

AN ASSESSMENT OF CULVERTS OF FISH PASSAGE BARRIERS IN A
MONTANA DRAINAGE USING A MULTI-TIERED APPROACH

by

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ABSTRACT

Restriction or blockage of fish movement due to culverts may have important consequences to fish populations. Problems include the direct loss of critical upstream habitats, and the loss of connectivity with neighboring populations; however, culvert barriers may also serve to protect native species from nonnative species encroachment. Culverts can impede fish movement due to high water velocities, inadequate water depths, and excessive outfall heights among other factors. Most previous studies have focused on fish passage at only a few culverts and thus the extent to which culverts impede fish passage across large drainage basins is largely unknown. In this study, a multi-tiered approach was used to assess fish passage through culverts throughout the upper Clearwater River drainage, Montana. The FishXing software program was used to assess juvenile and adult fish passage at 46 culverts across a wide range of stream discharge. At a subset of 20 culverts, population sampling upstream and downstream of each culvert at low flow was used to determine the degree to which culverts are influencing relative abundance, size structure, and species presence. At a further subset of 10 sites, passage was measured directly at low flow by monitoring the movement of marked fish through culverts with differing physical characteristics. FishXing results indicated that 76-85% of the culverts were barriers, depending on the streamflow and lifestage assessed. The population sampling results indicated that there were only a few differences in relative abundance or size structure at the culverts sampled at low flow, and there was little evidence to suggest that species presence was different below versus above the culverts. The direct passage study results showed that some passage occurred at 90% of the culverts studied at low flow. However, 7 of the 10 culverts showed some degree of passage impedance. There was a moderately significant positive relationship between passage impedance and outlet height ($r^2 = 0.41$, $P = 0.047$). In summary, the culverts were restricting passage to upstream habitats that may be important for spawning, growth, and survival, but they were generally not isolating populations nor serving as barriers to protect native species from non-native species encroachment.

INTRODUCTION

Providing adequate fish passage through culverts has been a topic of growing concern for fisheries biologists, engineers, and hydrologists over the last decade (Baker and Votapka 1990; Votapka 1991). The movement of fish throughout a watershed is vital for a number of life history requirements (Baker and Votapka 1990, Votapka 1991; Rieman and McIntyre 1993; Robison et al. 1999), and maintaining migratory corridors is critical for the stability and persistence of fish populations (Rieman and McIntyre 1993, 1995).

Restriction or blockage of fish movement from culverts may have important consequences to fish populations. The most obvious problems are associated with the direct loss of habitat upstream of the barrier, which is often critical for spawning and other seasonal habitat requirements. Less obvious are the problems related to habitat fragmentation and the isolation of populations. Loss of connectivity with neighboring populations due to migratory barriers has been recognized as an important factor influencing local extirpation (Winston et al. 1991; Schrank et al. 2001; Morita and Yamamoto 2002), yet the extent to which culverts fragment populations is largely unknown. Conversely, culverts may also serve as barriers to interchange between native and nonnative species and thereby serve to protect native species from nonnative species encroachment (Thompson and Rahel 1998; Kruse et al. 2001; Novinger and Rahel 2003).

Previous culvert research has focused primarily on the blocking or delaying of upstream spawning runs of large migratory adult salmonids (MacPhee and Watts 1976; Belford and Gould 1989). However, recent information suggests that spawning and non-

spawning movements of smaller salmonid and nonsalmonid species may be much more prevalent and extensive than previously thought. For example, in a literature review conducted to determine the state of knowledge on the movement and passage of juvenile and adult salmonids through culverts, Kahler and Quinn (1998) concluded that upstream movement was common among all species, age classes, and seasons. Thus, movement of all species and life stages must be considered in developing and evaluating culvert passage design criteria.

High water velocities, inadequate water depths, and excessive outfall heights are recognized as the main features of culverts that impede or block fish passage (Baker and Votapka 1990, Votapka 1991; Bates et al. 1999; ODF 2000). Because these hydraulic conditions differ markedly with discharge, it is important to consider the full range of hydrologic conditions that may occur during the course of the year when assessing fish passage conditions. For example, at high flows, excessive water velocities within the culvert may impede upstream movement, whereas at low flow, inadequate water depth or high outfall height may restrict passage. Other physical factors that may influence fish passage include: inlet drops (Baker and Votapka 1990; Votapka 1991; Fitch 1995; Robison et al. 1999), plunge pool conditions (i.e., air entrainment and pool depth), turbulence within the culvert (Bates et al. 1999), ice or debris blockage (Baker and Votapka 1990), lack of resting pools downstream or upstream (ODF 2000), and culvert alignment relative to the stream channel (Votapka 1991).

The swimming and jumping abilities of fish in relation to the aforementioned physical factors interact to determine the ability of a fish to pass upstream through a culvert. Fish species and size are the primary controllers of swimming and jumping

ability, but other factors such as water temperature, dissolved oxygen, motivation to move upstream, sex, physical condition, disease, and sexual maturity (MacPhee and Watts 1976; Baker and Votapka 1990; Bell 1991) are also involved. Most research to date has focused on the capabilities of large-bodied salmon and trout, and little is known about the swimming and jumping abilities of nonsalmonid fishes and of juvenile and small-bodied resident salmonids. As a result, the accuracy of fish passage models incorporating these abilities is unknown.

A number of different approaches have been used to investigate fish passage through culverts, each with distinct advantages and limitations. Direct approaches monitor movement of marked fish through culverts and relate passage ability to culvert hydraulics and fish species and size (Belford and Gould 1989; Fitch 1995; Warren and Pardew 1998; Kane et al. 2000). This type of approach is successful at determining both the passage status of the culvert and the passage capabilities of the species of interest, but it is labor intensive and therefore only practical for assessing a small number of culverts over a short period of time.

Indirect approaches to assess fish passage generally focus on either the physical conditions around and within the culvert or on fish population characteristics at the culvert site. FishXing (www.stream.fs.fed.us/fishxing/) is a widely used software program that combines culvert characteristics (slope, length, roughness, etc.) and stream discharge to model the hydraulic conditions in and near the culvert. The hydraulic conditions are then compared with the swimming and jumping abilities of fish to assess the passage status. However, the limited knowledge regarding the swimming and jumping abilities of many species and size classes potentially limits the accuracy and

applicability of the model. Although this type of hydraulic modeling may be useful for assessing a large number of culverts with a relatively small amount of field data collection, a thorough review of the literature has revealed that the accuracy of this method for predicting fish passage has not been extensively evaluated.

Comparison of fish population characteristics downstream and upstream of culverts can also be used as an indirect approach to evaluate fish passage (USFWS 2002). For example, population surveys performed upstream and downstream of a perched culvert indicated that cutthroat trout (*Oncorhynchus clarki*) density was 64% lower upstream than downstream (64.9 fish/30 m vs. 23.2 fish/30 m) and the size structure was skewed to a higher proportion of larger fish downstream of the culvert, suggesting that it was functioning as at least a partial barrier to upstream movement (USFWS 2002). Natural and man-made barriers are known to limit the upstream distribution of fish (Winston et al. 1991, Bryant et. al. 1999, Kruse et al. 2001, Schrank et al. 2001, Morita and Yamamoto 2002), thus species absence above a culvert may also imply that the culvert is a barrier to upstream passage. This “upstream and downstream” approach can therefore provide potentially valuable information about how culverts affect the abundance, size structure, and distribution of fish populations.

Most previous studies have focused on fish passage at only a few culverts and thus the extent to which culverts impede fish passage across large drainage basins is largely unknown. A comprehensive assessment of culverts is necessary in order to prioritize sites for maximizing fish passage improvement. In this study, I used a multi-tiered approach, combining both indirect assessment (hydraulic modeling, fish population characteristics downstream and upstream of culverts), and direct assessment (passage of

marked fish through culverts of varying physical characteristics) to assess fish passage at culverts throughout a large drainage basin. The three methods used to assess fish passage in the multi-tiered approach were compared to determine if similar results were obtained from the different methods.

STUDY AREA

The study area consisted of all the streams in the upper Clearwater River drainage, defined for this study by the area upstream of the Seeley Lake outlet (Figure 1). This area was chosen as the study location due to the large number of culverts of different types located throughout the watershed, varied land ownership and road types, a diverse fish assemblage, and an array of stream types and sizes. The watershed is located in northwestern Montana and encompasses approximately 370 square kilometers of private, federal, and state lands. The basin is bordered by the Swan Mountains on the east and the Mission Mountains to the west, both comprised of mainly carbonate sedimentary rocks. The valley and mountains were both heavily glaciated during the Quaternary period and subsequently glacial till and stream deposits are found extensively throughout the drainage.

The Clearwater River flows 47 kilometers in a southerly direction through a series of 8 lakes to the confluence with the Blackfoot River. There are two large manmade fish barriers on the Clearwater River (Figure 1) that were installed to limit the distribution of exotic species that were introduced into the lakes. Consequently, they block the upstream movement of all species. Large, low gradient streams characterize the lower reaches in the valley bottom with bridges comprising nearly all of the road crossings. Ascending from the valley floor, the middle and upper reaches are characterized by small, high gradient streams that are crossed repeatedly by timber harvest and forest access roads. A

