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ARTICLE

A Probabilistic Model for Assessing Passage Performance of Coastal Cutthroat Trout through Corrugated Metal Culverts

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Abstract
We conducted a series of volitional trials with wild-caught resident Coastal Cutthroat Trout *Oncorhynchus clarkii clarkii* in a 12.2-m-long, 1.8-m-diameter culvert test facility to develop a probabilistic model for predicting rates of upstream passage over a wide range of average velocities. The results of the passage trials indicated that the percentage of fish attempting passage and the percentage of fish successfully passing decreased as the trial target average velocity increased. At our highest trial average velocity of 2.4 m/s, 31% of test fish that chose to attempt passage passed after two nights of observation. Passage performance was generally better for larger fish, but this pattern was only statistically significant for a single trial (1.9 m/s). Fish ascended through the pipe more quickly as velocity increased. At higher test velocities fish favored the left side of the pipe (looking downstream), which contained a reduced-velocity zone created by the slightly oblique orientation of culvert corrugations. Our data provide the basis for a logistic model describing the probability of passage for Coastal Cutthroat Trout through bare corrugated metal culverts with no outlet drop. Empirical studies testing fish passage, such as this one, can inform culvert assessment protocols currently in use.

Corrugated metal culverts are a relatively inexpensive stream crossing structure, but they can inhibit fish movement due to high velocities and physical drops at the outfall (Park et al. 2008; Rolls 2011). Where unimproved forest roads in the Pacific Northwest intersect small to midsized streams, the crossing structure of choice has long been the corrugated metal pipe (CMP); thousands of these structures currently exist in steep headwater streams. Forest roads are critical for moving logs and other forest commodities to market and maintaining access for timber harvest, forest management activities, and public recreation. Maintenance of these extensive road networks, including the stream crossing structures, represents a significant and ongoing financial investment and obligation for private and public land managers alike. Increasingly the expectation and regulatory requirement is that stream crossings provide for upstream fish movement.

For stream-dwelling fish, movement is often necessary for gaining access to spawning and rearing habitat, food resources, and thermal or velocity refugia. Barriers to upstream movement can fragment habitats and isolate populations, reducing gene flow and the genetic diversity important for maintaining long-term population viability (Morita and Yamamoto 2002; Wofford et al. 2005). Factors that may impede upstream movement at culverts include a high velocity or an inadequate depth (both

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of which are related to steep slope), an excessive drop at the outlet, or an accumulation of debris at the inlet. It is common for culverts to create partial barriers (i.e., they are barriers on some flows, to some species, or for some life stages of a particular species; Kemp and O'Hanley 2010). For the unimproved forest road infrastructure in the Pacific Northwest, these partial barriers often occur in relatively steep headwater streams within reaches populated only by resident Coastal Cutthroat Trout *Oncorhynchus clarkii clarkii*, a species whose habitat is naturally fragmented by permanent and transient barriers such as bedrock waterfalls and slides, boulder and cobble cascades, and log jams (Gresswell et al. 2004). The additional habitat fragmentation and loss of connectivity caused by culverts representing partial or complete barriers has been cited as a concern for Coastal Cutthroat Trout (Latterell et al. 2003; Gresswell et al. 2004).

Identification, prioritization, and remediation of fish passage barriers have become key elements of stream and salmonid restoration efforts throughout western North America. An array of methods for assessing potential barriers at road crossing structures has been developed to date. While some information is available documenting fish passage through culverts, these data were not collected in a systematic way to capture the range of passage conditions fish are likely to face for the given crossing structure. Thus, the most common barrier assessment approaches use other methods for determining whether fish are capable of passage. For example, simulation-based assessments such as FishXing (Furniss et al. 2008) incorporate hydrological and fish swimming capability data. Recent studies have documented cases where simulations provide conclusions incongruent with field observations, overstating the level of passage risk to fish (Cahoon et al. 2005; Karle 2005; Burford et al. 2009). Other assessment approaches rely on expert systems that apply a passage value based on the judgment of a field crew (e.g., WDFW 2009), though these are rarely validated with empirical datasets (Kemp and O'Hanley 2010). In the case of both simulation and expert-based approaches, empirical fish passage data could help inform and improve the accuracy of fish passage assessments. Incorrect classification of barrier status and evaluation of the benefits to culvert replacement can either place valued fisheries resources at risk or, conversely, waste significant public and private funds with a more costly crossing option. Because there are hundreds of millions of dollars at stake (USGAO 2001) and it is highly improbable that all the suspected barriers can be corrected in a reasonable period of time, it is critical that barrier assessment protocols accurately reflect the risk to passability and the benefits for fish populations.

