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[Article]

Assessment of Trout Passage through Culverts in a Large Montana Drainage during Summer Low Flow

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Abstract.—We used a combination of methods to assess the degree of fish passage restriction from road culverts during summer low flow for westslope cutthroat trout *Oncorhynchus clarkii lewisi* and brook trout *Salvelinus fontinalis* across a large drainage basin. The FishXing fish passage model classified 41 of 45 (91%) culverts as barriers to upstream passage for 152-mm westslope cutthroat trout. Population sampling upstream and downstream of 23 culverts revealed little differences in westslope cutthroat trout or brook trout above and below culverts, although density declined upstream when culvert slopes exceeded 4.5% and outlet drops exceeded 20 cm. A passage experiment with marked trout at 12 culverts showed that the proportion of upstream movement averaged 2.45 times lower through culverts (mean, 0.37) than through natural stream reaches (mean, 0.63; $\chi^2 = 26.2$, $P < 0.001$). Outlet drop was the most important factor affecting passage success; probability of passage was low for small trout (<100 mm fork length) at outlet drops greater than 15 cm and for large trout (>100 mm) at outlet drops greater than 21 cm. Agreement between FishXing model predictions and observed upstream passage through test culverts was low overall (17%, $n = 12$); the model tended to overestimate the number of impassable culverts, underscoring a need for further field testing to refine the model. Overall, the high degree of upstream movement observed in our study for juvenile and adult westslope cutthroat trout and brook trout during the summer indicates that culvert passage is an important management consideration for stream salmonids during this period.

Culverts and other types of road crossings are among the most ubiquitous anthropogenic features of river networks; average densities exceeding one culvert per 5 stream kilometers are common in some drainages (e.g., Tchir et al. 2004). Recent studies have emphasized the need for more in-depth assessment of the effects of such structures on fish populations, given that a high proportion may impede fish passage over large areas. Of the 10,215 culverts on fish-bearing streams on federal lands in Oregon and Washington, an estimated 54% impede fish passage (USGAO 2001). In Labrador, 53% of culverts along a recently constructed highway were deemed impassable to juvenile and adult Atlantic salmon *Salmo salar* (Gibson et al. 2005); 61–74% of culverts in two Alberta watersheds were classified as passage barriers to juvenile and adult salmonids (Tchir et al. 2004), as were 77% of 86 culverts surveyed in Idaho (Lyman 2005).

Such restriction or blockage of fish passage at culverts results in the direct loss of spawning and rearing habitat upstream, thus reducing overall population productivity (Fausch et al. 2002). For example, Eaglin and Hubert (1992) found trout biomass in Wyoming streams was negatively related to culvert density. Local extirpation as a result of habitat fragmentation (Winston et al. 1991; Schrank et al. 2001; Morita and Yamamoto 2002) and population isolation attributable to reduced gene flow and reduced habitat connectivity from culvert barriers (Wofford et al. 2005) are also of concern. Given the large number of potential culverts acting as barriers and the high remediation costs involved (USGAO 2001), reliable and easily applicable tools are needed to assist managers in identifying impassable culverts and prioritizing their retrofitting or removal to improve passage success and habitat access (O'Hanley and Tomberlin 2005).

Previous fish passage research has focused primarily on the barriers to upstream spawning runs of anadromous salmonids. However, spawning and nonspawning movements of smaller nonandromous salmonid juveniles and adults and of nonsalmonid fishes in general may be equally prevalent and important for species persistence (Warren and Pardew 1998; Schmetterling and Adams 2004). A literature review on the passage of juvenile and adult salmonids through

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culverts concluded that upstream movement was common among all species, age-classes, and seasons (Kahler and Quinn 1998). High water velocity, inadequate water depth, and excessive outlet drops are recognized as the main features of culverts that can impede passage, with passage success depending on the swimming and leaping abilities of fish in relation to these physical factors (Votapka 1991).

Several different approaches have been used to evaluate fish passage through culverts. Monitoring movement of tagged fish through culverts allows direct determination of passage success in relation to discharge, culvert characteristics, and fish species and size (Belford and Gould 1989; Warren and Pardew 1998), but the method is labor intensive and generally practical only for assessing passage for a small number of individual fish and culverts over a short period of time. FishXing (Furniss et al. 2008) is a widely used software program that (1) combines stream discharge and culvert characteristics (slope, length, roughness) to predict hydraulic conditions in and near the culvert and (2) compares the combination of factors against a fish's swimming and leaping abilities to estimate passage success or failure. The model is useful for evaluating passage status of a large number of culverts with a relatively small amount of field data collection and for defining "passage windows" for species over a range of flow conditions (Cahoon et al. 2007). However, model accuracy is uncertain given a lack of information on swimming and leaping abilities of many fish species (Furniss et al. 2008), and only a few studies have compared model predictions with field observations (Rajput 2003; Karle 2005). Comparison of population characteristics (fish length, density, and species occurrence) upstream and downstream of culverts also has been used to assess degree of passage restriction (Resh 2005; McLaughlin et al. 2006). However, observed population differences could be partially or entirely attributed to other factors (e.g., habitat differences, predation, competition), or might be evident only during certain time windows such as spawning.

Ideally, road crossings should pass aquatic organisms at all life stages throughout all seasons of the year. However, most studies have concentrated on spawning migrations, and few studies have evaluated the extent to which culverts impede upstream movement of smaller-bodied salmonid adults and juveniles across an entire watershed during all seasons of the year. This is particularly true for the low-flow period during summer, despite the recognized significance of movement of both age groups during this period (Young 1996; Schmetterling and Adams 2004). The main objective of our study was to determine the extent of trout passage restriction at culverts within a large drainage basin during summer low flow. We sought to determine culvert features that influence upstream passage of juvenile and adult trout by using three different assessment methods: model predictions from FishXing; comparison of fish population characteristics downstream and upstream of culverts; and measurements of movement of marked fish through culverts with various hydraulic characteristics. Our secondary objective was to assess the level of agreement among the different culvert passage assessment methods.

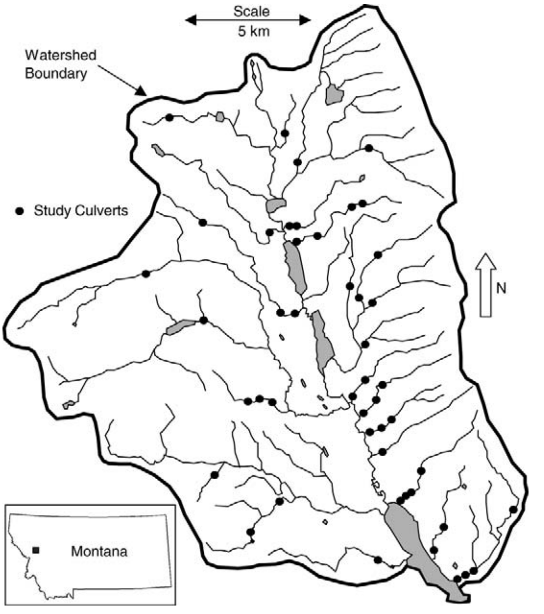

FIGURE 1.—Map of the upper Clearwater River basin, western Montana, showing locations of study culverts.

Study Area

The study area consisted of all the streams in the upper Clearwater River drainage upstream of the Seeley Lake outlet (Figure 1). We chose this area because of the large number of culverts of different types located throughout the watershed, the variety of land ownership and road types, and the presence of an array of stream types and sizes. Total available habitat in the study area was estimated at 196 km, determined as the linear distance of streams having less than 15% gradient. The watershed is located in northwestern Montana and encompasses approximately 370 km^2 of private, federal, and state lands. Twenty fish species live in the drainage, but most are found in lakes; only three native species (westslope cutthroat trout *Oncorhynchus clarkii lewisi*, bull trout *Salvelinus confluen-*

tus, and slimy sculpin *Cottus cognatus*) and three nonnative species (brown trout *Salmo trutta*, brook trout *Salvelinus fontinalis*, and brook stickleback *Culaea inconstans*) were detected in study streams.