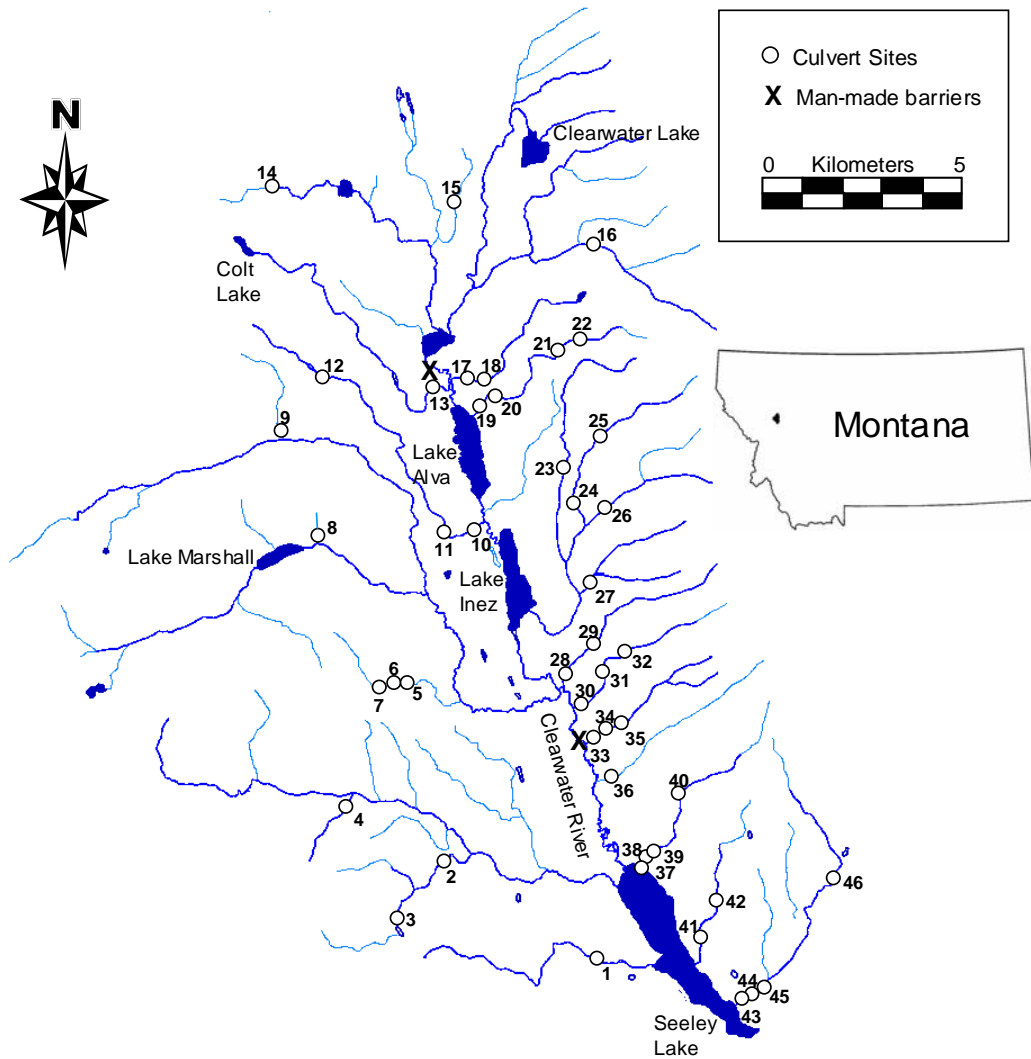


Figure 1. Map of the upper Clearwater River basin from the headwaters down to Seeley Lake outlet showing locations of all culvert sites studied and man-made barriers.

large proportion of these upper crossings are in the form of culverts, and bridges and fords are rare.

The fish assemblage in the Clearwater River drainage is comprised of approximately 20 different species of fish. Many of these species have been introduced into the low elevation lakes and the main stem of the Clearwater River for recreational

purposes. Native species that were encountered during this study were westslope cutthroat trout (*Oncorhynchus clarki lewisi*), bull trout (*Salvelinus confluentus*), and slimy sculpin (*Cottus cognatus*). Non-native species encountered were brook trout (*Salvelinus fontinalis*), brown trout (*Salmo trutta*), and brook stickleback (*Culaea inconstans*). Of particular concern regarding passage through culverts are the native bull trout and westslope cutthroat trout (Shane Hendrickson, Lolo National Forest, Missoula, Montana, personal communication). The bull trout is listed by the U.S. Fish and Wildlife Service as threatened under the Endangered Species Act (Federal Register, June 10, 1998) and the westslope cutthroat trout is classified as a Species of Special Concern in the state of Montana (Carlson 2003).

METHODS

A multi-tiered approach was used to assess fish passage through culverts throughout the entire upper Clearwater River basin. The FishXing software program was used to assess juvenile and adult fish passage at 46 culverts throughout the study area across a wide range of stream discharge. At a subset of 20 culverts, population sampling upstream and downstream of each culvert at low flow was used to determine the degree to which culverts were influencing relative abundance, size structure, and species presence. At a further subset of 10 sites, passage was measured directly at low flow by monitoring the movement of marked fish through culverts with differing physical characteristics. Results of the population sampling and direct passage assessment were then compared to the fish passage status as determined by the FishXing model.

FishXing Assessment

The FishXing software program was used to maximize the number of culverts for passage assessment, to evaluate the passage status for both juveniles and adults, and to assess the passage status over a wide range of stream discharge. In addition, model outputs were used to estimate the amount of potentially inaccessible stream habitat blocked by impassable culverts.

All culverts in the study area were surveyed and assessed for passage except those on streams that were judged to have little or no fisheries value based on the following criteria: (1) dry or intermittent stream as observed at the site; (2) discharge of less than 60

L/min; (3) sustained stream slope greater than 15% as measured on a 1:24,000 scale USGS topographic map; or (4) no fish presence as determined by electrofishing.

Field data collection was conducted at 27 sites from June through October 2002 and at 19 sites from July to October 2003 for a total of 46 sites (Figure 1) following a protocol developed for passage assessment using the FishXing model (Clarkin et al. 2003). Each site was assigned a unique stream crossing identification number and its location was recorded using a hand-held global positioning unit (Appendix A). For each culvert, the shape, dimensions, material, corrugation size, and inlet and outlet configuration were recorded. Substrate particle size upstream, downstream, and within the culvert was visually observed and ranked according to the first three substrate sizes that occupy the greatest area (1 = highest, 3 = lowest) to estimate channel roughness. Bankfull channel widths were measured at 5 randomly spaced locations over 30 m reaches both upstream and downstream of each culvert. A total station survey instrument was used to determine culvert slope and length, channel gradient upstream and downstream, outlet drop height (vertical distance from the invert of the culvert outlet to the water surface below) and plunge pool depth, and the tailwater cross-section dimensions. A Gurley flow meter was used to measure stream discharge at a cross-section located upstream of the influence of the culvert, and to measure water depth and velocity at the culvert inlet and outlet.

Field measurements of stream discharge taken during the summer low flow period were input into FishXing as the low passage flow. To determine the high passage flow, the 10% May exceedance flow was estimated for each site using the USGS regional regression equations for estimating monthly streamflow characteristics at ungaged sites

(Parrett and Cartier 1989). A 150 mm cutthroat trout was selected as the adult “analysis fish” in the FishXing model. Due to the lack of swimming ability information for juvenile cutthroat trout, a 60mm rainbow trout was selected as the juvenile “analysis fish” in the model. A minimum required water depth of 9.1 cm (0.3 feet) was used for adults and 3.1 cm (0.1 feet) for juveniles, based on recommendations found in the literature (Fitch 1995).

FishXing was then used to model each culvert to determine its barrier status for juveniles and adults at the designated low and high flows. Culverts classified as barriers were given a “barrier code” to designate the reason for the blockage as: (1) *V (velocity)* – water velocity in culvert exceeds swimming ability of fish; (2) *EB (excessive burst)* – water velocity in culvert causes fish to be exhausted at burst speed before reaching the upstream end; (3) *L (leap)* – excessive leap at outlet; and (4) *D (depth)* – water depth in culvert less than the designated minimum required water depth.

To determine the passage status at a series of flows intermediate to the designated low and high flows, the results from the uniform flow calculations output page in the FishXing model were examined. The passage results from the uniform flow calculations were combined with the passage results at low and high flows to establish whether each culvert was functioning as a total barrier, a partial barrier, or a non-barrier. A “total barrier” was defined as a culvert that blocks upstream passage to all fish, at all life stages, at all examined flows. A “partial barrier” was a culvert that is impassable to some, but not all, species or life stages. A “non-barrier” was a culvert that does not block passage for either juveniles or adults at any discharge between the designated low and high flows.

To estimate the total amount of suitable stream length deemed inaccessible due to culverts, digital planimeter was used to measure the lengths of all perennial streams in the study area from 1:24,000 USGS topographic maps with slopes less than or equal to 15%. The suitable stream lengths upstream of culverts classified as total barriers was then measured and summed them to determine the total stream length deemed inaccessible to upstream migrating adult and juvenile trout.

Comparison of Upstream and Downstream Population Characteristics

Electrofishing was used to sample upstream and downstream of a subset of 20 culverts to determine the degree to which culverts may have influenced relative abundance, size structure, and species presence. Because low conductivities (<100 $\mu\text{S}/\text{cc}$) in some streams prohibited the ability to sample efficiently, the subset of culverts was not randomly selected, however, they were carefully selected to well represent the culverts in the study. The 20 selected sites incorporated the wide range of culvert characteristics (slope, length, outlet drop height, culvert material type) observed throughout the study area. Sampling was conducted from July to August 2002 and in August 2003 during the summer low flow period.

Because my objective was to compare several fish population characteristics at a large number of sites over a broad geographic area, rather than to precisely determine abundance at a few locations, single pass electrofishing was used. Additionally, it has been concluded that when sampling to estimate the number of species in stream fish assemblages, that it is more efficient to sample a large area with one pass than to sample

a smaller area with multiple passes (Paller 1995). At each site, sampling was conducted over 90 m reaches immediately downstream and upstream of the culvert.

Care was taken to electrofish slowly and thoroughly through all areas in each reach during an upstream pass. A two or three-person crew used a Smith-Root model 15-D generator powered backpack electrofishing unit operated at a DC pulse frequency of 30-40 Hz, and 400 – 700 V depending on water conductivity. For consistency at a site, the same settings were always used in each reach downstream and upstream of the culvert. All captured fish were anesthetized, identified by species, and fork length was measured to the nearest millimeter.

To avoid bias associated with small sample sizes that result from low densities, comparisons were restricted to sites where the larger relative abundance was at least 5 fish / reach. Differences in relative abundance were tested for each species, and for all species combined, in all downstream versus all upstream reaches by using a two-tailed Wilcoxon paired-sample test. Relative abundance of each species at each site was examined by calculating the ratio of the larger relative abundance divided by the smaller relative abundance and then looking for cases where this ratio was substantially different than the 1:1 ratio that would be expected if the relative abundance was similar in the 2 reaches. Species presence was also compared in the downstream versus upstream reach at each of the 20 culvert sites that were sampled.

Size differences between each downstream and upstream reach were compared using a two-tailed Mann-Whitney test. To compare the overall size structure at all 20 culvert sites combined, a two-tailed Wilcoxon paired-sample test was used to determine

if there was a difference between the median lengths of each species, and for all fish combined, in all of the downstream versus upstream reaches

To account for the possible influence of habitat differences upstream and downstream of culverts, habitat features throughout each 90 m sampling reach were measured. Each reach was divided into habitat units (Overton et al. 1997) according to their main physical features. The habitat unit length was recorded and wetted width, average depth, and maximum depth was measured. Mann-Whitney tests were used to compare upstream versus downstream habitat variables. The data was tested for normality using Shapiro-Wilk tests and it was found to be non-normally distributed, therefore non-parametric tests were used for the analysis. For all tests, differences were considered significant if the p-value was ≤ 0.05 .

