Title

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Abstract: Road crossings that utilize culverts on fish-bearing streams can impede fish passage in several ways. The most common impediments include large outlet drops, insufficient water depths, and excessive velocity. High velocities can act as passage barriers, especially for fish that migrate during high-flow periods of the year such as westslope cutthroat trout and Yellowstone cutthroat trout. We performed a basin-wide culvert study to investigate fish passage across a large basin in Montana. A second study (in progress) focused on the velocity component of fish passage.

Our basin-wide culvert study was performed in the Clearwater River drainage near Seeley Lake, Montana. Fish species included westslope cutthroat trout, brook trout, brown trout, and bull trout. We studied 46 culverts over a range of culvert types and characteristics. We used a tiered approach to assess fish passage: analysis with FishXing, upstream and downstream population sampling, and direct-passage assessment. Results from the FishXing model from analysis of all 46 culverts indicate 76 to 85 percent are barriers at low flow, depending on the selection of minimum water depth. The upstream and downstream population-sampling analysis of a subset of 21 culverts indicated little or no significant difference in population characteristics (upstream characteristics compared to downstream characteristics). The direct-passage analysis of a subset of 12 culverts indicated no passage restriction at four culverts, some degree of passage restriction at seven culverts, and no passage at one. Our direct-passage study results may suggest more passage is occurring at low flows than the other methods suggest.

The basin-wide study did not address passage issues during high flows. We have embarked on a second study (in progress) to assess this high flow passage with field sites at Mulherin creek, located near the north boundary of Yellowstone National Park. The site is an important spawning tributary for Yellowstone cutthroat trout and rainbow trout. We are using a combination of field studies and computational fluid dynamic (CFD) modeling to assess high-velocity fish passage over a range of flows. Field studies include fish monitoring and detailed velocity mapping using a traditional 1-D current meter and a 3-D acoustic Doppler velocimeter (ADV). We have chosen to monitor direct assessment of fish passage using Passive Integrated Transponder (PIT) tags in individual fish and fixed antennas placed at five culverts and throughout the system. Preliminary results indicate that inlet-velocity patterns can persist through the culvert barrel. Fish movement observations show use of the low-velocity region for passage even at high flows (average barrel velocities at the outlet up to 2.2 m/s) with passage restricted at times, even though areas of lower velocities exist.

Introduction

Over the years, much research has been done to evaluate the effect that culverts in fish-bearing streams may have on fish populations. The primary physical factors that impede fish passage are fairly well documented and include outlet drop, excessive velocity, and insufficient water depth (Baker and Votapka 1990; Votapka 1991; Fitch 1995; Stein and Tillinger 1996). Some important biological considerations include fish species, size of fish, condition of fish, life history requirements, and movement timing (MacPhee and Watts 1976; Baker and Votapka 1990; Bell 1991; Stein and Tillinger 1996). More recent research has shown the importance of providing passage for not only adult salmonids, but also juvenile salmonids. Kahler and Quinn (1998) performed a literature review to assess movement of juvenile and adult salmonids and concluded that movement was common among all species, age classes, and seasons.

Determining the barrier status of a culvert can pose some interesting challenges because of the dynamic nature of the setting, both from a physical and biological standpoint. Past research methods can be split into direct and indirect methods of assessing fish passage at culverts. Direct methods typically use some sort of fish-marking technique followed by observations of fish movements through culverts over a period of time and comparison to hydraulic conditions such as water velocity and depth (Belford and Gould 1989; Fitch 1995; Warren and Pardew 1998). Indirect methods include using comparisons of upstream and downstream fish population characteristics and/or hydraulic modeling (Riley 2003).

This paper focuses primarily on a basin-wide culvert study designed to assess fish passage across a large basin in Montana. In the basin-wide study, we used a tiered approach with three separate methods: 1-D hydraulic modeling, upstream and downstream fish population sampling and habitat assessment; and direct passage using a mark-recapture technique. Information about the study area, methods, and results are presented in the body of this paper. An introduction to the companion study in progress is included in Appendix A. The companion study is designed to investigate the velocity component of fish passage, with specific goals of comparing fish movement timing to detailed culvert-hydraulic conditions.

Study Area

The Clearwater River flows in a southerly direction to its confluence with the Blackfoot River, with the Swan Mountains to the east and the Mission Mountains to the west. Streams in the basin that have culverts are generally first or second order, medium to high gradient, with primarily cobble substrate. No culvert crossings are located on the main stem of the Clearwater River; however, there are two man-made barriers on the main stem above Seeley Lake and a third in the lower portion of the drainage. Figure 1 shows the location of the study drainage within Montana and the study culverts.

Only the portion of the Clearwater River drainage upstream of and flowing into Seeley Lake was included in this study. The studied drainage area is 370 km^2. The drainage is heavily forested with a combination of coniferous and deciduous trees. Past and present land-use activities have resulted in a fairly complex network of roads with culvert crossings primarily on the smaller tributaries to the Clearwater River. Land ownership is a mixture of national forest land, state land, and private land.

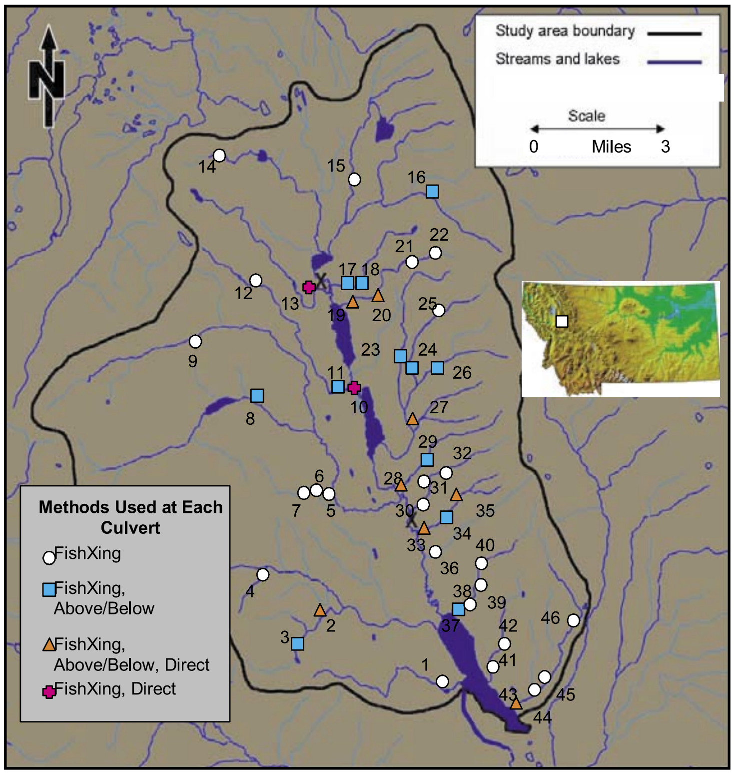

Figure 1. Map of Clearwater River drainage with locations of study culverts and methods used at each.