Methods

FishXing model.—We used FishXing version 3.0.11 (Furniss et al. 2008) to predict whether a culvert was a barrier or nonbarrier to upstream movement. Forty-five culverts were analyzed by using FishXing under the conditions observed in the field during the low flows of two consecutive summers, according to the recommended culvert assessment protocol for the model (Clarkin et al. 2005). Forty-seven unique culverts were examined, including only those culverts on streams having adequate flow (>60 L/min) and gradient (<15%; measured on a 1:24,000-scale topographic map) sufficient to support fish as corroborated by electrofishing. Only 45 of these were analyzed using FishXing; 1 of the 47 was replaced with a bridge after preliminary data were observed but before FishXing inputs could be recorded (site 484), and another (site 610) had been retrofitted with steel baffles to the extent that the hydraulic routine in FishXing was inappropriate (Furniss et al. 2008).

Culvert slope, length, channel gradient upstream and downstream of the culvert, outlet drop height, outlet plunge pool depth, the downstream cross-sectional geometry, inlet and outlet flow depths, and constriction ratio (culvert width/average bank-full width) were recorded at each culvert. Channel roughness was determined on the basis of physical characteristics of the culvert and visually estimated dominant substrate particle size within the culvert and adjacent stream channel. Bank-full channel widths were measured at five locations over 30-m reaches upstream and downstream of a culvert. Mean water velocity was measured at the culvert inlet and outlet with a current meter, and discharge was computed from a stream cross-section located in a natural stream reach upstream of the culvert.

At each culvert, the FishXing hydraulics model was calibrated by following the approach of Karle (2005). We calibrated the depth predictions of the model by minimizing the difference between observed and predicted flow depths, using flow depth as a correlate of velocity, which we could not measure along the length of the small-diameter study culverts. Culvert velocity was predicted from a combination of flow depth measurement, culvert slope, and bottom roughness. Bottom roughness was estimated by using values of Manning's n for the given culvert material or substrate as listed in the FishXing model. For model calibration, Manning's n was adjusted over a wide range of values (0.005–0.100) for successive model runs of predicted flow depth until the minimum average absolute relative error (AARE, %) between observed and predicted flow depths was achieved. We calculated AARE with y as the flow depth, either predicted (pred) or observed (obs), at each end of the culvert:

$$\text{AARE} = 100\left(\frac{1}{2}\right)\left[\left(\frac{|y_{\text{obs}} - y_{\text{pred}}|}{y_{\text{obs}}}\right)_{\text{inlet}} + \left(\frac{|y_{\text{obs}} - y_{\text{pred}}|}{y_{\text{obs}}}\right)_{\text{outlet}}\right].$$

The average AARE over all sites decreased modestly as a result of calibration, from 53.9% (range, 0–300%) before calibration to 47.8% (range, 0–260%) after calibration. For 11 of 45 culverts, the default Manning's n was also the calibrated Manning's n, indicating that calibration did not improve model predictions. Over all 45 culverts, the average Manning's n was 0.028 before calibration and 0.034 after calibration.

After hydraulic calibration, we determined passage for westslope cutthroat trout (hereafter, cutthroat trout) by using FishXing and a 152-mm cutthroat trout as the analysis fish. Swimming ability criteria of cutthroat trout were based on literature values from Bell (1991), as provided in the FishXing model. Cutthroat trout of this size represented about the 75th percentile of the size range of fish captured in the study area (mean, 85 mm fork length; range, 33–203 mm). We used a conservative user-selected minimum allowable flow depth for fish passage of 9.1 cm. These values were input into the model to produce output classification of a culvert's barrier status as either passable or impassable. If the culvert was classified as impassable, the cause was given by the model as (1) water velocity in the culvert exceeds the fish swimming ability (hereafter, velocity); (2) the outlet drop height exceeds the fish leaping capability (leap height); (3) water depth in the culvert is less than the prescribed minimum (depth); and (4) the outlet pool depth is insufficient to facilitate a jump into the outlet (pool depth).

Fish population characteristics.—We used single-pass electrofishing (Kruse et al. 1998) to sample 90-m reaches upstream and downstream of a subset of 23 study culverts. Because low conductivities (<100 μS/cm^3) precluded electrofishing in some streams, thus barring random selection of the subset, we selected the subset to represent the range of conditions of all the culverts in the study. A Smith-Root Model 15-D generator-powered backpack electrofishing unit was operated at a DC pulse frequency of 30–40 Hz at 400–700 V, depending on water conductivity. All captured fish were anesthetized and identified to species, and fork length was measured to the nearest millimeter. We limited our analysis to cutthroat trout and brook trout because brook sticklebacks, slimy sculpin, bull trout, and brown trout were collected at only a few (2–4) sites. Initial three-pass removal population estimates (VanDeventer and Platts 1989) conducted at two study sites indicated that a mean of 66% of total trout present were captured on the first pass and that the overall capture probability was 0.75.

We used a chi-square goodness-of-fit test to compare relative species abundance upstream and downstream of all culverts combined and at individual culverts. For individual culverts, we excluded sites with very low densities (<4 fish/reach) from the analysis. We used *t*-tests to examine length differences by species between downstream and upstream reaches for all culverts combined, as well as at individual culverts where at least 10 individuals of a species were collected both upstream and downstream of the culvert. We assessed the possible influence of culvert characteristics on downstream and upstream distribution of a species by plotting the upstream proportion of the total number caught downstream and upstream at a site against the culvert slope (potential velocity barrier) and the culvert outlet drop (potential leap barrier) and used simple linear regression to assess these relationships.

Passage experiment.—Direct passage of fish through culverts was measured at 12 study culverts during the low water flows of July through September during the second year of the study. Study culverts were selected to represent the range of culvert characteristics present in the study area. At each site, a reference reach and a treatment reach were designated, the reference reach being located immediately downstream of the treatment reach containing the culvert (Figure 2). The downstream end of the treatment reach was positioned near the downstream end of the culvert plunge pool, and the upstream end was positioned within 5 m of the culvert inlet. Treatment reaches varied in length from 17.3 to 33.8 m because of differences in culvert length and plunge pool dimensions. Stream surface areas encompassed by reference reaches were equivalent to those of the treatment reaches. Each reach was blocked at the downstream and upstream ends with 6-mm wire mesh. A trap box was positioned to capture fish at the upstream end of each reach. Trap boxes were constructed of 13-mm plywood and 6-mm wire mesh. Pyramid-shaped entrances were constructed in the traps to minimize the escape of trapped fish, and baffles were placed within trap boxes both to provide cover and flow refuge and to direct water through the entrance to create attraction flow. Wire mesh leads at the upstream

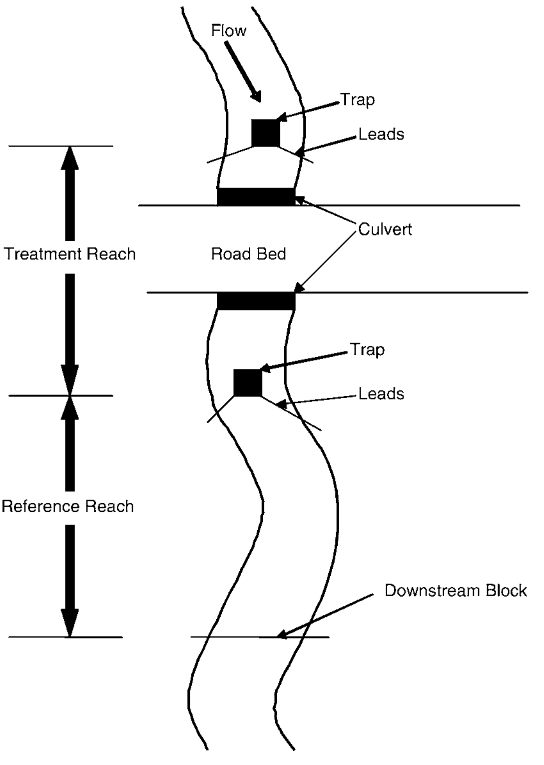

FIGURE 2.—Diagram showing design of an experiment examining trout passage at culverts.

end of each reach were positioned diagonally to direct fish towards the trap boxes.