Direct Passage Assessment

Direct passage was measured at 10 culverts where marked fish were released downstream of the culvert and recaptured in traps upstream. The sites were selected to be a representative sample of all the culverts in the study. The 10 selected sites incorporated the wide range of culvert characteristics (slope, length, outlet drop height, culvert material type) observed throughout the study area. Direct passage assessment was conducted during July to September 2003 during summer low flow.

At each site, a control and treatment reach of equal stream area were designated, with the control reach located immediately downstream of the treatment reach containing the culvert (Figure 2). Each reach was blocked at the downstream and upstream ends with 6-mm wire mesh that was supported by rebar stakes driven into the substrate. At the

upstream ends, a trap box was positioned to capture fish that moved upstream (Figure 2). Trap boxes were constructed of 13-mm plywood and 6-mm wire mesh. To minimize escapement of trapped fish, pyramid shaped entrances were constructed that forced fish to swim slightly upward into the box and thus kept the entrances away from the bottom of the trap. Additionally, baffles were constructed to provide cover and refuge from currents away from the entrances. To enhance attraction to the trap boxes, internal baffles were used to direct water through the entrance, creating an “attraction flow”. As well, the wire mesh leads at the upstream end of each reach were positioned diagonally to direct fish towards the trap boxes (Figure 2).

Once the traps were installed, existing fish in each reach were removed by electrofishing and placed downstream of the study section. Electrofishing was then used to collect 50 fish (except one site where only 40 fish were collected) upstream of the study section. Fish were anesthetized with clove oil, identified by species, and fork length measured to the nearest millimeter, and then divided into two similar groups of 20-25 based on species and size. Groups were then randomly assigned to either the treatment or control reach by flipping a coin. Pelvic fin clips were used to mark the fish according to their respective group: treatment fish received a right fin clip and control fish received a left fin clip. Upon recovery, fish were released into the lower end of their designated reach. Fish were then recaptured in the traps as they moved upstream toward their original capture location. The design was based on the motivation of displaced fish to return to their home location (Halvorsen and Stabell 1990).

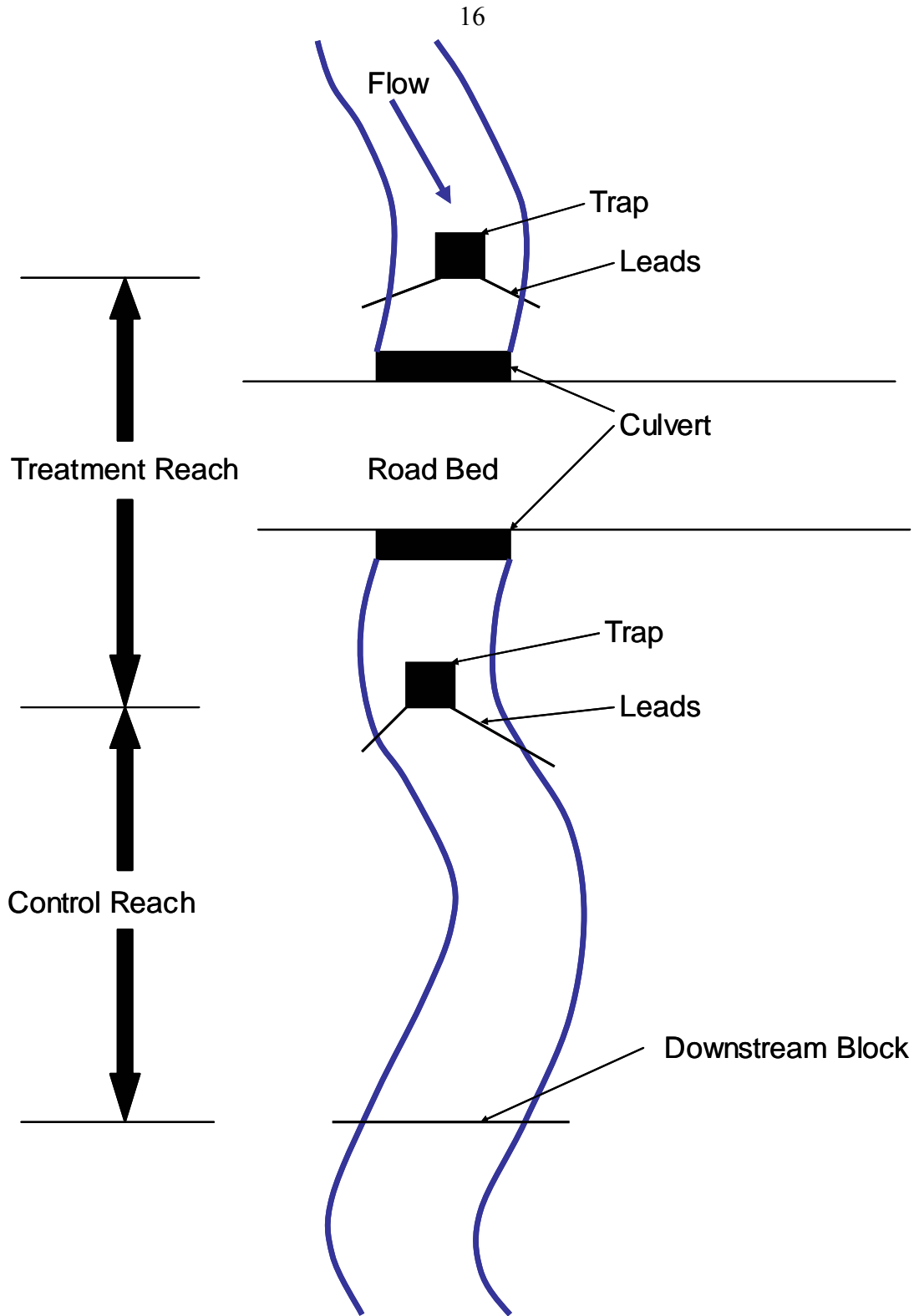


Figure 2. Diagram of the direct passage assessment study sites showing the arrangement of treatment and control reaches and locations of the culvert, fish traps, and leads.

The number of fish that moved upstream into the respective traps was monitored for three days after being released. Recaptured fish were anesthetized, identified by species, fork length measured to the nearest millimeter, checked for fin clips, and released upstream of the study section.

The hydraulic conditions at the site were monitored each day over the 3 day study period. A Gurley flow meter was used to measure discharge at an upstream cross-section and water depths and velocities were measured at the inlet and outlet of the culvert. Discharge, water depths, and velocities were averaged to determine the overall hydraulic conditions during the study period.

A fish passage “impedance ratio” was calculated to compare the proportions of fish moving upstream through the treatment (culvert) and control reaches. The ratio was calculated as: $(C-T)/C$ where C is the number of fish recaptured in the control reach and T is the number of fish recaptured in the treatment reach. A passage impedance ratio of zero or below specifies that the number of recaptures in the treatment (culvert) reach was greater than or equal to that of the control, indicating no restriction of passage through the culvert. A passage impedance ratio of 1 specifies that there were no fish that moved upstream through the treatment (culvert). Because the objective was to determine how much passage was restricted through the treatment reach (culvert) relative to the control reach, any negative values were assigned a minimum value of zero, indicating no passage impedance. A Chi-square test was used to determine if the number of fish passing through the treatment reach (observed) was significantly different than the number of fish passing through the control reach (expected) for each site. Simple and multiple linear regression were used to examine the relationship between the physical conditions of the

culvert and the fish passage impedance ratio. The fish passage impedance ratio was also compared to output from the FishXing model at low flow conditions to evaluate observed versus predicted passage status.

RESULTS

Summary of Culvert Characteristics

The physical characteristics of the 46 sampled culverts are listed in Table 1. Seven culverts had continuous substrate throughout their length, and 39 culverts had either no substrate or discontinuous substrate. The outlet configuration was at stream grade at 19 culverts, free-fall to pool at 18 culverts, free-fall to rock at 8 culverts, and cascaded over rocks at 1 culvert. Outlet drop height ranged from 0 cm to 64.3 cm with a mean of 11.6 cm (standard deviation = 17.3 cm). Culvert length ranged from 3.8 m to 28.6 m with a mean of 12.3 m (standard deviation = 4.6 m). Culvert slope ranged from -0.85% to 16.6% with a mean of 4.3% (standard deviation = 3.6%). Constriction ratio (culvert width / average bankfull width) ranged from 0.34 to 1.33 with a mean of 0.75 (standard deviation = 0.04) (Table 1 and Figure 3).

FishXing Assessment

At 46 culverts, the fish passage status for juvenile and adult trout was assessed. Seven of the 46 culverts had continuous substrate throughout their length, a culvert width similar to the bankfull channel width, and no outlet drop, thus simulating the natural stream channel. It has been acknowledged that FishXing should be used with extreme care when assessing passage through culverts with continuous substrate. This is because FishXing assumes that these culverts have flat homogenous beds when in fact there are likely irregularities in the substrate that would provide deeper lanes for passage at low

Table 1. The physical characteristics measured or observed for all 46 culvert sites studied. fp = free-fall to pool, fr = free-fall to rock, ag = at stream grade, cr = cascade to rock.