We specifically included all the trout detected in the basin in the study: westslope cutthroat trout (*Oncorhynchus clarki lewisi*), bull trout (*Salvelinus confluentus*), brook trout (*Salvelinus fontinalis*), and brown trout (*Salmo trutta*). Westslope cutthroat trout are a species of special concern in Montana (Carlson 2003) and bull trout are listed as endangered under the Endangered Species Act (Federal Register, June 10, 1998). Other species that we encountered during the study include slimy sculpin (*Cottus cognatus*) and brook stickleback (*Culaea inconstans*).

Methods

We used the FishXing model to assess passage concerns at all 46 crossings. At a subset of 21 culverts, we compared samples of upstream and downstream fish populations and riparian habitat characteristics. At another subset of 12 culverts, we used a mark-recapture-based protocol to directly observe fish passage through the culverts, as compared to passage through a control reach of a natural channel.

First, we identified and visited all culvert sites within the drainage and reduced the total number of study crossings to 46 by eliminating crossings we felt had little to no fisheries value based on the following criteria: (1) dry or intermittent as observed at the site; (2) discharge of less than 60 L/min; (3) sustained stream slope greater than 15 percent as measured on a 1:24,000 scale topographic map; or (4) no fish presence as determined by electrofishing.

Field data were collected from June through October 2002 and from July to October 2003. Field data collected at all 46 sites followed the protocol developed for passage assessment using the FishXing model (Clarkin et al. 2003) with some additional data collection. We surveyed the geometry of the culvert and the stream channel both upstream and downstream of the culvert using a total station. Key features surveyed include culvert slope, tailwater cross section, outlet drop, maximum pool depth, depth at jump location (estimated as the depth at 6 inches downstream of the culvert outlet invert), and upstream and downstream gradient. We collected substrate samples to determine the roughness characteristics of the channel and classified substrate into size ranges from silt to boulder, with identification of the dominant particle size.

FishXing is public-domain software that utilizes 1-D hydraulic calculations to estimate water depth and velocities in culverts and compares known fish swimming abilities to the modeled hydraulics. The software then assigns a passage status to the culvert. If a culvert is identified as a barrier, a code identifying the type of barrier is included as part of the output. Potential barrier codes include: excessive velocity (water velocity in the culvert exceeds swimming ability of the fish), insufficient depth (water depth in culvert less than designated minimum water depth), and leap (excessive leap height at outlet) (FishXing 1999). We analyzed all culvert sites with FishXing and separated the analysis into two categories: juvenile trout (rainbow trout with a length of 60 mm) and adult trout (cutthroat trout with a length of 150 mm). The size of the analysis fish was based on fish data collected during the upstream and downstream fish population-sampling events. The analysis discharge was measured at each site as part of the physical data collection. Discharge was measured in the stream channel near the culvert site using a Pygmy flow meter following a modified version of the USGS 0.6 depth method. The modeled discharge is comparable to base flow. We did assess higher flows at each crossing with FishXing; however, we didn't include them in this paper because the other methods were performed at base flow only.

We sampled fish upstream and downstream of 21 culverts to assess the degree to which culverts may have influenced fish species abundance, size structure (median length), and presence. Single-pass electrofishing in an upstream direction with a Smith-Root Model 15-D backpack electrofisher was used. Two samples were collected at each crossing: approximately 100 meters directly upstream and downstream of the culvert. All species captured were anesthetized, identified by species, and measured to the fork length.

The relative abundance of individual species was compared between upstream and downstream samples. A substantial difference in relative abundance indicates a twofold difference in the number of fish, with a minimum of five fish in the smaller sample. If one sample had less than five fish, the sample size was considered too small. Differences in median fish size between the upstream and downstream samples were assessed using a two-tailed Mann-Whitney test. We also pooled all trout by species upstream and downstream of the culvert sites and assessed the pooled differences using the same statistical method. Statistical results were significant if the p-value was ≤ 0.05.

Habitat characteristics such as wetted width, average depth, and maximum depth were measured in the upstream and downstream reaches following R1/R4 protocol (Overton et al. 1997) to evaluate the possibility that differences in relative abundance or median fish size might be attributable to differences in habitat characteristics. Mann-Whitney tests were used to assess differences in upstream and downstream habitat variables.

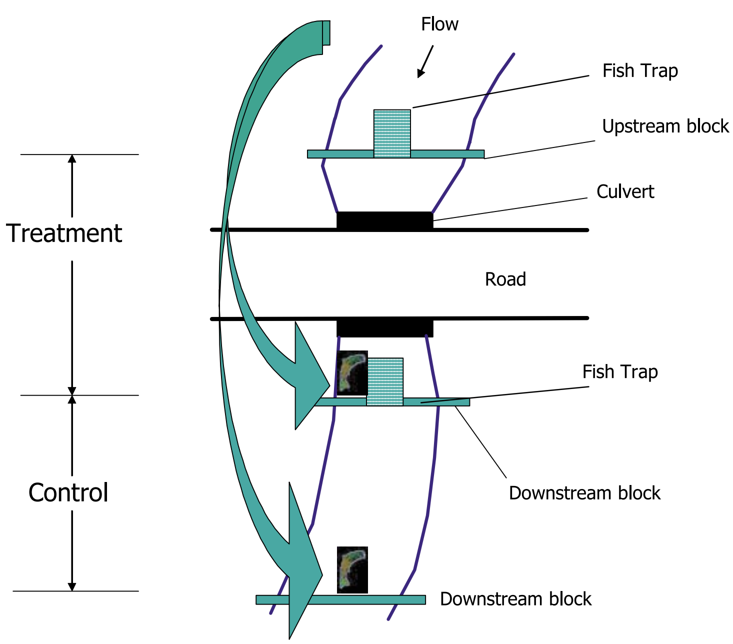

Figure 2. Diagram showing the experimental design for the direct-passage studies.