After trap installation, we removed fish in study reaches by electrofishing and placed them downstream of the study area. Test fish were then obtained by electrofishing upstream of the study reaches until 40–50 trout (brook trout, cutthroat trout, or combined) were collected. Test fish were anesthetized with clove oil, measured, and divided into two similar groups based on species and size. Groups were then randomly assigned to the treatment reach or the reference reach, and fish within each group were marked with pelvic fin clips. The marked fish were released into the downstream end of their designated reach. Fish were recaptured in the traps as they moved upstream toward their original capture location.

The number of fish that moved upstream into trap boxes was monitored for 72 h after release. Recaptured fish were anesthetized, identified by species, measured to the nearest millimeter, checked for fin clips, and released. The hydraulic conditions at each culvert were measured daily during the test period and averaged. Water depths and velocities were measured at the inlet

TABLE 1.—Interpretation of passage index (PI) values.

Value of PI	Interpretation
PI = 1	Some fish passed through the culvert (treatment) reach, but no fish passed through the reference reach.
0 < PI <1	Fish passed through both reaches, but more fish passed through the culvert reach than through the reference reach.
PI = 0	The same number of fish passed through both the culvert and reference reaches.
−1 < PI < 0	Fish passed through both reaches, but more fish passed through the reference reach than through the culvert reach.
PI = −1	Some fish passed through the reference reach, but no fish passed through the culvert reach.

and outlet of the culvert and at an upstream cross-section to compute discharge. During testing, daily water temperatures ranged from 7°C to 14°C.

We compared the frequencies of fish moving upstream through culvert (treatment) and natural stream (reference) reaches with a 2 × 2 chi-square contingency table. The odds of fish passage through the culvert versus the natural stream reaches was assessed with an odds ratio test, the results being considered significant if the 95% confidence interval (CI) of the ratio did not contain 1.0 (Quinn and Keough 2002). Effects of mean fish length on passage were first examined with *t*-tests. Test fish were then grouped into roughly equal size-classes (less than and greater than 100 mm), and the proportion of each size-class passing through test culverts was compared among the five different culvert features measured (slope, length, outlet drop, water depth, and water velocity) with use of a chi-square test.

To standardize comparison of movement among sites having different levels of within-site movement, we calculated a passage index (PI):

$$\mathrm{PI} = (P_t - P_r)/(P_t + P_r),$$

where P_t refers to proportion of marked fish passing through the treatment reach and P_r is the proportion passing through the reference reach. The PI is a dimensionless number ranging from −1 to + 1 and is interpreted as shown in Table 1. Simple linear regression was used ($\alpha = 0.10$) to examine relationships between the PI for all trout combined, and for small (<100 mm) and large trout (>100 mm) separately, in relation to physical conditions of the culvert that were likely to influence the ability of fish to leap into (outlet drop) and swim through the culvert (culvert slope, culvert length, water depth, current velocity).

Congruency between model predictions and field results.—To determine congruency among methods for assessing fish passage, we compared the level of agreement of culvert barrier status predicted by the FishXing model (passable or impassable) with field observations of upstream passage for the 12 test culverts.

Results

FishXing Model Application

The FishXing model classified 91% (41 of 45) of the studied culverts as barriers to upstream passage for 152-mm-long cutthroat trout and 9% (4 of 45) as passable (Table 2). Insufficient water depth was identified as the main barrier to passage (36 culverts, or 80%). The remaining five culverts were predicted to be impassable because of combinations of culvert length, velocity, water depth, and outlet pool depth.

Characteristics of Upstream and Downstream Fish Populations

In total, 356 brook trout and 533 cutthroat trout were captured by electrofishing 90-m reaches downstream and upstream of 23 culverts (Table 2). Site 499 was omitted from analysis because the stream was dry just upstream of the culvert. Cutthroat trout were present at 22 of 23 sites; brook trout were present at 15 of 23 sites. Among individual sites, a species was present downstream but absent upstream in only two sites (493, 498), whereas the reverse was observed in only four sites (487, 488, 495, 615). In all six cases where species were absent either downstream or upstream of a culvert, abundances in the opposite reach were low (≤4 fish/reach).

Cutthroat trout were found both upstream and downstream at all but 4 of the 23 sites. Where they were absent either upstream or downstream of a culvert, abundances were low (1–3 fish/reach) in the opposite reach. In no cases were cutthroat trout isolated above a culvert, as would be indicated by high density upstream and absence downstream. Cutthroat trout density was significantly higher downstream of culverts than upstream at only two sites (603 and 607; χ^2 tests: $P < 0.10$); downstream–upstream differences were not significant at the remaining 15 sites, at which densities were moderate to high. Brook trout also were present in equal numbers both upstream and downstream at nearly all sites where observed. Brook trout were absent downstream of culverts at 3 of the 15 sites where this species was found. At these

TABLE 2.—Physical characteristics of Clearwater River drainage, Montana, culvert study sites and summary of results of FishXing model analysis, upstream and downstream population surveys, and direct passage experiment (culvert types; c = circular or ellipse steel pipe, b = box culvert, and a = open-bottom arch; FishXing status: Pass = passable culvert, L = leap barrier, V = velocity barrier, Pd = outlet pool depth barrier, and D = depth barrier). Underlined values indicate significant ($P < 0.10$) differences in abundances or fork length (FL) of westslope cutthroat trout (CTT) and brook trout (BRT) sampled downstream versus upstream of study culverts. Passage index (PI) calculation is defined in Methods.