Site	Continuous Substrate	Outlet Configuration	Length (m)	Slope (%)	Outlet Drop Height (cm)	Constriction Ratio
1	no	fp	9.4	1.5	12.2	1.15
2	no	fp	10.7	3.4	6.1	0.55
3	no	ag	10.9	2.0	0.0	1.33
4	no	fp	12.6	7.1	6.1	0.56
5	no	fr	12.5	3.3	53.3	0.37
6	no	fp	16.9	16.6	2.1	0.34
7	no	fr	9.9	10.6	14.3	0.56
8	no	fp	9.4	2.1	3.0	0.86
9	no	fp	11.2	6.0	36.6	0.59
10	no	fp	12.4	0.9	9.1	0.70
11	no	ag	10.5	1.3	0.0	0.48
12	no	fp	8.6	2.9	49.4	0.66
13	no	fr	10.9	3.9	15.2	0.45
14	no	fp	11.2	2.1	30.5	0.44
15	yes	ag	12.5	5.5	0.0	1.16
16	yes	ag	12.1	0.8	0.0	0.89
17	no	ag	26.4	1.3	0.0	1.11
18	no	ag	9.3	4.9	0.0	0.92
19	no	ag	28.6	2.4	0.0	0.89
20	no	ag	11.8	4.4	0.0	1.20
21	no	fp	7.6	1.1	18.3	0.62
22	no	fp	9.5	5.6	5.5	0.66
23	yes	ag	11.8	1.6	0.0	0.84
24	no	ag	13.0	4.8	0.0	0.71
25	no	fp	8.7	6.7	3.0	0.53
26	no	cr	12.1	9.2	6.1	0.67
27	no	fr	11.8	7.6	24.4	0.52
28	no	ag	12.7	4.9	0.0	1.00
29	no	fr	13.7	9.9	27.4	0.70
30	no	fp	10.0	3.2	61.0	1.18
31	no	fp	9.9	1.5	18.9	0.78
32	yes	ag	6.2	1.0	0.0	0.70
33	no	fr	12.4	7.4	64.3	0.48
34	no	fr	14.3	10.6	30.8	0.52
35	no	fp	13.0	5.0	21.3	0.78
36	no	ag	11.0	3.2	0.0	1.17
37	yes	ag	8.1	-0.3	0.0	0.96
38	yes	ag	14.6	5.7	0.0	0.86
39	yes	ag	21.3	1.3	0.0	0.67
40	no	fr	12.4	12.2	4.6	0.64
41	no	ag	22.1	2.4	0.0	1.08
42	no	fp	12.4	6.1	4.9	1.28
43	no	fp	9.8	0.8	3.7	0.62
44	no	fp	13.8	2.7	3.7	0.67
45	no	ag	3.7	1.1	0.0	0.36
46	no	ag	11.1	-0.9	0.0	0.77

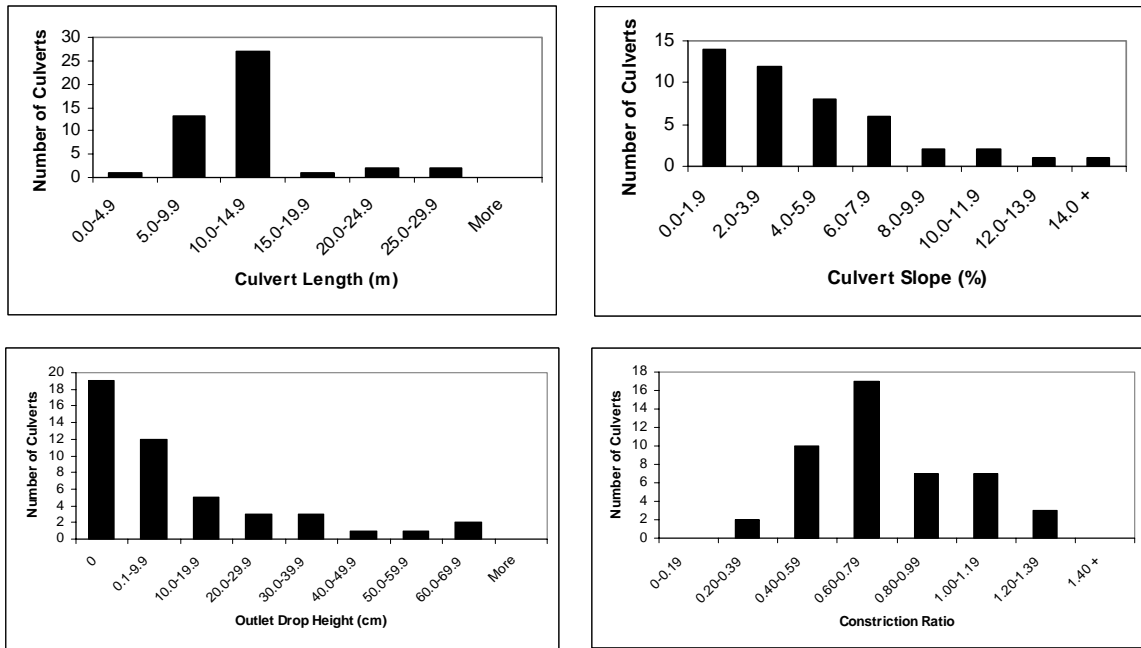


Figure 3. Histograms summarizing the physical characteristics measured at the 46 culverts studied in the upper Clearwater River basin.

flow and refuge from high water velocities at high flow (Clarkin et al. 2003). Accordingly, the culverts with continuous substrate that simulated the natural channel were considered passable to all species and life stages at all flows, without using the FishXing model.

For juvenile trout at low flow, 35 of 46 (76.1%) culverts were deemed as barriers to passage (Figure 4). Of these, most culverts had multiple factors that prevented fish passage according to the model. These factors included excessive leap height at the outlet ($n=24$), insufficient water depth ($n=18$), and high water velocity ($n=18$) (Table 2).

At high flow, 39 of 46 (84.8%) culverts were classified as barriers to juvenile trout passage (Figure 4). Water velocities exceeded juvenile trout swimming abilities in

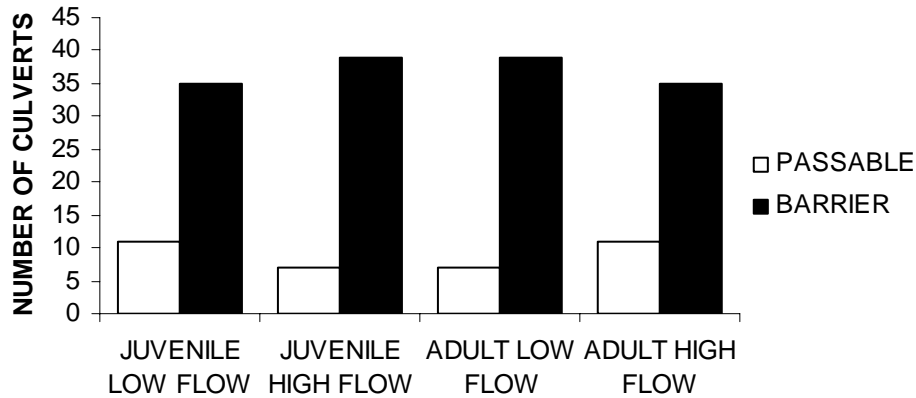


Figure 4. Results of FishXing assessment for juveniles and adults at low and high flow. Open bars indicate number of culverts that were considered passable; shaded bars indicate the number of culverts that were considered barriers to fish passage.

all 39 of these barrier culverts, and 19 of them also had an excessive leap height at the outlet (Table 2).

The majority of culverts were also deemed impassable at both low and high flow for adult trout. At low flow, 39 of 46 (84.8%) culverts were deemed barriers to adult fish passage (Figure 4), with insufficient water depth identified as a cause for passage blockage at all 39 of the barrier culverts. Excessive leap height at the outlet occurred at 16 culverts, whereas excessive water velocity occurred at only 1 site (Table 2).

At high flow, 35 of 46 (76.1%) culverts were classified as barriers to adult fish passage (Figure 4). Among barrier culverts, excessive water velocity was identified for blocking passage at 32 culverts, and an excessive outlet height was identified at 20 culverts. Even at high flow, insufficient water depth occurred for 8 of the 35 barriers (Table 2).

Table 2. Barrier status (P = passable, B = barrier) determined by FishXing assessment for each sampled culvert. For identified barrier culverts, reasons for barrier status are indicated as: v = water velocity in culvert exceeds swimming ability of fish; eb = water velocity in culvert causes fish to be exhausted at burst speed; l = excessive leap at outlet; and d = water depth in culvert less than the designated minimum required water depth.

Site	Juvenile Low Flow	Juvenile High Flow	Adult Low Flow	Adult High Flow	Overall Barrier Status
1	B(l)	B(l,v)	B(l,d)	B(l)	Total
2	B(l)	B(l,v)	B(d)	B(l,eb)	Total
3	P	B(eb)	B(d)	P	Partial
4	B(l,eb)	B(v)	B(d)	B(eb)	Total
5	B(l)	B(l,v)	B(l,d)	B(l,eb)	Total
6	B(d,v)	B(v)	B(d)	B(v)	Total
7	B(l,d,v)	B(l,v)	B(l,d)	B(l,v)	Total
8	B(l,d)	B(v)	B(d)	P	Partial
9	B(l,v)	B(l,v)	B(l,d)	B(l,eb)	Total
10	B(l)	B(l,v)	B(d)	B(l)	Total
11	P	B(eb)	B(d)	B(eb)	Partial
12	B(l,d)	B(l,v)	B(l,d)	B(l,eb)	Total
13	B(l,v)	B(l,v)	B(l,d,eb)	B(l,v)	Total
14	B(l,eb)	B(l,v)	B(l,d)	B(l,eb)	Total
15	P	P	P	P	Non
16	P	P	P	P	Non
17	B(d)	B(v)	B(d)	B(eb)	Total
18	P	B(v)	B(d)	B(eb)	Partial
19	B(d)	B(v)	B(d)	B(d,eb)	Total
20	B(v)	B(v)	B(d)	B(d,eb)	Total
21	B(l)	B(l,v)	B(l,d)	B(l)	Total
22	B(l,v)	B(l,v)	B(l,d)	B(l,d,eb)	Total
23	P	P	P	P	Non
24	B(d)	B(v)	B(d)	B(eb)	Total
25	B(d,v)	B(v)	B(d)	B(eb)	Total
26	B(v)	B(v)	B(d)	B(eb)	Total
27	B(l)	B(l,v)	B(l,d)	B(l,eb)	Total
28	B(d)	B(d,v)	B(d)	B(d,eb)	Total
29	B(l,d)	B(l,v)	B(l,d)	B(l,eb)	Total
30	B(l,d,v)	B(l,v)	B(l,d)	B(l,d,v)	Total
31	B(l,d)	B(l,v)	B(d)	B(l,d,eb)	Total
32	P	P	P	P	Non
33	B(l,d)	B(v)	B(l,d)	B(l,eb)	Total
34	B(l,d,v)	B(l,v)	B(l,d)	B(l,v)	Total
35	B(l,v)	B(l,v)	B(l,d)	B(l,eb)	Total
36	B(d,eb)	B(d,v)	B(d)	B(d,eb)	Total
37	P	P	P	P	Non
38	P	P	P	P	Non
39	P	P	P	P	Non
40	B(l,d,v)	B(l,v)	B(l,d)	B(l,v)	Total
41	B(d,eb)	B(v)	B(d)	B(d,eb)	Total
42	B(l)	B(v)	B(d)	B(d,eb)	Total
43	B(l,d,eb)	B(l,v)	B(d)	B(l,eb)	Total
44	B(l)	B(v)	B(d)	B(eb)	Total
45	B(v)	B(v)	B(d)	P	Partial
46	P	B(v)	B(d)	P	Partial

Overall, FishXing passage assessment for both juveniles and adults across the range of flows from the low flow to the high flow resulted in 7 of the 46 (15.2%) culverts being deemed “non-barriers”; 6 (13.0%) were deemed “partial barriers”; and 33 (71.7%) were deemed “total barriers” (Table 2). The 7 “non-barriers” all had continuous substrate throughout their length, had no outlet drop, and had slopes ranging from 0 to 5.8 % (mean = 2.2%). Of the 6 “partial barriers”, 5 had no outlet drop and the other had only a 3 cm drop, and slopes ranged from 0 to 4.9% (mean = 1.8%). Of the 33 “total barriers”, 7 had no outlet drop, 17 had a free-fall to pool, 8 had a free-fall to rocks, and 1 cascaded over rocks. The average outlet drop was 16.2 cm. The slopes ranged from 0.8% to 16.6% and were considerably steeper on average (5.2%) than the “non” or “partial barriers.”