We used a mark-recapture scheme to directly assess fish passage at 12 culverts (figure 2). We divided the site into a treatment reach that included the culvert and a control reach in the natural channel. The area of the treatment reach, not including the culvert, was measured and used to determine the area for the control. The control reach was always located downstream of the treatment reach. Prior to initiating the experiment, we removed fish from both reaches by electrofishing. We then collected a sample of 40 to 50 fish well upstream of the experimental reach and separated them into two equal groups based on size and species. We placed wire mesh in the stream to block the experimental reaches at the upstream and downstream ends with a fish trap placed at the upstream end of each reach. We clipped the left pelvic fin of all control fish and the right pelvic fin of all treatment fish for re-identification. The fish were set free in the stream at the bottom of each reach. During each successive day for three days following the release, we collected discharge, inlet and outlet depths, and inlet and outlet velocities and recorded the number of marked and unmarked fish captured in each trap.

Several comparisons were made to analyze the direct-passage data. Figure 3 shows how we calculated the passage rate and passage indicator. We then used both simple and multiple linear regression to evaluate the effect of physical characteristics including culvert slope, outlet drop, culvert length, water depth, change in slope (between upstream channel slope and culvert slope), and constriction ratio on the passage indicator. The constriction ratio was calculated as the ratio of the culvert width to the average bankfull width. Mann-Whitney tests were used to assess whether the recaptured fish in the treatment had similar lengths to the recaptured fish in the control.

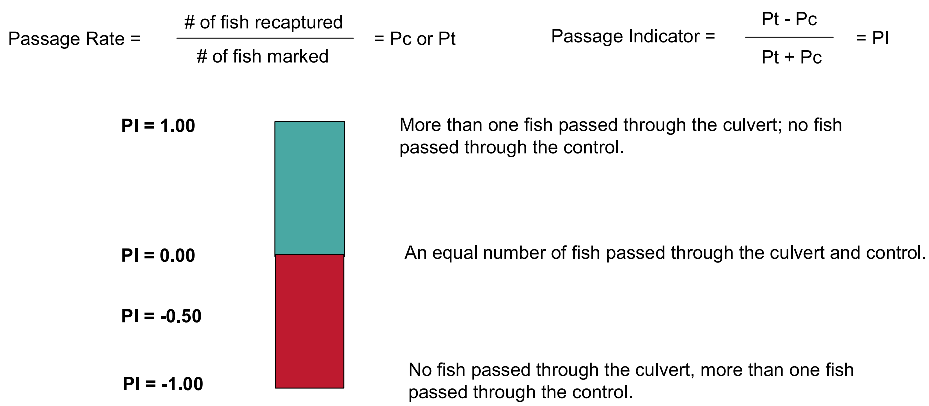

Figure 3. Diagram showing how the passage rate and passage indicator were calculated for each direct-passage study.

Results

Physical characteristics of the 46 culvert sites are listed in table 1. Culvert slopes ranged from an adverse slope of -0.9 to 16.6 percent with a mean of 4.3 percent. Outlet drops ranged from 0 cm to 64.3 cm with a mean of 11.6 cm. Culvert lengths ranged from 3.8 m to 28.6 m with a mean of 12.3 m. Constriction ratios ranged from 0.34 to 1.33 with a mean of 0.75. The study streams average bankfull widths ranged from 0.91 m to 4.54 m with a mean of 2 m.

FishXing identified 35 of the 46 culvert sites as barriers at low flow for adult fish. Figure 4 summarizes the type of barrier designation (insufficient depth, excessive leap, or water velocity). All 35 of the barrier culverts were identified as having insufficient water depth. It should be noted that some culverts were designated as having multiple types of barriers, insufficient depth, and excessive leap for instance. Six of the 11 culverts that were not identified as water-depth barriers simulate natural channel conditions. Therefore, these sites were considered passable at low flow. These sites were analyzed with FishXing by changing the settings to indicate the culvert was embedded and increasing the roughness to a value equivalent to the substrate size in the culvert. FishXing protocol recommends caution when analyzing culverts with substrate bottoms as the physics of 1-D hydraulics cannot account for irregular flow patterns that will exist as water moves over the irregular substrate surface. These irregularities provide reduced velocities and micro-eddies that the fish, especially juvenile fish, can utilize to pass. It is interesting to note that FishXing identified five of the six pipes with natural channel beds as barriers to adults because of insufficient water depth.

Table 1. Physical characteristics of all 46 culvert sites studied

Site	Continuous Substrate	Length (m)	Slope (%)	Outlet Drop Height (cm)	Constriction Ratio
1	N	9.4	1.5	12.2	1.15
2	N	10.7	3.4	6.1	0.55
3	N	10.9	2.0	0.0	1.33
4	N	12.6	7.1	6.1	0.56
5	N	12.5	3.3	53.3	0.37
6	N	16.9	16.6	2.1	0.34
7	N	9.9	10.6	14.3	0.56
8	N	9.4	2.1	3.0	0.86
9	N	11.2	6.0	36.6	0.59
10	N	12.4	0.9	9.1	0.70
11	N	10.5	1.3	0.0	0.48
12	N	8.6	2.9	49.4	0.66
13	N	10.9	3.9	15.2	0.45
14	N	11.2	2.1	30.5	0.44
15	Y	12.5	5.5	0.0	1.16
16	Y	12.1	0.8	0.0	0.89
17	N	26.4	1.3	0.0	1.11
18	N	9.3	4.9	0.0	0.92
19	N	28.6	2.4	0.0	0.89
20	N	11.8	4.4	0.0	1.20
21	N	7.6	1.1	18.3	0.62
22	N	9.5	5.6	5.5	0.66
23	Y	11.8	1.6	0.0	0.84
24	N	13.0	4.8	0.0	0.71
25	N	8.7	6.7	3.0	0.53
26	N	12.1	9.2	6.1	0.67
27	N	11.8	7.6	24.4	0.52
28	N	12.7	4.9	0.0	1.00
29	N	13.7	9.9	27.4	0.70
30	N	10.0	3.2	61.0	1.18
31	N	9.9	1.5	18.9	0.78
32	N	6.2	1.0	0.0	0.70
33	N	12.4	7.4	64.3	0.48
34	N	14.3	10.6	30.8	0.52
35	N	13.0	5.0	21.3	0.78
36	N	11.0	3.2	0.0	1.17
37	Y	8.1	-0.3	0.0	0.96
38	Y	14.6	5.7	0.0	0.86
39	Y	21.3	1.3	0.0	0.67
40	N	12.4	12.2	4.6	0.64
41	N	22.1	2.4	0.0	1.08
42	N	12.4	6.1	4.9	1.28
43	N	9.8	0.8	3.7	0.62
44	N	13.8	2.7	3.7	0.67
45	N	3.7	1.1	0.0	0.36
46	N	11.1	-0.9	0.0	0.77

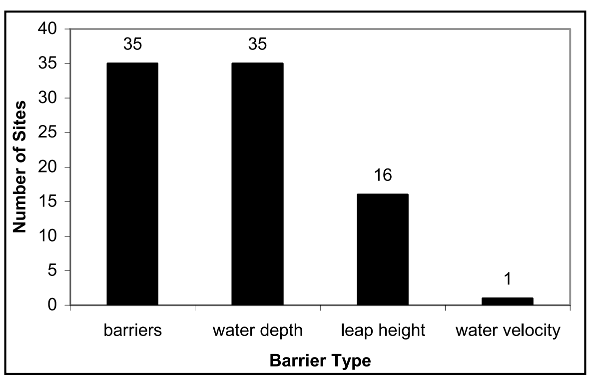

Figure 4. Barrier determinations for low flow adult fish analyses by FishXing. We used a minimum water depth of 3 cm for low flow based on size of adult fish, observed water depths in natural channels and conditions fish moved through without impedance as observed during direct passage experiments.