			Culvert feature					Fish Xing barrier status	Upstream/downstream population survey abundance (FL; mm)			
									CTT		BRT	
Stream	Site	Culvert type	Length (m)	Width/ diameter (m)	Slope (%)	Outlet drop (cm)	Constriction ratio		Down	Up	Down	Up
Uhler	482	c	12.4	1.2	0.9	9.1	0.70	Pass	–	–	–	–
Richmond	488	c	28.6	1.5	2.4	0	0.89	D	27 (79)	26 (84)	0	4 (52)
Richmond	487	c	11.8	1.8	4.4	0	1.20	D	27 (73)	31 (75)	0	1 (75)
Camp	500	c	11.8	1.0	7.6	24	0.52	D	26 (91)	18 (92)	6 (106)	4 (123)
Uhler	481	c	10.5	1.5	1.3	0	0.48	D	5 (53)	4 (76)	36 (81)	38 (90)
Seeley	615	b	9.8	1.2	0.8	4	0.62	D	0	1 (148)	12 (77)	17 (98)
Fawn	495	c	10.7	1.4	3.4	6	0.55	D	17 (90)	21 (98)	0	2 (139)
Findell	605	b	12.7	1.2	4.9	0	1.00	D	9 (91)	9 (91)	10 (79)	2 (63)
Inez	498	c	11.8	1.5	1.6	0	0.84	D	3 (91)	0	32 (91)	32 (89)
Benedict	607	c	13.0	1.3	5.0	21	0.78	D, L, Pd	26 (86)	14 (82)	11 (98)	5 (119)
Benedict	608	b	10.0	1.8	3.2	61	1.18	D, L, Pd	13 (105)	13 (73)	6 (92)	25 (69)
Colt	483	c	10.9	1.6	3.9	15	0.45	L, V			–	
Clearwater	484	c	11.2	1.7	2.5	15	0.33	Omitted	17 (49)	11 (62)	–	–
Clearwater	485	a	12.1	4.1	0.8	0	0.89	Pass	1 (92.4)	2 (103)	–	–
Richmond	489	c	26.4	1.8	1.3	0	1.11	D	13 (81)	14 (85)	12 (101)	10 (65)
Richmond	490	c	9.3	1.5	4.9	0	0.92	D	26 (89)	20 (79)	12 (110)	5 (93)
Marshall	493	c	9.4	0.9	2.1	3	0.86	D	1 (74)	0	19 (78)	21 (91)
Swamp	497	c	12.4	1.5	3.0	0	–	D	0 (–)	0 (–)	52 (83)	24 (95)
Inez	499	c	8.7	1.0	6.7	3	0.53	D	21 (120)	dry	0	dry
Rice	601	c	8.1	1.5	−0.3	0	0.96	D	4 (127)	7 (118)	0	0
Inez	602	c	13.0	1.4	4.8	0	0.71	D	20 (99)	12 (94)	0	0
Camp	603	c	12.1	1.6	9.2	6	0.67	D	15 (95)	4 (117)	0	0
Findell	604	c	13.7	1.1	9.9	27	0.70	D	8 (112)	6 (108)	0	0
Fawn	606	c	10.9	1.2	2.0	0	1.33	D, L, Pd	6 (89)	9 (116)	0	0
Benedict	609	c	6.2	0.6	1.0	0	0.35	D	13 (73)	13 (64)	25 (69)	9 (75)
Bertha	492	c	11.2	0.9	2.1	30	0.44	Pass	–	–	–	–
Seeley	617	c	3.7	0.7	1.1	0	0.36	Pass	–	–	–	–
Rice	612	c	12.4	1.1	12.2	5	0.64	D, V	–	–	–	–
Bertha	486	c	12.5	2.0	5.5	6	1.16	D	–	–	–	–
Clearwater	491	c	11.2	1.1	6.0	37	0.59	D	–	–	–	
Archibald	494	c	9.4	1.4	1.5	12	1.15	D	–	–	–	–
Sheep	496	c	12.6	1.5	7.1	5	0.56	D	–	–	–	–
Rice	611	c	21.3	1.2	1.3	0	0.67	D	–	–	–	–
Auggie	613	c	12.4	1.5	6.1	5	1.28	D	–	–	–	–
Auggie	614	c	22.1	1.2	2.4	0	1.08	D	–	–	–	–
Seeley	616	c	13.8	1.4	2.7	4	0.67	D	–	–	–	–
Seeley	618	c	11.1	1.1	−0.9	0	0.77	D	–	–	–	–
Uhler	619	c	8.6	1.5	2.9	49	0.66	D	–	–	–	–
Murphy	620	c	12.4	0.9	7.4	64	0.48	D	–	–	–	–
Murphy	621	c	14.3	0.9	10.6	31	0.52	D	–	–	–	–
Murphy	622	b	9.9	1.2	1.5	19	0.78	D	–	–	–	–
Richmond	624	c	9.5	0.6	5.6	5	0.66	D	–	–	–	–
Richmond	625	c	7.6	0.6	1.1	18	0.62	D	–	–	–	–
Clearwater	626	c	12.5	0.9	3.3	53	0.37	D	–	–	–	–
Clearwater	627	c	16.9	0.9	16.6	2	0.34	D	–	–	–	–
Clearwater	628	c	9.9	1.1	10.6	14	0.56	D	–	–	–	–
Rice	610	c	14.6	1.4	5.7	0	0.86	Baffled	–	–	–	–

sites, abundance was low upstream (1–4 fish/reach). No sites had brook trout present downstream but absent upstream. Brook trout density was significantly higher upstream than downstream at one site (608; $P < 0.001$) and significantly higher downstream than upstream at another (609; $\chi^2 = 11.65$, $P < 0.001$). At all other sites with moderate to high densities upstream and downstream ($n = 9$), brook trout densities were similar ($P = 0.16–0.86$). Upstream density was less than or equal to 50% of downstream density at three sites for cutthroat trout (490, 603, and 607) and three sites for brook trout (605, 607, 609).

TABLE 2—Extended.

	Proportion moving upstream (initial N) in passage experiment						
	Reference reach			Culvert reach			
Stream	CTT	BRT	Total	CTT	BRT	Total	Experiment PI
Uhler	0.0 (2)	0.43 (23)	0.40 (25)	0.5 (2)	0.87 (23)	0.84 (25)	0.35
Richmond	0.61 (23)	0.0 (2)	0.56 (25)	0.68 (22)	1.0 (3)	0.72 (25)	0.13
Richmond	0.67 (24)	0.0 (1)	0.64 (25)	0.67 (24)	0.0 (1)	0.68 (25)	0.03
Camp	0.84 (19)	0.0 (1)	0.80 (20)	0.58 (19)	0.0 (1)	0.55 (20)	−0.19
Uhler	0.20 (5)	0.10 (20)	0.12 (25)	0.17 (6)	0.05 (19)	0.08 (25)	−0.20
Seeley	– (0)	0.93 (15)	0.93 (15)	–	0.60 (15)	0.60 (15)	−0.22
Fawn	0.74 (23)	– (0)	0.74 (23)	0.35 (23)	– (0)	0.35 (23)	−0.36
Findell	0.80 (25)	– (0)	0.80 (25)	0.24 (25)	– (0)	0.24 (25)	−0.54
Inez	0.0 (1)	0.58 (24)	0.56 (25)	0.0 (1)	0.17 (24)	0.16 (25)	−0.56
Benedict	0.43 (14)	0.45 (11)	0.44 (25)	0.07 (15)	0.10 (10)	0.02 (25)	−0.69
Benedict	1.00 (10)	0.93 (14)	0.96 (24)	0.07 (15)	0.10 (10)	0.08 (25)	−0.85
Colt	1.00 (2)	0.52 (23)	0.56 (25)	0.0 (2)	0.0 (23)	0.0 (25)	−1.00
Clearwater	–	–	–	–	–	–	–
Clearwater	–	–	–	–	–	–	–
Richmond	–	–	–	–	–	–	–
Richmond	–	–	–	–	–	–	–
Marshall	–	–	–	–	–	–	–
Swamp	–	–	–	–	–	–	–
Inez	–	–	–	–	–	–	–
Rice	–	–	–	–	–	–	–
Inez	–	–	–	–	–	–	–
Camp	–	–	–	–	–	–	–
Findell	–	–	–	–	–	–	–
Fawn	–	–	–	–	–	–	–
Benedict	–	–	–	–	–	–	–
Bertha	–	–	–	–	–	–	–
Seeley	–	–	–	–	–	–	–
Rice	–	–	–	–	–	–	–
Bertha	–	–	–	–	–	–	–
Clearwater	–	–	–	–	–	–	–
Archibald	–	–	–	–	–	–	–
Sheep	–	–	–	–	–	–	–
Rice	–	–	–	–	–	–	–
Auggie	–	–	–	–	–	–	–
Auggie	–	–	–	–	–	–	–
Seeley	–	–	–	–	–	–	–
Seeley	–	–	–	–	–	–	–
Uhler	–	–	–	–	–	–	–
Murphy	–	–	–	–	–	–	–
Murphy	–	–	–	–	–	–	–
Murphy	–	–	–	–	–	–	–
Richmond	–	–	–	–	–	–	–
Richmond	–	–	–	–	–	–	–
Clearwater	–	–	–	–	–	–	–
Clearwater	–	–	–	–	–	–	–
Clearwater	–	–	–	–	–	–	–
Rice	–	–	–	–	–	–	–

