability that a given fish would successfully enter and pass all culverts in the system, even when each culvert along that path had shown to be passable. This approach considers all distractions from passing through the system, including motivation, availability of downstream spawning habitat, predation, mortality, culverts, natural barriers and a host of other issues. When examining the role of culverts exclusively in a stream system , it is recommended that the passage probability for each successive culvert be applied in series (multiplicatively). In the stream study reach, the distribution of tagged fish detected in the system was not uniform, even in the most downstream reach that had no identifiable barriers. This indicates that caution should be exercised when assuming that stream miles or spatial measures of habitat richness are of equal value regardless of position in the system when assessing the priority of a barrier for replacement or repair.

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Appendix A

Additional Photos of the Study Culverts

Figure A-1. Culvert 1 outlet. Note the stage recorder installed in the stilling basin on the right-hand side of the photo. The PIT tag antenna was not installed at the time the photo was taken.

Figure A-2. Culvert 2 outlet. Note the water undulating over the submerged baffles.

Figure A-3. Inside the barrel of culvert 3, looking upstream. Note the combined effect of baffles and infill of stream bed material on the water surface profile.

Figure A-4. Culvert 4, looking upstream from the plunge pool.

Figure A-5. The outlet and part of the plunge pool of culvert 5.

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Appendix B

A Basic Design Procedure for Fish Passage in Culverts

The following is a basic procedure for incorporating FishXing into culvert design taken from:

Cahoon, J. E., T. McMahon, L. Rosenthal, M. Blank and O. Stein. 2007. Warm water species fish passage in Eastern Montana culverts. FHWA/MT-07-009-8182.

1. Develop the annual hydrograph. This could be based on stream gauging, correlation with a gauged basin, or runoff estimates based on historic or synthetic rainfall. The hydrograph could be a static estimate using long term averages, or several hydrographs could be developed to better represent statistical variations in stream flow. Periods of no flow are certainly allowed in intermittent flow cases.

2. Determine the species that should be represented in the fish passage analysis. This may be based on economy of modeling effort. That is, multiple species may be deemed to have similar swimming abilities and mobility time periods, and could thus be represented by a single surrogate species. Or the selection of the model fish could be based on native versus non-native species, or overall abundance of certain species, or goals for reintroducing species that have been impaired. The size class should also be considered.

3. Examine the hydrograph and determine if there are critical time periods where passage is important. For example, some fish are known to have upstream mobility requirements for spawning activity that correspond to certain time periods or flow triggers.

4. Design the culvert to meet all goals other than fish passage using traditional means.

5. Take the design from step 4 and subject it to FishXing for a range of flows to identify the passage windows for each of the model fish selected in step 2.

6. Compare all of the passage windows from step 5 and create a composite window that has the highest allowable low flow and the lowest allowable high flow. This is the design window, and is also the most conservative passage window.

7. Superimpose the design window of step 6 onto the hydrograph of step 1. At this point there is some subjectivity. Does the design window cover a sufficient portion of the hydrograph? Does the design window indicate fish passage during the critical periods identified in step 3. If the design team concludes that the culvert is adequate, than the design proposed in step 4 is accepted. If not, the team should return to step 4 and alter the components of the design that are responsible for prohibiting passage according to FishXing (velocity, length, slope, outlet drop, etc.).

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