FishXing results indicate 35 of 46 culvert sites were barriers at low flow for juvenile fish. Figure 5 summarizes the barrier designation for these culverts. More velocity barriers were designated for juvenile fish compared to adult fish because smaller fish have weaker swimming abilities. FishXing identified two of the six pipes having a natural channel bed as barriers because of insufficient water depth. As before, we considered these crossings to be passable at low flow because they had met the natural channel-simulation criteria.

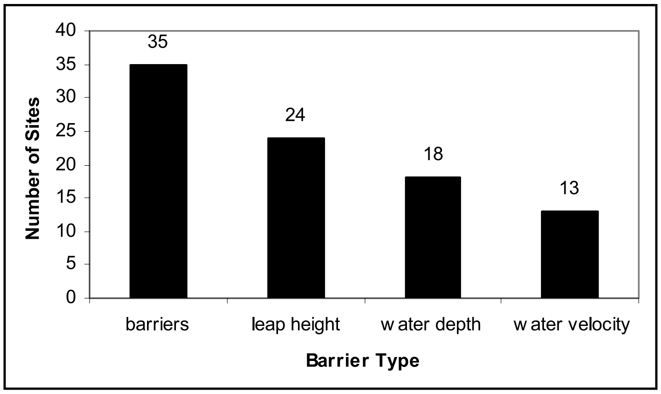

Figure 5. Bar chart showing the barrier determination for low flow, juvenile analyses by FishXing.

While sampling fish upstream and downstream of 21 culverts, we cataloged a total of 989 fish. Figure 6 presents the number of fish by species sampled downstream of all culverts. Figure 7 presents the number of fish by species sampled upstream of the culverts. Appendix B includes a table with numbers of fish by species captured upstream and downstream of the culverts. Brook trout ranged in length from 34 mm to 176 mm with a median length of 83 mm. Westslope cutthroat trout ranged in length from 26 mm to 203 mm with a median length of 89 mm. Bull trout ranged in length from 81 mm to 218 mm with a median length of 108 mm. Brown trout ranged in length from 110 mm to 142 mm with a median length of 127 mm.

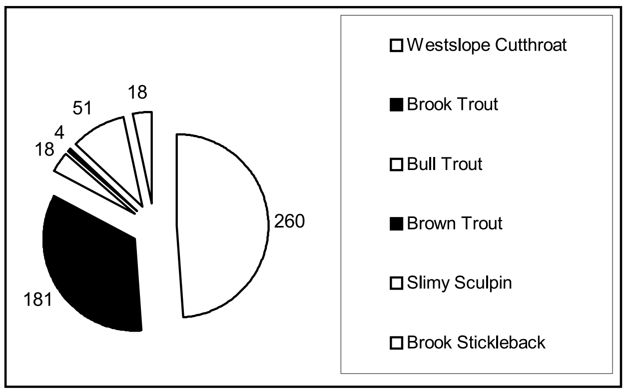

Figure 6. Number of fish by species collected downstream of culvert sites.

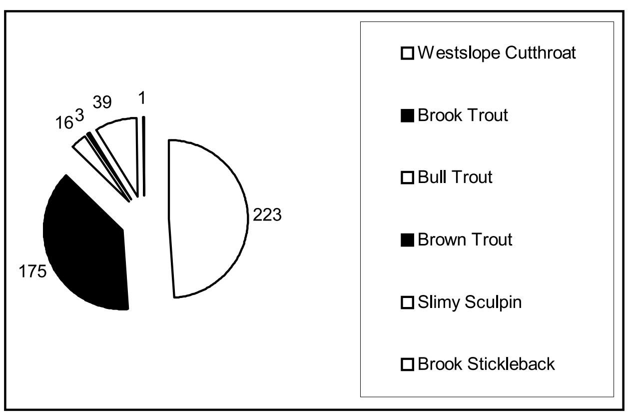

Figure 7. Number of fish by species collected upstream of culvert sites.

We compared the number and size of fish cataloged above the culvert to fish cataloged below the culvert at each site by trout species and for all trout combined. While there were occasional differences in count or size by species, there was no evidence to suggest that any species should be considered or examined separately from trout in general with respect to count or size in the upstream/downstream sampling. When considering all trout, there was only one site that had twice as many or more trout downstream of the culvert than upstream. On the average, there were 1.17 times as many trout detected downstream of the culvert than upstream. Two sites had significantly larger fish on one side of the culvert than the other. One site had larger fish downstream of the culvert, one site had larger fish upstream of the culvert, and the remaining 19 sites had similar-sized fish on either side of the culvert (Mann-Whitney, 95 percent confidence interval). Three of the 21 sites had different habitat designation on each side of the culvert.

The results of the direct passage trials were analyzed by species and for all trout at each culvert. Again, there was no evidence to maintain species differentiation, so the results we present here are for all trout combined. Overall, 172 of 283 fish were recaptured in the control (61 percent) and 101 of 283 fish were recaptured in the treatment reaches (36 percent). The average size of all fish recaptured in the control was 103 mm, compared to an average size of all fish recaptured in the treatment of 107 mm.

The direct-passage results are summarized in figures 8 and 9. Four of the sites had PI values greater than 0.00, indicating more fish moved through the treatment (culvert) than control (natural channel). Seven sites had PI values between 0.00 and -0.85, indicating more fish moved through the control than the treatment, but that fish did move through both sections, indicating that the culvert was not a total barrier to fish passage. One site had a PI value of -1.00, indicating no fish moved through the treatment and that fish did move through the control.