Across all sites combined, the mean lengths of cutthroat trout (downstream = 85.2 mm, upstream = 85.9 mm; t = 0.26, P = 0.79) and brook trout (downstream = 85.7 mm, upstream = 86.1 mm; t = 0.11, P = 0.91) were similar downstream and upstream of culverts. Only a few sites had significant size differences, and no patterns of size difference were apparent. Brook trout were significantly longer (t-tests: $P < 0.10$) downstream than upstream at one culvert (500), whereas the reverse was true at another culvert (489; see Table 2). At two sites, cutthroat trout were significantly longer downstream than upstream (490

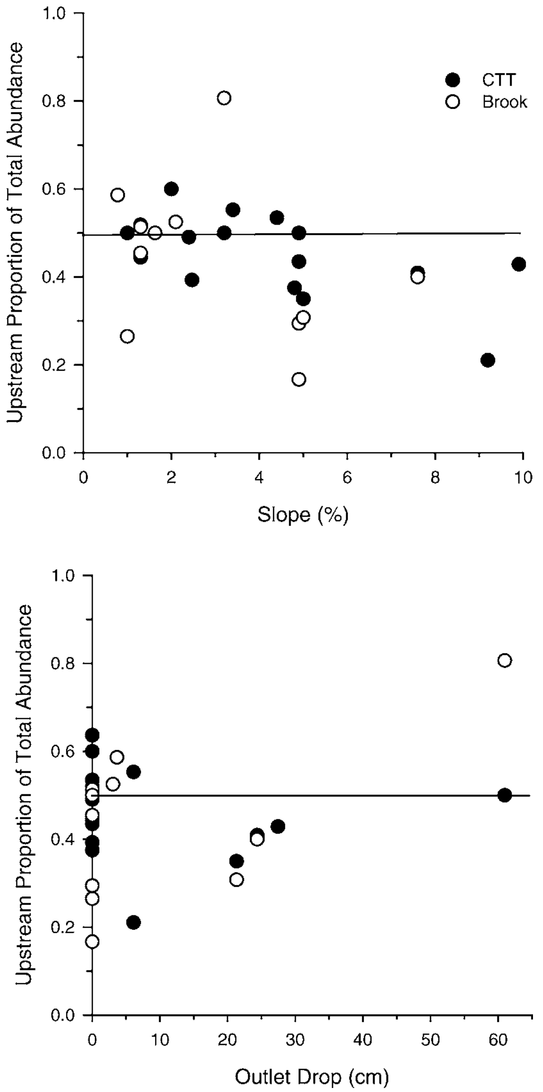

FIGURE 3.—Upstream proportion of the total abundance of brook trout and westslope cutthroat trout (CTT) sampled in 90-m reaches downstream and upstream of 21 study culverts in relation to culvert slope and outlet drop. Horizontal line indicates equal number of trout captured upstream and downstream.

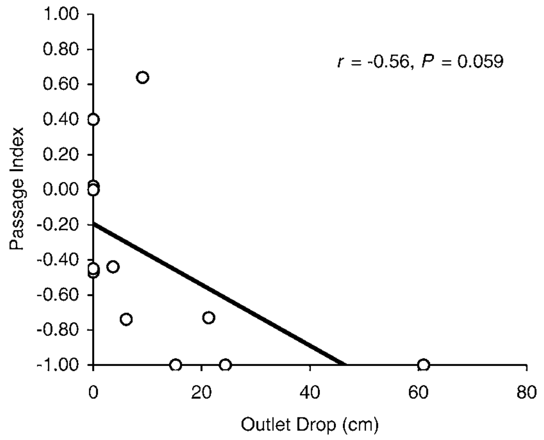

FIGURE 4.—Ratio of movement (passage index, PI; see text for description) of small (<100 mm fork length) westslope cutthroat trout and brook trout through 12 reference and culvert study reaches during the fish passage displacement experiment in relation to culvert outlet drop.

and 608), whereas the reverse was true at another site (481). In all other cases where densities were high enough to allow adequate statistical comparison (≥10 fish/reach), mean lengths of cutthroat trout (nine sites) and brook trout (five sites) were similar ($P > 0.10$) between downstream and upstream reaches.

Cutthroat trout and brook trout density upstream of culverts declined at most sites when culvert slopes exceeded 4.5% and outlet drop heights exceeded 20 cm (Figure 3). The proportion of cutthroat captured upstream of culverts was negatively related to culvert slope ($r = -0.67$, $P = 0.003$), and the upstream proportion of brook trout was negatively related to outlet drop ($r = -0.57$, $P = 0.06$). Neither the relationship between brook trout proportion upstream and culvert slope ($r = -0.36$, $P = 0.27$) nor that between cutthroat trout proportion upstream and outlet drop ($r = -0.14$, $P = 0.62$) was significant.

Passage Experiment

At 12 test culverts, a total of 539 brook trout and cutthroat trout were captured, marked, and released during displacement experiments to assess fish passage. Cutthroat trout made up 55% of the test fish and brook trout made up 45%. Lengths (mean ± SE) of fish released in reference (93.8 ± 1.9 mm) and treatment (94.8 ± 1.8 mm) reaches were similar ($t = 0.39$, $P = 0.70$); however, because released brook trout were slightly but significantly larger than cutthroat trout (101.3 ± 1.9 mm versus 92.1 ± 1.4 mm; $t = 3.9$, $P < 0.0001$), we analyzed passage of these species both combined and separately. Sample sizes were insufficient to allow comparison of relative passage success between species while controlling for length differences.

Across all sites combined, upstream movement of marked fish was significantly lower through culverts than through natural stream reaches ($\chi^2 = 26.2$, $P < 0.001$). The proportion of marked fish recaptured averaged 0.63 in reference reaches (range, 0.12–0.95) and 0.37 in culvert reaches (range, 0.00–0.84). The