The total available stream length in the study area was 195.6 km. Of this, 75.0 km (38.3%) were located upstream of the 33 aforementioned culverts classified as “total barriers” (Figure 5), and were thus considered inaccessible at all flows to fish residing downstream. Of the 24 streams sampled, barrier culverts occurred in the lower reaches of 17 of these, potentially restricting fish passage over much of the stream length (Figure 5).

The 20 culverts assessed by comparing the downstream and upstream population characteristics were also assessed with the FishXing model. The FishXing model results indicated that 4 culverts were considered non-barriers, 4 culverts were considered partial barriers, and 12 culverts were considered total barriers. However, comparison of the population characteristics downstream and upstream of these sites indicated very few differences overall. Species presence was the same downstream and upstream of all 20 culverts, relative abundance ratios indicated that a large majority of the sites had a similar

number of fish upstream and downstream of the culvert, and the median length of a species differed at only 2 sites. These findings demonstrate that some of the existing methods used to assess fish passage through culverts produce differing results.

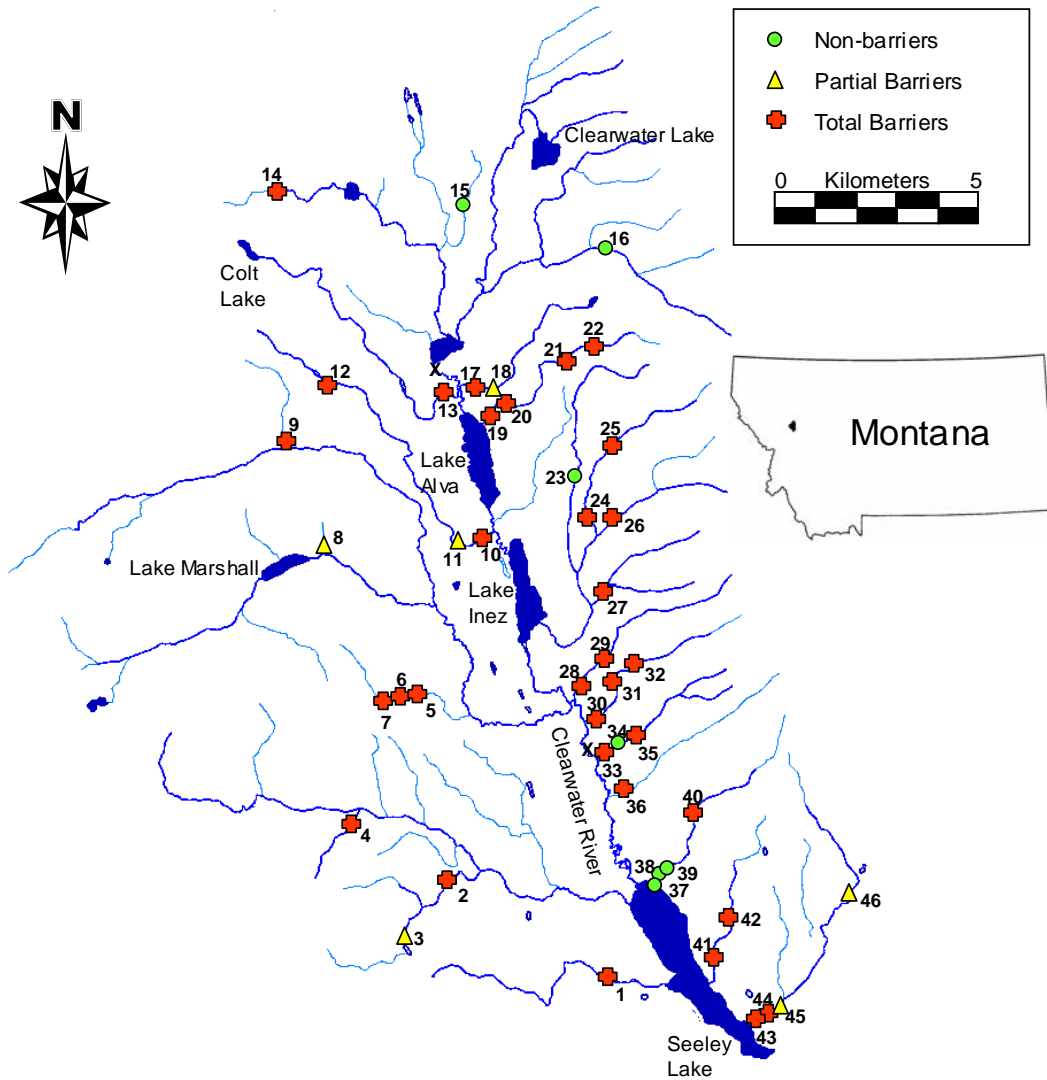


Figure 5. Map showing locations of culverts classified as non-barriers, partial barriers, and total barriers.

Comparison of Upstream and Downstream Population Characteristics

I sampled upstream and downstream of 20 culverts on 14 streams. Streams ranged from 0.91 m to 4.54 m in bankfull width. Cutthroat trout and brook trout were the most common species, accounting for 49% and 36%, respectively, of the total number of fish sampled. Slimy sculpin, bull trout, brook stickleback, and brown trout comprised the remaining 15% of fish sampled.

Species presence was similar upstream and downstream of the 20 sampled culverts where sample size was sufficient for comparison, suggesting that culverts were not strongly influencing the distribution of fish species throughout the study area. However, there were 4 instances at 4 culvert sites (8, 23, 30, and 43) where a species present downstream of the culvert was not present upstream (Table 3). In all 4 instances, the relative abundance of the species present downstream of the culvert was very low (< 5 fish / 90 m). As a result, the “not present” status upstream of the culvert may likely be due to a low detection probability associated with the low density, as opposed to an actual lack of species presence due to a culvert barrier. For example, sampling upstream 200 m of culvert 30, at culvert 31, confirmed the presence of brown trout which were not detected immediately upstream of culvert 30. Similarly, at an additional 5 culvert sites (2, 19, 20, 31, and 43), the reverse pattern was observed where a species present upstream of the culvert was not present downstream (Table 3). Again, in all instances, the relative abundance of the species present upstream of the culvert was very low (< 5 fish / reach), further supporting the notion that the “not present” status may likely be due to a low detection probability associated with the low density.

Table 3. Summary of downstream and upstream population sampling results of 20 culvert sites, including Mann-Whitney tests for comparison of fish lengths. Ct = cutthroat trout, Bk = brook trout, Bl = bull trout, Br = brown trout, Ss = slimy sculpin, Bs = brook stickleback. (ss = sample size too small)

Site	Species	Downstream Reach			Upstream Reach			Mann-Whitney P-value
		Number / 90m	Median Length	Length Range	Number / 90m	Median Length	Length Range	
2	Ct	17	94	35-151	21	96	73-143	0.22
	Ss	30	55	37-77	7	46	40-64	0.37
	Bl	0	-	-	1	140	140-140	ss
	Bk	0	-	-	2	139	128-150	ss
3	Ct	6	94	42-130	9	127	42-179	0.19
8	Ct	1	74	74-74	0	-	-	ss
	Bk	19	50	36-164	21	102	36-133	0.15
11	Ct	5	61	34-71	4	70.5	60-102	0.17
	Bk	36	86	46-176	38	91.5	46-166	0.07
16	Ct	1	103	103-103	2	111.5	110-113	ss
	Bl	10	89	81-132	12	90.5	83-143	0.29
17	Ct	13	64	53-119	14	79	53-136	0.79
	Bk	12	99.5	47-167	10	59	49-99	0.01
	Bs	14	48.5	39-61	1	54	54-54	0.49
18	Ct	26	87.5	57-134	20	78	52-105	0.12
	Bk	12	103	57-146	5	105	58-118	0.75
19	Ct	27	67	54-128	26	81.5	49-132	0.52
	Bk	0	-	-	4	52	48-54	ss
20	Ct	27	65	45-113	31	64	50-123	0.86
	Bk	0	-	-	1	75	75-75	ss
23	Ct	3	90	89-95	0	-	-	ss
	Bk	32	78.5	62-155	32	73	62-149	0.91
24	Ct	20	100.5	59-149	12	95	60-131	0.55
26	Ct	15	102	54-154	4	116.5	105-129	0.45
27	Ct	26	93.5	53-137	18	95	56-110	0.68
	Bk	6	104.5	85-129	4	124	115-128	0.09
28	Ct	9	91	75-107	9	95	68-105	0.93
	Bk	10	72	60-109	2	62.5	62-63	0.11
29	Ct	8	107.5	75-178	6	101.5	86-149	0.90
30	Ct	13	92	58-163	13	61	33-203	0.01
	Bl	7	158	128-218	1	172	172-172	0.51
	Bk	6	94	48-154	25	54	48-154	0.15
	Br	4	119	110-142	0	-	-	ss
31	Ct	13	61	33-203	13	66	29-116	0.76
	Bl	1	172	172-172	2	179	174-184	ss
	Bk	25	54	48-154	9	68	40-160	0.77
	Br	0	-	-	3	135	127-138	ss
35	Ct	26	72	41-186	14	73.5	26-126	0.91
	Bk	11	85	50-144	5	114	76-158	0.34
37	Ct	4	128	111-140	7	115	101-146	0.26
43	Bk	12	73.5	34-131	17	103	37-162	0.15
	Ct	0	-	-	1	148	148-148	ss
	Ss	21	44	31-80	32	43.5	27-76	0.94
	Bs	4	49	43-52	0	-	-	ss

Size structure of each species was also similar upstream and downstream of each culvert in all but 2 cases (Table 3). At site 17, the median length of brook trout was 99.5 mm downstream of the culvert and 59 mm upstream (Table 3), and there were 6 fish over 100 mm downstream of the culvert but none upstream. This culvert had no outlet drop, and a slope of only 1.3%, but at 26.4 m it was the considerably longer than the 12.3 m average. At site 30, the median length of cutthroat trout was 92 mm downstream of the culvert and 61 mm upstream (Table 3). This culvert was only 10 m long, and had a slope of 3.2%, but the outlet drop of 61 cm was among the highest in the study. However, the occurrence of habitat differences upstream and downstream of the culvert may also have contributed to size structure differences.