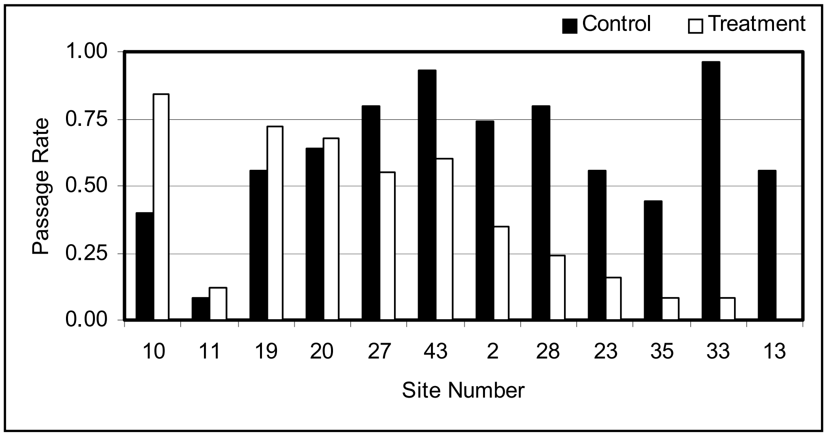

Figure 8. Passage rate for control and treatment by site number.

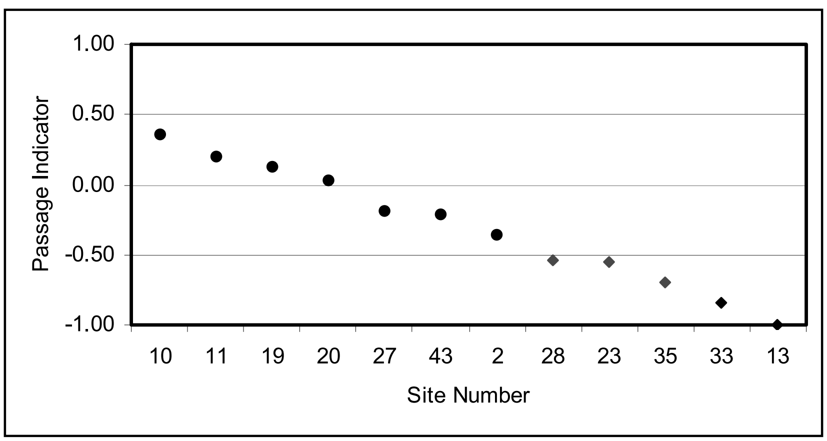

Figure 9. Passage indicator by site number.

Both simple linear regression and multiple linear regression were used to evaluate the effect of physical characteristics (slope, outlet drop, culvert length, water depth, change in slope, and constriction ratio) on the passage indicator. There were no significant relationships found at the 95 percent confidence level. The most significant relationship was found between the passage indicator and outlet height ($p = 0.095$). Figure 10 shows a plot of the passage indicator and outlet-drop height with the regression line ($R^2 = 0.2538$).

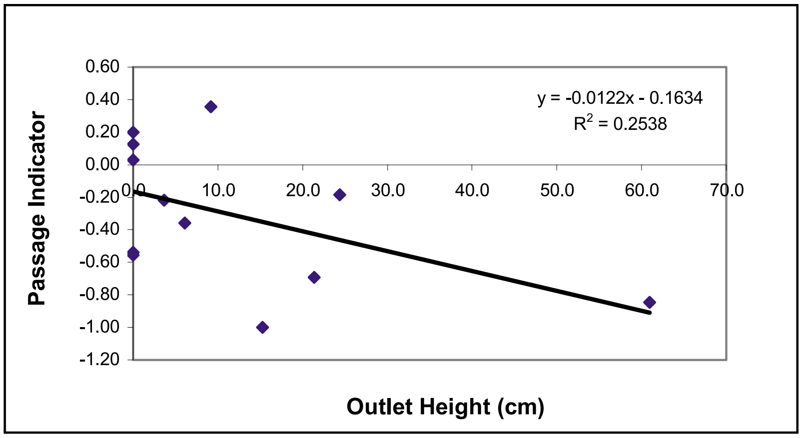

Figure 10. Relationship between passage indicator and outlet drop for all 12 direct passage sites (p = 0.095).

Discussion

Table 2 presents a comparison of the FishXing results and the direct passage results. Some physical data from each culvert is also included for comparison. One of the more interesting findings of this study is that, depending on the method used, different conclusions regarding the barrier status of a culvert may be reached.

Table 2. Comparison of FishXing results, direct passage results, and physical data. B = barrier, P = passable, l = excessive leap at outlet; d = insufficient water depth; v = water velocity exceeds swimming ability of fish; eb = water velocity in culvert causes fish to be exhausted at burst speed

	FishXing Results		Direct Passage Results	Physical Data				
Site Identification	Adult	Juvenile	Passage Indicator	Slope (%)	Outlet Drop (cm)	Substrate (yes/no)	Length (m)	Constriction Ratio
2	B(d)	B(l)	-0.36	3.4	6.1	no	10.7	0.55
10	B(d)	B(l)	0.35	0.9	9.1	no	12.4	0.70
11	B(d)	P	0.20	1.3	0.0	no	10.5	0.48
13	B(l,d,eb)	B(l,v)	-1.00	3.9	15.2	no	10.9	0.45
19	B(d)	B(d)	0.13	2.4	0.0	no	28.6	0.89
20	B(d)	B(v)	0.03	4.4	0.0	no	11.8	1.20
23	P	P	-0.56	1.6	0.0	yes	11.8	0.84
27	B(l,d)	B(l)	-0.19	7.6	24.4	no	11.8	0.52
28	B(d)	B(d)	-0.54	4.9	0.0	no	12.7	1.00
33	B(l,d)	B(l,d)	-0.85	7.4	64.3	no	12.4	0.48
35	B(l,d)	B(l,v)	-0.69	5	21.3	no	13.0	0.78
43	B(d)	B(l,d,eb)	-0.22	0.8	3.7	no	9.8	0.62

For example, site 10 had a passage indicator of 0.35, but was identified by FishXing as a barrier to both adult and juvenile fish. On the other hand, site 23 had a passage indicator of -0.56, but was identified as passable to both adult and juvenile fish by FishXing. The direct passage results do indicate that fish moved through culverts at low flow; however, these results also show that culverts are limiting the movement in some pipes (seven of 12 studies) and (in one case) the culvert may be a total barrier (site 13), though further study at higher flows would need to be done to gain confidence in identifying this culvert as a total barrier.