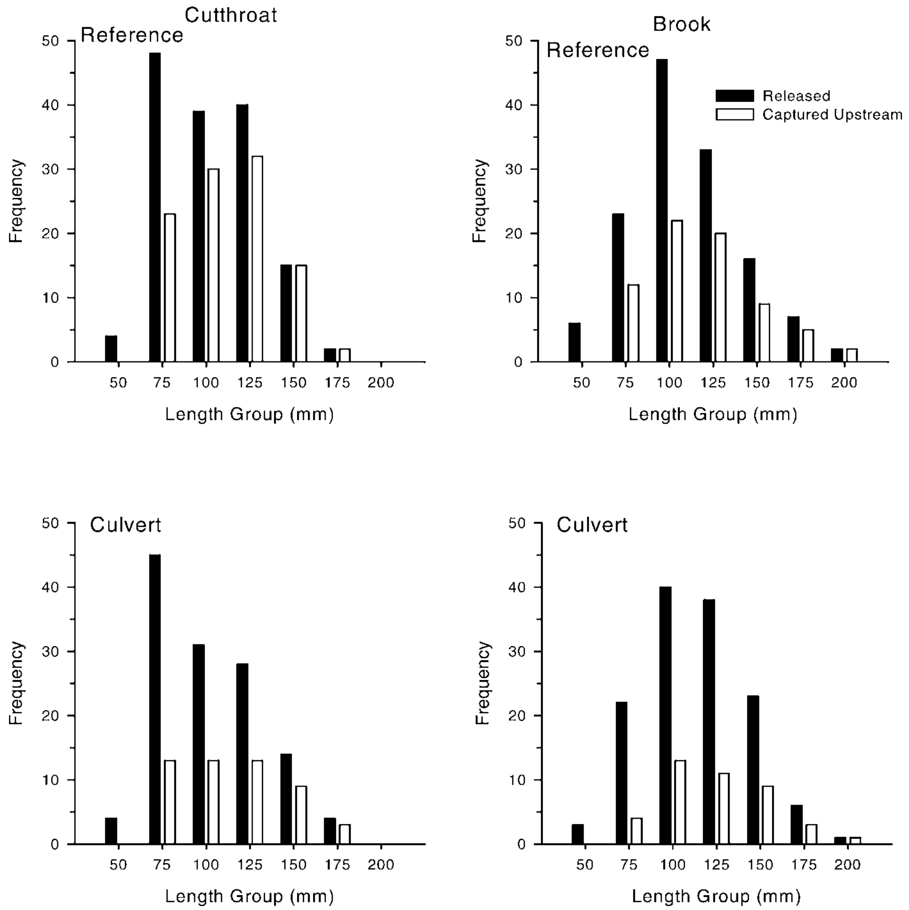

FIGURE 5.—Number of westslope cutthroat trout and brook trout moving upstream through reference and culvert reaches in relation to fish fork length. Dark bars refer to number of fish marked and released; open bars refer to number recaptured for each length-group. Values shown represent the upper end of each length-group.

odds of fish passage was 2.45 times greater (95% CI, 1.74–3.47; does not contain 1.0) through natural stream reaches for all trout combined and 3.15 (95% CI, 1.95–5.11) and 1.94 (95% CI, 1.17–3.24) times greater for cutthroat trout and brook trout, respectively. Significant passage restriction (<50% movement through culvert compared with reference reach; PI ≤ -0.36) was observed at six culverts (483, 495, 498, 605, 607, 608); in these locations, the proportion of marked fish that moved through natural stream reaches ranged from 0.40 to 1.00 (mean, 0.68) and the proportion that moved through culvert reaches ranged from 0.00 to 0.35 (mean, 0.14; Table 2). Movement through culverts was especially restricted at sites 483, 607, and 608, where only 0–10% of the 25 released fish moved through culverts, compared with 40–100% in associated reference reaches.

For all trout combined, there were no significant associations between passage success and culvert slope ($r = -0.28$, $P = 0.38$), culvert length ($r = 0.38$, $P = 0.38$), water depth ($r = 0.01$, $P = 0.97$), and water velocity ($r = 0.33$, $P = 0.35$). However, passage success of small trout (<100 mm) was negatively associated with outlet drop ($r = -0.56$, $P = 0.059$; Figure 4). There were no other significant associations with culvert characteristics and passage of either small or large (>100 mm) fish. Data transformations to assess potential nonlinear associations did not improve model fit.

Cutthroat trout and brook trout that passed through culverts and natural stream reaches were significantly longer (mean ± SE) than fish that did not move (natural stream reaches: 102.2 ± 2.2 mm versus 80.9 ± 2.8 mm, $t = 5.9$, $P < 0.001$; culverts: 106.8 ± 2.9 mm versus 88.1 ± 2.2 mm, $t = 5.1$, $P < 0.001$; Figure 5). No fish less than 50 mm passed through either culvert or natural stream reaches, whereas 75% of

TABLE 3.—Proportion of small (<100-mm) and large (100–200 mm) trout (westslope cutthroat trout and brook trout combined) moving upstream through culverts in fish passage experiments in relation to culvert slope, length, outlet drop, water depth, and water velocity.

Culvert feature	Category (sites *N*)	Proportion moving upstream (initial *N*) for length-group	
		<100 mm	>100 mm
Slope (%)	<2 (4)	0.35 (49)	0.44 (41)
	2–4 (4)	0.21 (51)	0.36 (47)
	4–7.6 (4)	0.29 (55)	0.50 (40)
Length (m)	9–13 (11)	0.24 (139)	0.39 (119)
	28.6 (1)	0.63[a] (16)	0.89[b] (9)
Outlet drop (cm)	0–15 (9)	0.38 (119)	0.74[a] (93)
	21–24 (2)	0.14 (22)	0.43 (23)
	61 (1)	0.00[b] (14)	0.18 (11)
Water depth (cm)	2–3.5 (5)	0.23 (69)	0.43 (51)
	3.5–12 (4)	0.34 (47)	0.56 (41)
	12–20 (3)	0.31 (39)	0.30 (36)
Water velocity (cm/s)	35–60 (4)	0.24 (58)	0.33 (42)
	62–75 (5)	0.25 (72)	0.48 (41)
	140 (1)	0 (2)	0.61 (18)
Overall	Culvert	0.30[a] (145)	0.42[a] (114)
	Reference	0.52 (167)	0.74 (115)

[a] χ^2 test: $P < 0.05$.
[b] Fisher's exact test (cell counts < 5): $P < 0.05$.

released fish greater than 175 mm passed successfully. Overall, the length of trout that moved upstream was similar between culvert and natural stream reaches (cutthroat trout: $t = 0.7$, $P = 0.50$; brook trout: $t = 0.9$, $P = 0.35$).

Across all sites, both small (<100 mm) and large (>100 mm) fish moved significantly less frequently through culverts than through natural stream reaches (small fish: 30% versus 52%, $\chi^2 = 13.7$, $P < 0.001$; large fish, 42% versus 74%, $\chi^2 = 23.3$, $P < 0.001$). Culvert slope, culvert length, and water depth did not appear to differentially affect passage of small and large fish (Table 3). Small and large fish passed through culverts at depths as shallow as 2.0–3.5 cm at rates similar to that across all culverts combined, and both size groups passed the longest culvert (28.6 m) at proportions greater than expected. Small and large fish passed through culvert velocities of 35–75 cm/s at expected levels. At the highest-velocity culvert (500; 140 cm/s), 61% of large fish successfully passed upstream, whereas no small fish successfully passed, although only two fish less than 100 mm long were released. Outlet drop restricted passage of small fish to a greater degree than large fish. Passage restriction for either length-group was not significantly different than that measured for all culverts at outlet drops of 0–15 cm and for large fish at outlet drops of 21–24 cm. However, only 2 of 22 (14%) small fish passed successfully at outlet drops of 21–24 cm ($P = 0.16$) and 0 of 14 small fish passed through the culvert having the highest outlet drop of 61 cm (608; $P = 0.03$; Table 3). Despite the large outlet drop, 2 of the 11 large fish released successfully passed through this culvert (106- and 150-mm-long brook trout) but the passage rate (0.18) was less than half that expected ($P = 0.15$).

Congruency between Methods

Of the 12 test culverts, FishXing classified one culvert as passable and 11 culverts as barriers to passage. Field results matched model predictions for 2 of the 12 test culverts (Table 2), for an overall congruency of 17%. Upstream movement occurred in the one culvert deemed passable by the model (100% congruency; 482). In contrast, congruency was low (9%) for culverts classified as total barriers by the model (481, 483, 487, 488, 495, 498, 500, 605, 607, 608, 615). At these sites, upstream passage was observed in all but one of the test culverts (483), although four of the test culverts showed evidence for restricted passage (PI values ranging from –0.36 to –0.85; Table 2).