Analyses of size structure for each species at all sites combined indicated that fish lengths were similar ($P = 0.10 - 0.97$) upstream and downstream of the culverts (Table 4). As well, analysis of size structure for all species combined at all sites combined also indicated that fish lengths were similar ($P = 0.35$) upstream and downstream of the culverts (Table 4).

Table 4. Summary of upstream and downstream population sampling for all sites combined, including Mann-Whitney tests for fish lengths and Wilcoxon tests for relative abundance. Ct = cutthroat trout, Bk = brook trout, Bl = bull trout, Br = brown trout, Ss = slimy sculpin, Bs = brook stickleback, All = all species combined.

Species	All Downstream Reaches			All Upstream Reaches			Mann-Whitney P-value	Wilcoxon P-value
	Number	Median Length	Length Range	Number	Median Length	Length Range		
Ct	260	84	33-203	223	86	26-203	0.97	0.50
Bk	181	83	34-176	175	84	36-166	0.63	0.73
Bl	18	112	81-218	16	114.5	83-184	0.73	0.77
Br	4	119.5	110-142	3	135	127-138	0.29	0.68
Ss	51	52	31-80	39	44	27-76	0.10	1.00
Bs	18	48	39-61	1	54	54-54	0.36	0.12
All	532	78.5	31-218	457	83	26-203	0.35	0.38

Examination of the histogram that displayed the distribution of the relative abundance ratios indicated that a large majority of the sites had a similar number of fish upstream and downstream of the culvert (Figure 6). However, in 9 cases, there were at least twice as many fish in one reach relative to the other, suggesting passage may be restricted at these sites. In eight of these cases, relative abundance was greater downstream of the culvert, whereas only 1 case had a greater relative abundance upstream. Relative abundance was similar ($P = 0.12 - 1.0$) for each species in all downstream versus all upstream reaches (Table 4), however small sample sizes for bull trout, brown trout, and brook stickleback provided very little power to detect statistically significant differences. The relative abundance of bull trout (18 vs. 16 fish) and brown trout (4 vs. 3 fish) appeared to be very similar in all downstream versus all upstream reaches. In contrast, at the 2 sites where they were sampled, there were a total of 18 brook stickleback in the downstream reaches versus only 1 in the upstream reaches, suggesting a significant passage restriction for this species (Table 4). Relative abundance was also similar ($P = 0.38$) for all species combined in all downstream versus all upstream reaches (Table 4).

Significant differences in habitat variables in the reach downstream versus upstream of each culvert were detected at 3 of the 20 sites (# 11, 30, and 31). Consequently, the differences in population characteristics at sites 30 and 31 may be due to differences in habitat conditions as opposed to being a result of restricted movement through the culverts.

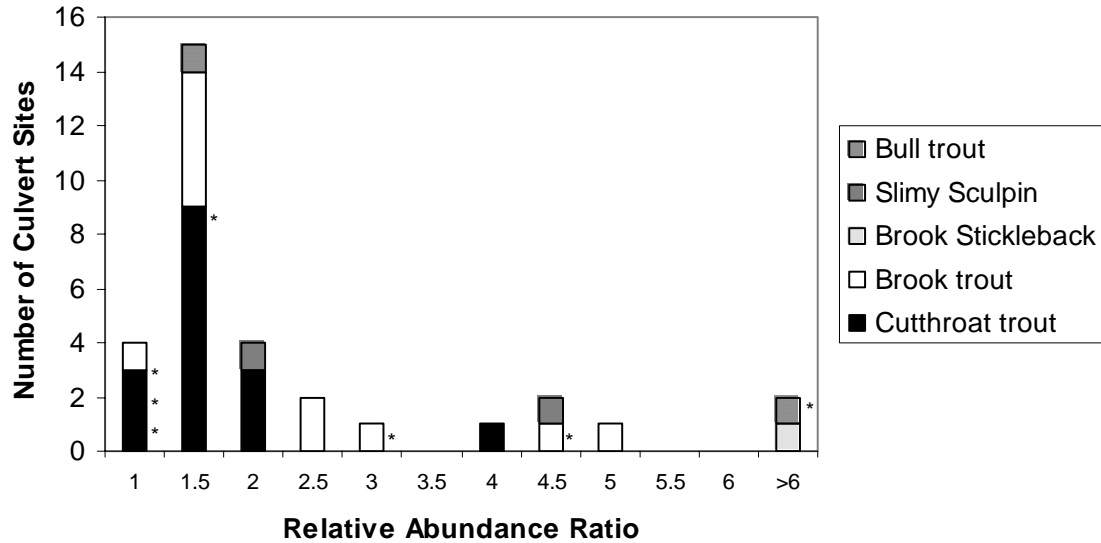


Figure 6. Histogram showing the ratios of the relative abundance of each species in the downstream and upstream reaches at each site. (* indicates sites with statistically significant habitat differences)

Direct Passage Assessment

At the 10 selected culvert sites, a total of 490 fish were captured, marked, and released for the direct passage assessment. Of these, 284 (60.9%) were cutthroat trout, 180 (38.6%) were brook trout, 2 (0.4%) were bull trout, and 24 (5.2%) were slimy sculpin. Slimy sculpin were excluded from further analysis due to a very low recapture rate (3 of 12) in the control reaches, which indicates that the methodology used here may not be effective for this species. The average length of fish released in the control reaches was 96 mm and ranged from 29 mm to 199 mm. The average length of fish released in the treatment reaches was 97 mm and ranged from 35 mm to 183 mm. The lengths of marked fish were similar between each treatment group and control group at all 10 sites (Mann-Whitney tests, $P = 0.38 - 0.95$).

Overall, 156 of 233 (67.0%) fish were recaptured after moving upstream through the control reaches, averaging 103 mm in length. In the treatment reaches, 94 of 233 (40.3%) fish were recaptured and averaged 107 mm. At all 10 sites, the lengths of recaptured fish were similar to the lengths of those marked for both the treatment and control groups (Mann-Whitney tests, $P = 0.07 - 0.99$).

Results from the Chi-square analysis indicated that number of fish that passed through the treatment reach was significantly different than the number of fish that passed through the control reach for 7 of the 10 sites ($P \leq 0.05$; Table 5). Three culverts had a passage impedance ratio that was negative, indicating that more fish passed through the treatment (culvert) reach than through the control reach (Table 5). Because the objective was to determine how much passage was restricted through the treatment reach (culvert) relative to the control reach, the negative values were assigned a minimum value of zero, indicating no passage impedance, and these modified values are presented as the corrected passage impedance ratio (Table 5).

Table 5. The number of fish recaptured in each reach, the passage impedance ratio and corrected passage impedance ratio, and the results from the Chi-square tests.

Site	Number of Fish Recaptured in Treatment Reach	Number of Fish Recaptured in Control Reach	Un-Corrected Passage Impedance Ratio	Corrected Passage Impedance Ratio	Chi-square	P-value
2	8	17	0.53	0.53	4.76	0.03
10	21	10	-1.10	0.00	12.10	< 0.01
13	0	14	1.00	1.00	14.00	< 0.01
19	18	14	-0.29	0.00	1.14	0.29
20	17	16	-0.06	0.00	0.06	0.80
27	11	16	0.31	0.31	9.00	< 0.01
28	6	20	0.70	0.70	9.80	< 0.01
30	2	24	0.92	0.92	20.20	< 0.01
35	2	11	0.82	0.82	7.36	< 0.01
43	9	14	0.36	0.36	1.79	0.19

One of the 10 culverts was a complete fish passage barrier (100% passage impedance). Three culverts had a passage impedance of zero, two culverts had less than 50% passage impedance, and 4 culverts had greater than 50% passage impedance (Table 5). Two of the 3 culverts that had a passage impedance of zero had no outlet drop, while the third had an 18 cm outlet drop. The 2 culverts with less than 50% passage impedance had outlet drops of 9 and 34 cm. Three of the 4 culverts with over 50% passage impedance had outlet drops ranging from 9 – 61 cm (mean = 30.3), and the culvert that had 100% passage impedance had an outlet drop of 46 cm (Table 5).

Results from the simple linear regression analyses using the un-corrected passage impedance ratio showed that no significant relationships were found between the un-corrected passage impedance ratio and culvert slope, outlet height, water depth, length, or constriction ratio ($P = 0.20 - 0.90$). However, results from the simple linear regression analyses using the corrected passage impedance ratio indicated that there was a significant positive relationship ($P=0.047$) between corrected passage impedance and outlet height, although the strength of the relationship was only moderate ($r^2=0.41$) (Figure 7). No significant relationships were found between corrected passage impedance and culvert slope ($r^2=0.08$, $P=0.43$), water depth ($r^2=0.01$, $P=0.76$), length ($r^2=0.22$, $P=0.17$), or constriction ratio ($r^2=0.05$, $P=0.54$).

Results from the multiple linear regression analysis using the un-corrected passage impedance ratio showed that there was no significant relationship between any combination of physical characteristics (slope, outlet height, water depth, length, and constriction ratio) and the un-corrected passage impedance ratio. In addition, results from the multiple linear regression analysis using the corrected passage impedance ratio

showed that there was no significant relationship between any combination of physical characteristics (slope, outlet height, water depth, length, and constriction ratio) and the corrected passage impedance ratio.

The 10 culverts assessed with the direct passage method were also assessed with the FishXing model at the same low flow conditions measured during the direct passage study. The model indicated that all 10 culverts were barriers to both juveniles and adults at this flow (Table 6). For juveniles, the factors that led to the barrier designation were an excessive leap at the outlet (n=7), excessive water velocity (n=6), and insufficient water depth (n=4). For adults, insufficient water depth was identified as a factor at all 10 sites, and an excessive leap at the outlet (n=4), and excessive water velocity (n=1) were also identified as factors that led to the barrier designation (Table 6).