Varying the minimum water depth from 3 cm to 9 cm did not have a large effect on the number of barriers identified for adult fish by FishXing. With the minimum depth set at 9 cm, 39 of 46 culverts were deemed a barrier, compared to using a minimum depth of 3 cm, which resulted in 35 of 46 culverts identified as barriers. An accurate representation of the setting (both from a physical and biological standpoint) of the culvert crossing is very important when utilizing an indirect approach such as FishXing. For example, utilizing a minimum water depth of 3 cm may seem ridiculous at first glance. When you consider that many streams had depths in riffles of only 3 cm, the size of the adult fish in the study basin (median length for adult cutthroat was 87 mm), and the direct passage studies show adult fish passing unimpeded through 3 cm of water the use of this shallow of a minimum depth may be appropriate for the setting.

A study recently completed in Alaska designed to assess a culvert barrier-assessment protocol that includes use of the FishXing software identified the need to represent the hydraulics and hydrology of the setting accurately; otherwise, a conservative bias can be added to the passage status of a culvert (Karle 2005). As an example from this study, the researcher found that accurate calibration of the FishXing software using field-measured water depths corresponding to a measured flow rate improved the accuracy of the model. The uncalibrated model identified the culvert as a barrier for the entire period of analysis, which covered 1510 days. The calibrated model reduced the number of days the culvert was deemed a barrier to 173 days.

The data from the upstream and downstream sampling does not provide much information with regards to the barrier status of the culverts in this study. In almost all cases, the fish count, size, and habitat indicators were similar on either side of the culvert. This does not mean the culvert is passable or impassable as these fish could have been above the crossing prior to installation of the culvert and there may be sufficient habitat to sustain a population above the crossing, or the culverts may be partial barriers that allow fish movement at some flows. Other studies have found more success using comparison of fish characteristics upstream and downstream of culverts as a means of assessing culvert barriers (Riley 2003). In the case of the Riley studies, many of the fish were anadromous salmonids and the life-history requirements of these fish are very different than those in the Clearwater drainage. The different life-history requirements of anadromous salmonids, such as the relatively small amount of time they spend in freshwater compared to resident species, may account for the success in using this method to assess passage. The upstream/downstream population characteristics method may have proven more useful in our study for assessing barrier status if it were performed during periods of the year when fish were migrating to spawning locations.

This study is limited by the fact that no field tests were performed during high-flow periods of the year. The primary reason this was not done is the difficulty presented by collecting representative samples of fish during the high water periods of the year in this area, and to a lesser extent the difficulty in accessing some sites during the runoff season. The highest flows of the year in this drainage are typically related to spring snowmelt runoff which occurs in May or June. The companion study discussed in Appendix A is designed to investigate fish-passage issues at a range of flows, including spring runoff.

Conclusions

We found that some culverts limited passage in the drainage even during low flow and, in at least one case, the culvert seemed to act as a low-flow total barrier. However, we also found that more passage is occurring than might have been previously thought. FishXing results compared to the direct passage results indicate that the program can be a conservative estimator of fish passage at culverts during low flow. This finding points to the need for better representation of the hydraulics in the culvert, with emphasis on the distribution of velocities and linking the stream to the culvert. It also points to the need for more study of fish swimming abilities, especially with regards to leaping behavior. For example, fish may have utilized the upwelling currents in the plunge pool to surmount fairly high leap heights, a behavior not unlike that observed by Stuart (1962).

In general, the upstream and downstream population sampling was not very useful for identifying the barrier status of a culvert. It would be interesting to run several upstream and downstream studies at the same culvert over a range of flows to investigate temporal patterns in the abundance, size structure, and fish compositions.

Care must be taken when applying only one technique to assess the barrier status of a culvert. If FishXing identifies a culvert as passable, we found it to likely be passable, so no further study is warranted. If FishXing identifies a culvert as a barrier, further study utilizing a more-intensive field investigation may be warranted to refine the barrier status.

As a final point, it is very important to accurately represent the setting, both physically and biologically, when analyzing culverts with any method.

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Biographical Sketch: Matt Blank received a B.S. in geological engineering from the University of Wisconsin-Madison in 1994 and a M.S. in civil engineering from Montana State University in 2002. He is presently a Ph.D. candidate in civil engineering at Montana State University specializing in hydraulics, hydrology, and fish passage. After receiving his B.S., he spent several years doing environmental consulting work based out of Anchorage, Alaska. He specialized in contaminated site assessment and remediation, groundwater-quality studies, and site characterization. His current research interests involve fish passage, hydraulic modeling, and analysis of aquatic impacts of roads and road-maintenance activities.

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Appendix A. Studies in Progress

Study location

We selected Mulherin creek located near Gardiner, Montana as the study drainage for the velocity study (figure 1A). Mulherin creek is a tributary of the Yellowstone river. It is a fairly high gradient stream, with an average gradient from the headwaters to the mouth of 11.6 percent, and gradients of 2 to 5 percent through the study reach. Large substrate, primarily cobble and boulder, dominates the drainage, with some bedrock control in the vicinity of the study reach. The stream has base flows around 0.3 cms with a flow of 2.7 cms as measured in June 1983 (USGS 1986). Average bank full width is approximately 6 m. The stream has low sinuosity through most of the study reach.

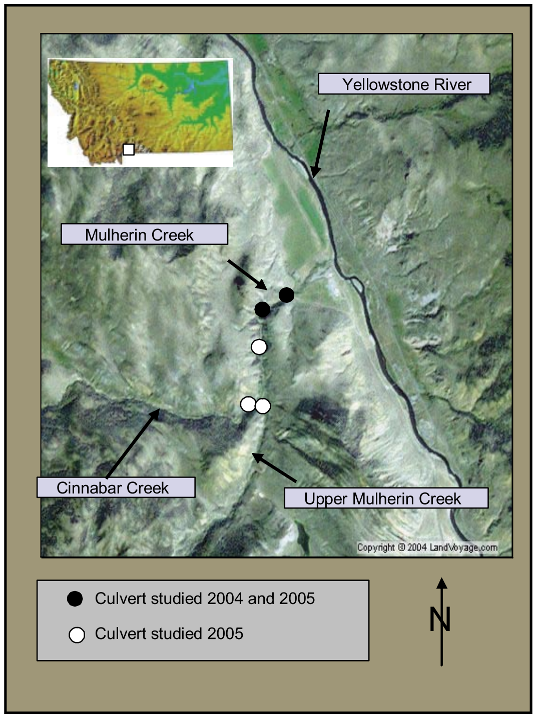

Figure 1A. Map of Mulherin Creek drainage with locations of study culverts.

There are a series of five culverts in the lower drainage, with three on the main stem of the creek and two directly above the confluence of Upper Mulherin Creek and Cinnabar Creek. These culverts present a nice range of physical characteristics and passage conditions. Table 1A summarizes key physical information for the culverts. Only culvert 1 and 2 were studied in 2004, with the other three culverts added to the study in 2005.