Discussion

Reconnecting habitat isolated by fish passage barriers through culvert retrofitting and removal is considered one of the more efficient and effective techniques for restoring salmonid populations (Roni et al. 2002; Sheer and Steel 2006). However, the effects of culverts on fish distribution and abundance at the watershed scale remain poorly understood (Tchir et al. 2004). We used a combination of methods to assess the degree of passage restriction of cutthroat trout and brook trout from road culverts within a large, montane drainage. In our study, only 4 of 45 culverts in the study area (9%) were classified by the FishXing model as fully passable for 152-mm cutthroat trout during summer low flow. Direct observation of fish passage through a subset of 12 culverts further showed that upstream movement of trout through natural stream reaches was about 2.45 times greater than through culverts, although only 1 of these 12 culverts failed to pass fish. Population sampling upstream and downstream of a subset of 23 culverts indicated that passage was not blocked to the extent that (1) cutthroat trout or brook trout became locally extirpated above a barrier or (2) a culvert isolated cutthroat trout from brook trout encroachment.

Because of the large number of road crossings within drainage networks, software models and screening criteria have been developed for classifying culverts as passable or impassable to upstream movement (e.g., Clarkin et al. 2005; Coffman 2005; Gibson et al. 2005; Gardner 2006). However, in a review of the literature we found few studies that have validated model predictions with measurements of actual fish passage in the field. Rajput (2003) reported 71% congruency between FishXing predictions of barrier status and patterns of species loss upstream of road crossings in a warmwater fish assemblage in Arkansas. In our study, we found an overall low congruency (17%) between model predictions and observed passage rates through test culverts. Much of the discrepancy was due to FishXing overestimating the number of impassable culverts; upstream passage was observed in 9 of the 10 culverts classified as complete barriers by the model.

Several factors could account for the discrepancy between model predictions of culvert barrier status and observed passage success in the field. First, the difference in outputs among assessment methods could account for some of the difference. FishXing provides an either–or, "passable or impassable" output, whereas in our passage experiments, passage was a probabilistic outcome. For example, five of the nine culverts deemed impassable by FishXing had evidence of significantly reduced upstream passage compared with passage in control reaches, suggesting the FishXing model may be a better predictor of low, rather than zero, passage probability. Second, our results suggested that some culvert features identified as affecting barrier status in the FishXing model did not appear to be significant factors influencing upstream movement in the passage experiments. In particular, low water depth was classified as the principal barrier to movement by FishXing, but large (100–200-mm) cutthroat trout and brook trout passed through test culverts with low water depths (2.0–3.5 cm) at similar rates as in deeper water depths. The minimum water depth criteria used in the model (9.1 cm) was well below the recommended minimum depths of 20–24 cm for culvert passage by juvenile and adult trout (Bates et al. 2003; ODFW 2004; Gibson et al. 2005), indicating a need for further field validation of this model parameter. A third difference is the accuracy of the swimming speed data used to predict culvert passage success in FishXing. Swimming speed data are typically derived from laboratory swimming speed trials, including the literature values for cutthroat trout reported by Bell (1991) in the FishXing model, which may not be good predictors of passage under field conditions (Haro et al. 2004; Peake 2004). Finally, hydraulic predictions of the model may also influence accuracy of fish passage predictions. Karle (2005) reported that the accuracy of the water velocity predictions of the hydraulic portion of the FishXing model was improved after field testing and hydraulic model calibration. In this study, we used flow depth rather than water velocity to calibrate the model to local site conditions. However, we found that variation in flow depth estimates from the model remained high (50%) and improved only marginally after calibration. Thus, culvert passability could also be influenced by the accuracy of the velocity and depth predictions of the model.

Species absence or very low abundance upstream of culverts has been a commonly used indicator of a passage barrier (Winston et al. 1991; Resh 2005; McLaughlin et al. 2006). In our study, sampling upstream and downstream of 23 culverts showed little indication that fish distributions in the drainage were restricted from culvert barriers. However, our results did indicate reduced trout density above culverts with slopes greater than 4.5% and outlet drops greater than 20 cm. The general lack of difference in upstream and downstream sampling may have been due to several factors. First, our model application and sampling were limited to the summer low-flow period and in only one reach above and below each culvert. Upstream movement during other times of the year, especially during spawning migrations of cutthroat trout near peak discharge, may have been sufficient to maintain population recruitment upstream. Second, the generally low densities of trout upstream and downstream of culverts in many of our study streams, typical of low-order streams with low productivity, limited inferences about passage status. Third, the presence of cutthroat trout and brook trout upstream of a culvert may not indicate barrier status: both species are able to maintain self-sustaining populations isolated above total passage barriers, provided there are several kilometers of suitable habitat upstream (Novinger and Rahel 2003;

Wofford et al. 2005). In future studies, application of the study design proposed by McLaughlin et al. (2006) for assessing passage restriction at low-head barrier dams (comparison of relative abundances above and below barriers and reference reaches at multiple sites) would improve the sensitivity of this method for assessing barrier status, particularly if coupled with new genetic tools capable of detecting the degree of population connectivity upstream and downstream of barriers at small spatial scales (Knaepkens et al. 2004; Wofford et al. 2005).

Testing of culvert passage in the field can be problematic because, in addition to culvert conditions, low passage rates can be attributed to lack of motivation to move upstream (Haro et al. 2004). Consequently, field evaluations of passability of culverts and other fishways have tended to restrict testing to the spawning migration period, when there is a strong innate motivation to move upstream (e.g., Belford and Gould 1989; Haro et al. 2004). However, our fish passage experiments clearly showed a strong propensity for upstream movement of juvenile and adult trout during summer low flow; 52% of marked small trout and 74% of large trout moved upstream across natural stream reaches during 72-h test periods.

We attempted to minimize the influence of potential motivational differences by capturing test fish upstream, displacing them downstream, and relying on homing tendency as a common motivational factor for swimming upstream through test culverts to return to their home area (Halvorsen and Stabell 1990). Passive mark–recapture studies, wherein fish are marked upstream and downstream of culverts without active displacement (e.g., Warren and Pardew 1998; Rajput 2003), tend to have much lower recapture rates than observed in our study, potentially complicating inferences about culvert passability (Coffman 2005). An important aspect of our test design was use of an internal control group collected from the same population, which allowed us to compare relative movement rates between culverts and natural stream reaches simultaneously. Because fish passage is a probabilistic event dependent on multiple factors, use of this design over multiple trials and a range of culvert conditions could aid in the development of models that managers could use to predict passage probability under different hydraulic conditions (Haro et al. 2004) and to test the efficacy of baffles or other culvert modifications for increasing passability (Macdonald and Davies 2007). A limitation of our design is that the upstream traps deployed for measuring passage rates would become unusable at higher flows. Alternatively, use of passive integrated tag detectors placed at culvert inlets and outlets (Castro-Santos et al. 1996; Solcz 2007) would allow passage monitoring over a wide range of flows.

Outlet drop was identified as the most important factor affecting fish passage among study culverts. Federal and state road-crossing criteria consider 10–15 cm as the maximum allowable outlet drop for culvert passage of juvenile trout (those < 150 mm in length; e.g., Bates et al. 2003; ODFW 2004; Lyman 2005) and 24 cm for adult trout (>150 mm in length; Lyman 2005). Our finding of little or no upstream movement by small trout (<100 mm) through culverts having outlet drops greater than 15 cm and by large trout (>100 mm) at outlet drops greater than 21 cm supports these threshold criteria. Plunge pool depth appeared to influence successful passage relative to outlet drop. Two large trout successfully traversed a culvert with a 61-cm outlet drop, well above expected capabilities, whereas no trout passed through another culvert with an outlet drop of 15 cm. The former culvert had a small but deep plunge pool downstream of the culvert, whereas the outlet of the latter culvert fell directly onto rocks. The FishXing model and culvert passage criteria recognize the interaction of outlet drop and plunge pool depth on culvert passability (Lyman 2005; Furniss et al. 2008), and our results suggest that more detailed testing of this interaction in the field would be a fruitful avenue for future research.