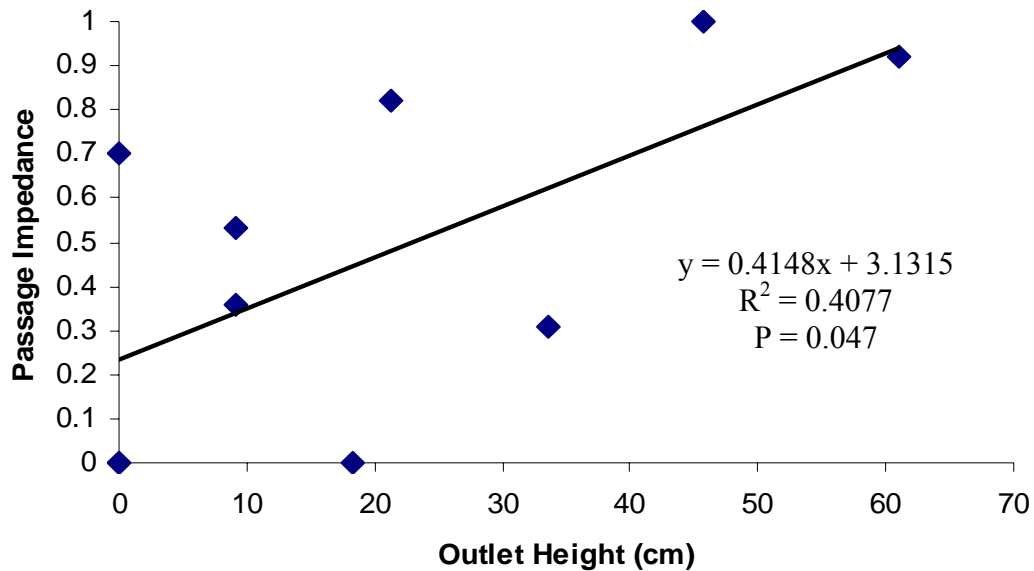


Figure 7. The relationship between passage impedance and outlet height for the 10 direct passage assessment sites ($r^2=0.408$, $p=0.047$).

Table 6. Table showing the passage impedance ratio and FishXing results for the direct passage assessment sites. P = passable, B = barrier, v = water velocity in culvert exceeds swimming ability of fish, eb = water velocity in culvert causes fish to be exhausted at burst speed, l = excessive leap at outlet, and d = water depth in culvert less than the designated minimum required water depth.

Site	Corrected Passage Impedance Ratio	FishXing Juvenile Passage Status	FishXing Adult Passage Status
2	0.53	B(l)	B(d)
10	0.00	B(l,v)	B(d)
13	1.00	B(l,v)	B(l,d,eb)
19	0.00	B(d)	B(d)
20	0.00	B(v)	B(d)
27	0.31	B(l)	B(l,d)
28	0.70	B(d)	B(d)
30	0.92	B(l,d,v)	B(l,d)
35	0.82	B(l,v)	B(l,d)
43	0.36	B(l,d,eb)	B(d)

DISCUSSION

Basin-wide assessment using the FishXing model showed nearly all the culverts examined were considered barriers to upstream fish passage, and only the culverts that simulated the natural channel were considered “non-barriers.” In contrast, the direct passage study results showed that some passage was occurring at 90% of the 10 culverts studied at low flow, although 70% of the culverts showed some degree of passage impedance. Furthermore, population sampling upstream and downstream of culverts gave no evidence to suggest that culverts were limiting the distribution of fishes in the study area. However, there were 2 sites with significant differences in size structure, suggesting that they may have been functioning as partial barriers to fish passage at low flow.

The findings of this study indicated that the existing methods used to assess fish passage through culverts could produce contrasting results, indicating that these methods need further refinement. Yet, a combination of these methods can be used to gain an understanding of the extent to which culverts impede fish passage throughout a large drainage basin.

There are distinct advantages and limitations associated with each of the methods used in this study to evaluate fish passage through culverts. The FishXing model can be used to assess a large number of culverts, but questions regarding the accuracy of the model make it more suitable for identifying culverts with potential passage concerns than for predicting the amount of passage that actually occurs. Comparison of population characteristics downstream and upstream of culverts can provide valuable information

regarding how culverts affect fish populations, but this method is also unable to determine the amount of passage that is actually occurring. Furthermore, in this study, this method was limited to relatively low streamflow conditions and to streams with suitable conductivity, due to the need to electrofish efficiently. It was also labor intensive, thus limiting the number of sites that could be sampled with this method. In contrast to these indirect approaches, the direct passage method can be used to determine the amount of passage that actually occurs through culverts, but it was also labor intensive and restricted to times when streamflow conditions were low enough to electrofish effectively and maintain in-stream traps.

Results of the application of the FishXing hydraulic model showed that 85% of the 46 culverts assessed in the Clearwater drainage were considered to be either partial or total barriers to upstream fish passage. This high proportion of barriers was similar to findings from a U.S. Forest Service assessment conducted from 1999 to 2001 in Washington and Oregon that reported 72% of the 2,986 surveyed culverts as barriers (United States General Accounting Office 2001). In this study, the slightly higher figure that was found may have been a result of a large proportion of culverts in the study area occurring on relatively high gradient streams (0.3% - 16.5%; mean = 5%), whereas the road crossings on the lower gradient streams were comprised mostly of bridges. In general, as the slope of a culvert is increased, water velocity increases and water depth decreases (Chow 1959), both of which may lead to passage problems (Baker and Votapka 1990, Votapka 1991; Bates et al. 1999; ODF 2000). As well, high water velocity may increase the amount of scour that occurs at the tailwater control, which in turn increases the outlet drop and thus potential passage problems associated with an excessive outfall

height. Therefore, the larger the proportion of steep culverts on high gradient streams, the larger the proportion that are likely to be considered barriers.

All 7 of the culverts that were deemed “non-barriers” overall were considered so because they had continuous substrate throughout, no outlet drop, and a width similar to the average bankfull width, thus simulating the natural channel. Six of these channel simulation culverts were run in FishXing to compare against the original “passable” classification they received by simulating the natural channel. One culvert was unable to be run in FishXing due to interior baffles that complicate the hydraulic conditions, so the model cannot be used. Results for juveniles at low flow show that 2 of the 6 culverts were barriers, both due to insufficient water depth. For juveniles at high flow, all 6 culverts were barriers due to excessive water velocity. Results for adults at low flow show that 5 of 6 culverts were barriers due to insufficient water depth. For adults at high flow, all 6 culverts were passable. In summary, all 6 culverts that simulate the natural channel were considered partial barriers according to the FishXing model. However, as previously mentioned, it has been acknowledged that FishXing should be used with extreme care when assessing passage through culverts with continuous substrate, because FishXing assumes that these culverts have flat homogenous beds when in fact there are likely irregularities in the substrate that would provide deeper lanes for passage at low flow and refuge from high water velocities at high flow (Clarkin et al. 2003). With this in mind, and since the conditions in these culverts were similar to the natural conditions in the channel, I believe that the original classification of “passable” was a logical and accurate assessment.

The selection of an appropriate ‘minimum water depth’ in the model may be a key factor in determining whether culverts are considered passable. In FishXing, the ‘minimum water depth’ is selected by the user, and is typically based on recommendations from assorted publications concerning fish passage. It is generally considered to be dependent on the size of the fish, with larger fish requiring more depth. In addition, the water depth in the riffles near the culvert should be taken into account when determining what minimum water depth to use, as the water depth in the culvert should not be expected to be greater than that in the adjacent natural channel. Moderately shallow minimum water depths (9.1 cm for adults and 3.1 cm for juveniles) were used due to the relatively small size of the fish encountered during the study and the shallow water depths observed in the natural stream channels. Larger migratory fish would require a greater water depth, and this should be taken into consideration when deemed necessary.

Despite the fairly shallow water depths that were used, insufficient water depth was frequently identified as a factor (39% - 85% of the 46 culverts) leading to the barrier designation for both juveniles and adults at low flow in the FishXing model (Table 2). The direct passage study indicated that adult fish were passing unimpeded through water depths of only 3.1 cm, so the model was modified with 3.1 cm as the minimum water depth for adults. An additional 4 culverts were considered passable to adults at low flow using this modified model, but all 4 were still considered barriers to either juveniles or adults at some flow. Thus, the selection of the minimum required water depth was not a major factor in determining whether the culverts were classified as barriers by the FishXing model.

A majority of the “total” barrier culverts were located in the lower reaches of small tributaries and often occurred in close proximity to other barriers on the same tributary (Figure 5). The 75 km of stream deemed inaccessible was comprised of numerous sections of 20 relatively small first and second order tributary streams, while the larger streams were generally free of culvert barriers (Figure 5). In most cases, a barrier existed in the lower reach of the tributary, often near the confluence with the Clearwater River. As a result, nearly the entire suitable stream length of each tributary was upstream of the lowest barrier (Figure 5). In addition, there was often another barrier just upstream of the lowest barrier. This configuration needs to be taken into account when prioritizing fish passage improvement projects, as the replacement of the lowest barrier would only provide access to a small segment of previously inaccessible habitat before the next barrier blocks the remainder of upstream habitat. Accordingly, fish passage improvement projects would be most efficient if they were implemented on streams where the removal of a barrier would provide access to a large segment of previously inaccessible habitat. For example, on Agency Creek in Oregon, the replacement of just 2 barrier culverts provided access to over 12 km of spawning habitat (www.grandronde.org/).

The statistically significant differences in habitat variables that were detected at 3 sites were consistent with differences that were noted when visually observing habitat conditions and stream morphology during the field data collection. Site 11 had a distinct reach break at the culvert, with a slow and deep, low gradient (0.3%), sinuous meadow section above the culvert and a steeper (2.2%), less sinuous, pool-riffle morphology below. Above the culvert at site 30, the wetted width was significantly wider, the

gradient was distinctly lower, and the substrate was smaller. At site 31, the wetted width was significantly narrower above the culvert, and the gradient was noticeably higher.

Differences in population characteristics were often associated with the aforementioned differences in habitat conditions upstream and downstream of culverts. Accordingly, these differences in population characteristics may be due to differences in habitat conditions as opposed to being a result of restricted movement through the culverts. The differences in population characteristics at these sites with habitat differences accounted for 1 of the 2 cases where lengths differed significantly and 3 of the 9 cases where relative abundance was more than 2 times greater than the adjacent reach.

The time of year and the streamflow conditions under which downstream and upstream population sampling was conducted could also have influenced results. Significant differences in size structure and relative abundance downstream and upstream of a culvert have been documented for cutthroat trout (USFWS 2002), indicating that the culvert was a barrier. However, relatively few differences were found in size structure or relative abundance for any species during this study. This may partially be a result of the time of year and the streamflow conditions under which population sampling was conducted. Differences would be most likely to be found when there was a considerable upstream migration and only when passage was significantly restricted. For instance, in the aforementioned study, sampling was conducted during their spawning migration in the spring when streamflow was high. Accordingly, differences in relative abundance or size structure downstream and upstream of a culvert could indeed suggest that it was a barrier, however a lack of differences does not necessarily confirm that the culvert was not a barrier.