Mulherin creek has resident and migratory trout species, including rainbow trout (*Oncorhynchus mykiss*), Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*), and brown trout (*Salmo trutta*) . Yellowstone cutthroat trout are a species of special concern in Montana (Carlson 2003). Mulherin creek is a major spawning tributary for trout living in the Yellowstone river.

Table 1A. Summary of physical characteristics of culverts in the velocity study

Culvert ID	Shape	Width (m)	Height (m)	Diameter (m)	Length (m)	Internal Structure	Slope (%)	Outlet Drop (cm)	Constriction Ratio
Culvert 1	box	3.7	2.0	-	11.4	none	2.0	48.8	0.57
Culvert 2	box	3.7	1.8	-	9.6	concrete baffles	0.8	47.9	0.57
Culvert 3	box	3.7	1.8	-	9.7	concrete baffles with substrate	1	18.3	0.56
Culvert 4	circular	-	-	2.1	9.1	none	1.1	46..6	0.44
Culvert 5	circular	-	-	1.8 to 2.1 (pipe changes diameter)	10.9	none.	6.6	54.9	0.44

Figure 2A. The outlet of culvert 1, a box pipe (l), and the outlet of culvert 4 (r).

Methods

Stage-discharge relationships for Lower Mulherin Creek, Upper Mulherin Creek, and Cinnabar Creek were developed using stilling wells with Trutrack data recorders. A minimum of 10 discharge measurements following the USGS 0.6 method near each gauge location were collected at various points in the hydrograph for establishment of the stage-discharge relationship. Power regression was used to fit an equation of flow as a function of stage. Water temperature was collected using the TruTrack data recorder.

Inlet and outlet depths in the culverts were measured at various flows. Depths were collected from a series of staff gauges installed in all four corners of culvert 1 and culvert 2. Depths were measured using a graduated rod at culverts 3, 4, and 5.

Velocity data were collected as sets in culvert 1 and culvert 2 with the aid of a trolley system. Figure 3A shows the Acoustic Doppler Velocimeter (ADV) collecting data in culvert 2. The trolley system allows for an absolute minimum of flow disturbance as the instrument is the only object to penetrate the flow field. These sets comprised combinations of inlet-velocity profiles and plan-view profiles. Velocity measurements were collected using both a pygmy current meter and an ADV. The pygmy current meter was set to collect average velocities at 30-second averaging periods. The ADV was set to sample at 25 Hz for a minimum of 1 minute. The ADV collects velocities in three directions: x, y, and z. The high frequency of the ADV allows for some estimation of point turbulence. The density of point-velocity measurements varied according to the dynamics of the flow in the culverts. During periods of fluctuating flow, as experienced on the rising and falling limbs of the spring runoff hydrograph, data sets were collected in less than 6 hours. Late in the summer, when flows were more stable, data sets were collected over a period of time that ranged up to two days. A typical inlet-velocity profile would include data collected at every 15-cm horizontal and 3-cm vertical. Plan-view velocity data sets were typically collected at a height of 6 cm above the culvert bed, with horizontal spacing of 15 cm and longitudinal spacing of 1.5 m.

Figure 3A. ADV harness in culvert 2 inlet region.

Idaho weirs with fish traps were used to collect fish. During 2004, alphanumeric visual implant (VI) tags were implanted in fish. Three sets of weirs and traps were used: one near the mouth of the stream, one below the culvert, and one above the culvert. Traps upstream of the initial marking location were used to recapture fish to assess their movement timing. Traps were checked daily at a minimum from early May to mid-July. This method was not very efficient for recapturing fish. Additional funding became available between 2004 and 2005; therefore, we switched the fish-monitoring method to PIT tagging with antennae.

During the 2005 field season, PIT tags were implanted in fish as they migrated from the Yellowstone river. An Idaho weir with a fish trap was used initially to capture the fish. Antennae readers were placed at each of the five culvert crossings, with a minimum of one antennae at the culvert outlet and a second antennae at the culvert inlet. This configuration will allow us to identify the exact time a fish attempted to pass a culvert, the number of attempts, the time it took to swim through the culvert, and the number of attempts to pass successfully. The movement-timing data will be compared to detailed velocity maps prepared from a combination of field-data collection and computer modeling.

Preliminary results from 2004

An inlet velocity profile collected with the ADV on August 8, 2004 at culvert 1 is shown in figure 4A. The figure shows the x-, y-, and z-components of velocity at points in a cross section located at the upstream inlet of culvert 1. Figure 4A also shows the turbulent kinetic energy (TKE) at that cross section. Figure 5A shows a plan view of velocity contours collected August 9, 2004 in culvert 1.

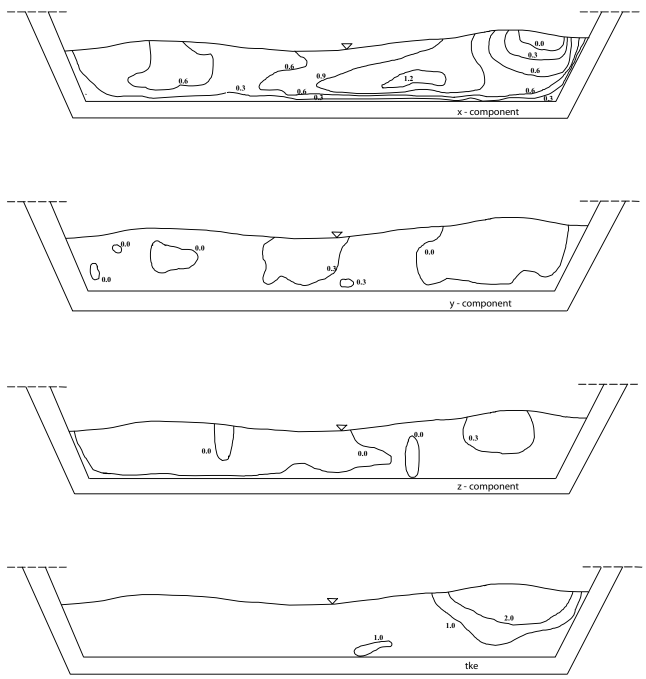

Figure 4A. x-, y-, and z-velocity components and tke contours at inlet of culvert 1 collected on August 8, 2004. Discharge during measurement averaged 0.85 m/s. Velocity contours are in m/s. Note: Only bottom portion of culvert is shown; dashed lines on sides are breaks.