In conclusion, our results concur with previous studies showing that upstream movement is common in both juvenile and adult cutthroat trout and brook trout during the summer (Riley et al. 1992; Young 1996; Adams et al. 2000; Schmetterling and Adams 2004) and indicate that culvert passage is an important management consideration for stream salmonids during this period. Moreover, the large number of culverts that exist in most drainages, coupled with our findings that culverts restricted upstream passage more than natural stream reaches did, supports previous work pointing to the high potential that passage restriction will influence population connectivity and productivity over a wide area (Eaglin and Hubert 1992; Roni et al. 2002; Tchir et al. 2004; Gibson et al. 2005). Development of passage probability models (Haro et al. 2004; Macdonald and Davies 2007) should allow for better quantification of passage restriction over a range of culvert conditions beyond the current predictions of culvert status as passable or impassable. Finally, our study results indicate that a combination of methods is required to fully assess culvert passage at the watershed scale.

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References

Adams, S. B., C. A. Frissell, and B. E. Rieman. 2000. Movements of nonnative brook trout in relation to stream channel slope. Transactions of the American Fisheries Society 129:623–638.

Bates, K., B. Bernard, B. Heiner, J. P. Klavas, and P. D. Powers. 2003. Design of road culverts for fish passage. Washington Department of Fish and Wildlife, Olympia. Available: http://wdfw.wa.gov. (September 2007).

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

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

Cahoon, J., T. McMahon, L. Rosenthal, M. Blank, and O. Stein. 2007. Warmwater species fish passage in Montana culverts. U.S. Department of Transportation, Federal Highway Administration, Report FHWA/MT-07–009/8182, Washington, D.C.

Castro-Santos, T., A. Haro, and S. Walk. 1996. A passive integrated transponder (PIT) tagging system for monitoring fishways. Fisheries Research 28:253–261.

Clarkin, K., A. Conner, M. J. Furniss, B. Gibernick, M. Love, K. Moynan, and S. Wilson Musser. 2005. National inventory and assessment procedure for identifying barriers to aquatic organism passage at road-stream crossings. U.S. Forest Service National Technology and Development Program, Transportation Report 7700, San Dimas, California.

Coffman, J. S. 2005. Evaluation of a predictive model for upstream fish passage through culverts. Master's thesis. James Madison University, Harrisonburg, Virginia.

Eaglin, G. S., and W. A. Hubert. 1992. Effects of logging and roads on substrate and trout in streams of the Medicine Bow National Forest, Wyoming. North American Journal of Fisheries Management 13:844–846.

Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:483–498.

Furniss, M., M. Love, S. Firor, K. Moynan, A. Llanos, J. Guntle, and R. Gubernick. 2008. FishXing, version 3.0. U.S. Forest Service, San Dimas Technology and Development Center, San Dimas, California. Available: www.stream.fs.fed.us/fishxing. (October 2008).

Gardner, A. 2006. Fish passage through road culverts. Master's thesis. North Carolina State University, Raleigh.

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

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

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

Kahler, T. H., and T. P. Quinn. 1998. Juvenile and resident salmonid movement and passage through culverts. Washington State Transportation Center Report T9903, Seattle.

Karle, K. F. 2005. Analysis of an efficient fish barrier assessment protocol for highway culverts. U.S. Department of Transportation Report FHWA-AK-RD-05–02, Washington, D.C.

Knaepkens, G., E. Verheyen, P. Galbusera, and M. Eens. 2004. The use of genetic tools for the evaluation of a potential migration barrier for the bullhead. Journal of Fish Biology 64:1737–1744.

Kruse, C. G., W. A. Hubert, and F. J. Rahel. 1998. Single-pass electrofishing predicts trout abundance in mountain streams with sparse habitat. North American Journal of Fisheries Management 18:940–946.

Lyman, C. A. 2005. Fish passage at road crossings assessment. Caribou-Targhee National Forest Final Report, Idaho Falls, Idaho.

Macdonald, J. I., and P. E. Davies. 2007. Improving the upstream passage of two galaxid fish species through a pipe culvert. Fisheries Management and Ecology 14:211–230.

McLaughlin, R. L., L. Porto, D. L. G. Noakes, J. R. Bayliss, L. M. Carl, H. R. Dodd, J. D. Goldstein, D. B. Hayes, and R. G. Randall. 2006. Effects of low-head barriers on stream fishes: taxonomic affiliations and morphological correlates of sensitive species. Canadian Journal of Fisheries and Aquatic Sciences 63:766–779.

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

Novinger, D. C., and F. J. Rahel. 2003. Isolation management with artificial barriers as a conservation strategy for cutthroat trout in headwater streams. Conservation Biology 17:772–781.

ODFW (Oregon Department of Fish and Wildlife). 2004. Fish passage criteria. Available: www.dfw.state.or.us. (September 2007).

O'Hanley, J. R., and D. Tomberlin. 2005. Optimizing the removal of small fish passage barriers. Environmental Modeling and Assessment 10:85–88.

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

Quinn, G. P., and M. J. Keough. 2002. Experimental design and data analysis for biologists. Cambridge University Press, New York.

Rajput, S. 2003. The effects of low-water bridges on movement, community structure and abundance of fishes in streams of the Ouachita Mountains. Master's thesis. Arkansas Tech University, Russellville.

Resh, V. H. 2005. Stream crossings and the conservation of diadromous invertebrates in South Pacific island streams. Aquatic Conservation: Marine and Freshwater Ecosystems 15:313–317.

Riley, S. C., K. D. Fausch, and C. Gowan. 1992. Movement of brook trout (*Salvelinus fontinalis*) in four small subalpine streams in northern Colorado. Ecology of Freshwater Fish 1:112–122.

Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. North American Journal of Fisheries Management 22:1–20.

Schmetterling, D. A., and S. B. Adams. 2004. Summer movements within the fish community of a small montane stream. North American Journal of Fisheries Management 24:1163–1172.

Schrank, S. J., C. S. Guy, M. R. Whiles, and B. L. Brock. 2001. Influence of instream and landscape-level factors on the distribution of Topeka shiners *Notropis topeka* in Kansas streams. Copeia 2001:413–421.

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

Solcz, A. 2007. Assessment of culvert passage of Yellowstone cutthroat trout in a Yellowstone River spawning tributary using a passive integrated transponder system. Master's thesis. Montana State University, Bozeman.

Tchir, J. P., P. J. Hvenegaard, and G. J. Scrimgeour. 2004. Stream crossing inventories in the Swan and Notikewin River basins of northwest Alberta: resolution at the watershed scale. Pages 53–62 *in* G. J. Scrimgeour, G. Eisler, B. McCulloch, U. Silins, and M. Monita, editors. Proceedings of the Forest Land-Fish Conference II. Alberta Conservation Association, Edmonton, Canada.

USGAO (U.S. General Accounting Office). 2001. Restoring fish passage through culverts on Forest Service and BLM lands in Oregon and Washington could take decades. Subcommittee on Interior and Related Agencies, House of Representatives Report GAO-02-136, Washington, D.C.

VanDeventer, J. S., and W. S. Platts. 1989. Microcomputer software system for generating population statistics from electrofishing data; user's guide for Microfish 3.0. U.S. Forest Service General Technical Report INT-254.

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

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

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

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

Young, M. K. 1996. Summer movements and habitat use by Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*) in small, montane streams. Canadian Journal of Fisheries and Aquatic Sciences 53:1403–1408.