Natural and man-made barriers are known to limit the upstream distribution of fish (Winston et al. 1991, Bryant et al. 1999, Kruse et al. 2001, Schrank et al. 2001, Morita and Yamamoto 2002), leading in some cases to local extirpation upstream due to loss of connectivity (Winston et al. 1991, Morita and Yamamoto 2002). However, very little evidence was found in this study to suggest that culverts were limiting the distribution of fishes in the study area. While these findings may suggest that the culverts studied were not functioning as total barriers, it is also possible that there were isolated self-sustaining populations upstream of total barriers, as isolation does not immediately result in extirpation.

In the direct passage experiment, it was found that fish were able to pass successfully through culverts where the physical conditions would generally be considered impassable according to much of the current literature and also according to the FishXing model (Table 6). For example, site 27 was considered a barrier by FishXing due to both an excessive leap and insufficient water depth. It had a culvert slope of 7.6%, an outlet drop of 34 cm, and an average water depth of 3.1 cm, yet there was only a small degree of passage impedance (31%) (Table 6). Furthermore, site 30 had a slope of 3.2%, an outlet drop of 61 cm, and an average water depth of 6.1 cm. It was considered a barrier by FishXing due to both an excessive leap and insufficient water depth (Table 6). The passage impedance rate was high at 92%, however a 106 mm and a 150 mm trout were able to pass successfully. These findings demonstrate that the fish in this study were able to pass through shallower water depths than previously recognized. Furthermore, these results also showed that the fish in this study were able to leap into,

and successfully pass through, culverts that would be considered to have an excessive leap according to both the literature and the FishXing model.

Results from the simple linear regression analysis indicated that outlet height was the most significant factor in determining the amount of fish passage impedance at low flow, but insufficient water depth appeared to impede passage at one culvert. Site 28 had a slope of 4.9%, no outlet drop, and an average water depth of just 1.5 cm (0.05 ft), yet had a relatively high (70%) passage impedance (Table 6). There was no passage impedance at a similar culvert with a comparable slope (4.4%) and no outlet drop, thus the very shallow water depth was likely the factor that impeded passage.

There was only one site where no fish passed successfully through the culvert. Site 13 was considered a barrier by FishXing due to a large outlet drop (excessive leap), insufficient water depth, and excessive water velocity (Table 6). The culvert had a slope of 3.9%, an outlet drop of 46 cm, and an average water depth of 3.1 cm. While fish passed successfully through similar conditions at other culverts, none passed through this culvert. However, this was most likely due to a lack of a suitable jump location, as the outlet configuration was such that the water plunged directly onto rocks.

Fish length may be an important factor in determining the ability of fish to pass through culverts, since swimming ability is known to increase with a fish's body length (MacPhee and Watts 1976, Jones et al. 1974). However, little evidence was found to support this, as the lengths of fish passing through the treatment (culvert) reaches were similar to the lengths of those which passed through the control reaches. Furthermore, fish of many different lengths were found passing through the same physical conditions. This is similar to findings from a previous field study of 6 culvert sites in Montana where

it was concluded that there was no relation between the length of trout and passage ability (Belford and Gould 1986). It was suggested by the authors that this may have been a result of smaller fish being able to use the lower-velocity zones (boundary layer) near the bottom or sides of the culvert more efficiently than larger fish. More recently, the use of these lower-velocity zones by juvenile fish has been documented through a field study (Kane et al. 2000). This may have been the case in the direct passage study, however, I suspect that it may have also indicated that water velocity, and thus swimming ability, was not a major factor in determining passage ability at low flow.

Conclusions and Management Implications

The results from the direct passage assessment indicated that the majority of culverts were restricting passage to numerous upstream habitats that may be important for spawning, growth, and survival, but they were generally not isolating populations nor serving as complete barriers to protect native species from non-native species encroachment. Furthermore, the results also suggested that the current FishXing model may overestimate the number of barriers to fish passage.

While the direct passage results indicated that more passage was occurring at low flow than may have been expected, how much passage is occurring at other flows is still uncertain. In particular, further investigation is needed to determine the extent of passage impedance occurring at higher streamflows, as the resulting elevated water velocities in the culverts are likely to restrict or block passage (Baker and Votapka 1990, Votapka 1991; Bates et al. 1999; ODF 2000).

Ideally, all culverts would pass all migratory species and life stages at all flows, but this study showed that a majority of the culverts studied had some degree of passage impedance. However, the amount of passage impedance that can occur without having substantial negative impacts to fish populations is unknown and thus warrants further research.

In order to prioritize culvert sites to maximize the effectiveness of fish passage improvement projects, an accurate method to evaluate the amount of fish passage that is occurring through culverts is crucial. This and other studies (United States General Accounting Office 2001) indicate that some of the commonly used tools to evaluate fish passage result in large numbers of culverts being classified as barriers. While this may be useful for estimating the overall extent of the problems regarding culvert barriers, managers will need a tool to assess the amount of passage that is occurring, or level of concern, for each of the barriers. This information could then be used in conjunction with other factors such as the quantity and quality of upstream habitat to prioritize fish passage improvement projects and subsequently maximize the effectiveness.

The FishXing model is a commonly used tool to evaluate the fish passage status of culverts, but the users of the model need to be careful when they interpret the results. For example, in this study, fish were able to successfully pass unimpeded through shallow water depths (3.1cm) that were considered barriers by the model (Table 6) and according to the current literature. However, careful interpretation of the results regarding water depth could lessen the tendency to label these culverts “barriers”, when it may be more appropriate to note that shallow water depth could be a concern. Replacement of a depth “barrier” such as this would likely produce very little response

from the fish population, if indeed passage was already occurring as the results of this study suggest. In addition, a majority of the recommended minimum water depths found in the literature are not based on field tests of fish passage through culverts, and the results of this study support the need for more research into this topic.

While careful interpretation of the model results may help remedy the problem of designating culverts with shallow water depth as “barriers”, other refinements are needed to increase the overall accuracy of the model. For instance, this study also indicated that fish were able to pass through culverts identified as barriers due to an excessive leap height at the outlet. While further research will be necessary to determine exactly how the fish were able to overcome these physical conditions, it appears that their swimming and jumping abilities may be greater than previously recognized. However, I suspect that they may also be using the upward currents in the plunge pool for assistance with their leaps (Stuart 1962). Regardless of the cause for these discrepancies, further field testing could be used to calibrate the model and thus increase the overall accuracy, ultimately producing a tool that could help managers make better informed decisions regarding fish passage improvement projects.

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APPENDIX A

CULVERT LOCATIONS

Table 7. Location (latitude and longitude), stream name, and the USDA Forest Service culvert identification numbers for the 46 culverts studied.

Site	Latitude	Longitude	Stream Name	Culvert ID Number
1	N 47 11.474	W 113 32.145	Archibald Creek	0116-000481
2	N 47 12.890	W 113 35.479	Fawn Creek	0116-000482
3	N 47 12.003	W 113 36.495	Fawn Creek	0116-000483
4	N 47 13.603	W 113 37.621	Sheep Creek	0116-000485
5	N 47 15.438	W 113 36.184	Unnamed Creek	0116-000486
6	N 47 15.452	W 113 36.446	Unnamed Creek	0116-000487
7	N 47 15.339	W 113 37.228	Unnamed Creek	0116-000488
8	N 47 17.476	W 113 38.286	Unnamed Creek	0116-000489
9	N 47 18.991	W 113 38.925	Unnamed Creek	0116-000490
10	N 47 17.628	W 113 34.929	Uhler Creek	0116-000491
11	N 47 17.622	W 113 35.507	Uhler Creek	0116-000492
12	N 47 19.839	W 113 38.125	Uhler Creek	0116-000493
13	N 47 19.702	W 113 35.802	Colt Creek	0116-000494
14	N 47 22.594	W 113 39.256	Bertha Creek	0116-000495
15	N 47 22.206	W 113 35.257	Unnamed Creek	0116-000496
16	N 47 21.752	W 113 32.350	East Fork Clearwater River	0116-000498
17	N 47 19.802	W 113 34.838	Unnamed Creek	0116-000499
18	N 47 19.788	W 113 34.629	Unnamed Creek	0116-000500
19	N 47 19.524	W 113 34.717	Richmond Creek	0116-000601
20	N 47 19.601	W 113 34.622	Richmond Creek	0116-000602
21	N 47 20.298	W 113 33.032	Richmond Creek	0116-000603
22	N 47 20.388	W 113 32.638	Richmond Creek	0116-000604
23	N 47 18.428	W 113 33.003	Unnamed Creek	0116-000605
24	N 47 18.084	W 113 32.780	Inez Creek	0116-000606
25	N 47 18.845	W 113 32.375	Inez Creek	0116-000607
26	N 47 17.927	W 113 32.172	Camp Creek	0116-000608
27	N 47 16.862	W 113 32.448	Unnamed Creek	0116-000609
28	N 47 15.620	W 113 32.963	Findell Creek	0116-000610
29	N 47 16.016	W 113 32.248	Findell Creek	0116-000611
30	N 47 14.768	W 113 32.313	Benedict Creek	0116-000612
30	N 47 15.175	W 113 32.625	Murphy Creek	0116-000613
31	N 47 14.768	W 113 32.313	Benedict Creek	0116-000614
31	N 47 15.807	W 113 32.027	Murphy Creek	0116-000615
32	N 47 15.812	W 113 31.770	Murphy Creek	0116-000616
35	N 47 14.800	W 113 31.846	Benedict Creek	0116-000617
36	N 47 14.115	W 113 31.978	Sawyer Creek	0116-000618
37	N 47 12.857	W 113 31.283	Rice Creek	0116-000619
38	N 47 12.928	W 113 31.239	Rice Creek	0116-000620
39	N 47 12.947	W 113 31.230	Rice Creek	0116-000621
40	N 47 13.840	W 113 30.543	Rice Creek	0116-000622
41	N 47 11.842	W 113 30.138	Auggie Creek	0116-000623
42	N 47 12.425	W 113 29.775	Auggie Creek	0116-000624
43	N 47 10.934	W 113 29.097	Seeley Creek	0116-000625
44	N 47 10.979	W 113 28.887	Seeley Creek	0116-000626
45	N 47 11.027	W 113 28.760	Seeley Creek	0116-000627
46	N 47 12.629	W 113 27.285	Seeley Creek	0116-000628