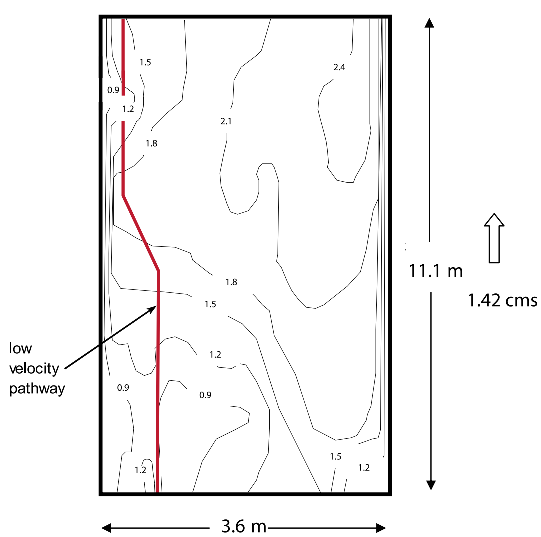

Figure 5A. August 9, 2004 plan view of x-velocity in culvert 1 collected with Pygmy meter. Velocity contours are in m/s. Measurements collected at 6 cm above the culvert bed.

The plan-view data show the development of a low-velocity region along the left wall of the culvert. This low-velocity region is created by the skew of the culvert with the natural stream alignment and roughness elements, consisting of boulders and a log just upstream of the culvert inlet. Fish-movement observations verified use of the low-velocity region for passage through this culvert even at high flows (average barrel velocities at the outlet up to 2.2 m/s), with passage restricted at times, even though areas of lower velocities exist.

A total of 390 fish were captured and cataloged during the course of the 2004 fish collection portion of the project. The predominant species collected was Yellowstone cutthroat trout, at a total of 339. Figure 6A compares the average daily flow observed during the period from May 1 to August 31, 2004 against the number of YCT captured. The fish were observed to enter in mass during the falling limb of the hydrograph when water temperatures consistently reached 12° C during the afternoon hours.

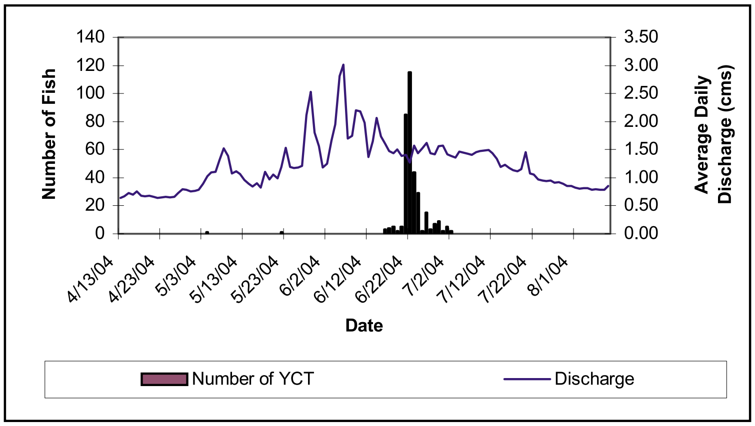

Figure 6A. Average daily flow compared to number of YCT captured, summer 2004.

A total of 91 leaping attempts were observed between June 16 and July 6, 2004 at culvert 1. Of these, 34 were successful in leaping into the culvert barrel and 18 were successful in passing through the culvert. Figure 7A presents a summary of the leaping observations. The fish behavior in the outlet pool was similar to observations made at waterfalls in England (Stuart 1962). Often, a fish was observed breaking the surface with just its head at the plunge of the free overfall, as if it were visually assessing the size of the leap. Leap attempts seemed to intensify over time. The first leap often was unsuccessful because the fish did not leap high enough to clear the free overfall. Subsequent leaps were higher and stronger. Once inside the culvert barrel, fish typically swam upstream and towards the left side of the culvert, using the lower velocity zones mentioned earlier.

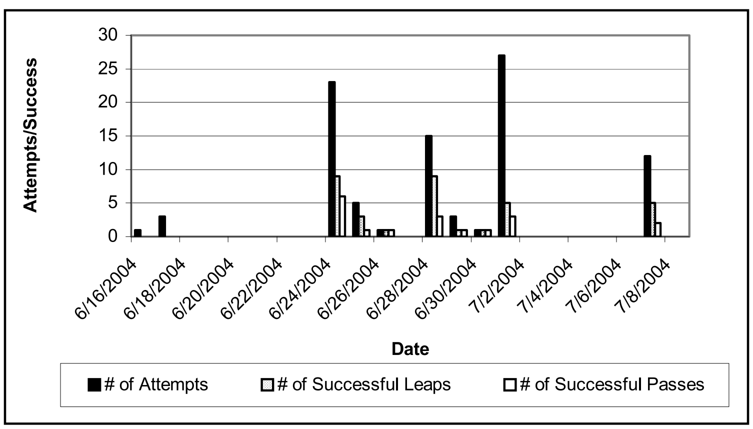

Figure 7A. Summary of leaping observations at culvert 1, 2004 field season.

Work in progress

A 3-D computer model is under development for simulating velocity patterns in the culverts studied at Mulherin Creek. The velocity maps shown above are used for model calibration and validation. The measured and modeled velocity data (1-D and 3-D) will be compared to fish movement data from the trapping and PIT tagging experiments. In addition, we plan to use the modeling to explore how far inlet-velocity patterns created by stream geometry will propagate through a culvert before they become muted by the culvert geometry.

Appendix B. Summary table of Upstream/Downstream Sampling in Clearwater drainage

Ct = cutthroat trout, Bk = brook trout, Bl = bull trout, Br = brown trout, Ss = slimy sculpin, Bs = brook stickleback

Site Number	Species	Number Downstream	Number Upstream
2	Ct	17	21
	Ss	30	7
	Bl	0	1
	Bk	0	2
3	Ct	6	9
8	Ct	1	0
	Bk	19	21
11	Ct	5	4
	Bk	36	38
16	Ct	1	2
	Bl	10	12
17	Ct	13	14
	Bk	12	10
	Bs	14	1
18	Ct	26	20
	Bk	12	5
19	Ct	27	26
	Bk	0	4
20	Ct	27	31
	Bk	0	1
23	Ct	3	0
	Bk	32	32
24	Ct	20	12
26	Ct	15	4
27	Ct	26	18
	Bk	6	4
28	Ct	9	9
	Bk	10	2
29	Ct	8	6
30	Ct	13	13
	Bl	7	1
	Bk	6	25
	Br	4	0
31	Ct	13	13
	Bl	1	2
	Bk	25	9
	Br	0	3
35	Ct	26	14
	Bk	11	5
37	Ct	4	7
43	Bk	12	17
	Ct	0	1
	Ss	21	32
	Bs	4	0