Recent studies have identified the need for empirically based fish passage data, which have the potential to further inform assessment protocols currently in use while also facilitating the development of a new probabilistic approach (Haro et al. 2004; Cahoon et al. 2007; Burford et al. 2009). For culverts located in headwater streams of the Pacific Northwest, information regarding the passage performance of Cutthroat Trout could help to inform passability assessment protocols. Additionally, these data could lay the foundation for an empirically derived function for Cutthroat Trout passability through CMPs, providing a tool for quantitatively assessing the risk to nonpassage and inform decisions on culvert replacement. We tested the volitional passage performance of Coastal Cutthroat Trout in an experimental culvert test facility. These tests spanned a range of average velocities typical of those found at road crossings in headwater stream systems and were used to develop a probabilistic model for assessing passage success.

METHODS

Study site.—Fish passage trials were performed at an experimental culvert test bed (CTB) facility located at the Washington Department of Fish and Wildlife Skookumchuck Fish Hatchery (for a detailed description of facility construction see Pearson et al. 2005). The facility provides a platform for testing fish passage through culverts of different diameters, with the capacity for discharges of up to 0.57 m^3/s and adjustable slopes of up to 10%. Its water source originates from the Skookumchuck Reservoir immediately upstream from the hatchery, and an in-line electromagnetic flowmeter (McCrometer) allows for the instantaneous measurement of discharge. This study used a single helically wound corrugated steel culvert with a circular diameter of 1.83 m and a length of 12.2 m. Corrugations had an amplitude of 2.54 cm and a wavelength of 7.62 cm, with a right-hand spiraled pitch of 5.3°. The pipe was left bare for all trials, free of baffle structures or natural substrate. Discharge and slope were varied to achieve a range of target water velocities, and tailwater pool surface elevation was controlled by an adjustable stop-log weir to maintain similar pipe outlet conditions across all trials. An enclosure constructed of a wooden frame covered by 6.4-mm wire mesh was used to contain fish within the tailwater pool at the entrance to the culvert.

Detection system.—Detection of fish movement during passage trials relied on the development of a half-duplex passive integrated transponder (PIT) system. An array of four radio frequency identification (RFID) antennas was constructed within the test culvert to detect fine-scale movements of each tagged individual during the trials. Two types of antennas were used: two pass-through antennas at the downstream and upstream ends of the pipe, and two pass-under antennas near the midpoint in the pipe. The pass-through antennas detected fish across the entire width of the pipe, and each of the two pass-under antennas was tuned to only detect fish on the left or right side of the pipe. Pass-through antennas at the culvert entrance and exit were tuned so the fields detected fish as they entered and exited the culvert but not if they were milling about or holding in front of the culvert. Detection of tagged fish at pass-under antennas occurred approximately from the culvert midline outward and within 0.5 m downstream and upstream of the antennas. A zone approximately 15 cm wide along the culvert midline between the pass-under antennas purposefully had no detection for determining passage through the midline. Midline passage was determined by subtracting passage on the left and right sides from all passage detections. A pass-under antenna for detecting midline passage was not possible due to the coupling of electrical fields. Types of movements recorded for each fish included entries into the pipe, unsuccessful passage attempts, successful passes through the culvert, and the side (left or right) of the culvert used for each of these events. We synched five Oregon RFID single antenna high performance LF HDX, ISO 11784 compatible readers together to record detections. Half-duplex Texas Instrument PIT tags (12 mm $\times$ 2.5 mm) were used for all trials. A previous comparison of the performance of tagged and untagged fish in the CTB indicated no tag effect on rates of participation and passage.

Field capture and handling.—Coastal Cutthroat Trout used in passage trials were collected from headwater tributaries of the Skookumchuck River (latitude 46.756822 N, longitude –122.580845 W). All fish capture locations were separated from the CTB facility by the Skookumchuck Reservoir and an impassable dam. Test fish (20–29 individuals per trial) were collected during separate field samplings so that only naïve fish were used in each trial. The trial population size was constrained by the level of effort and time required to capture fish as well as by keeping densities low in the transport tank to minimize stress. Minimizing density-related stress was also important during the pretrial holding periods and the trials themselves. Fish were collected with a Smith-Root LR-24 backpack electrofisher using power output settings that minimized risk of injury to the fish (voltage range 600–650, frequency 30 Hz, duty cycle 12%). Any individuals that did not immediately recover or that had visible marks or physical deformities or injuries were not used for the trials. Fish were transported to the CTB in an aerated 170-L transport tank.

At the CTB all fish were anaesthetized in a solution of MS-222 (tricaine methanesulfonate; 40 mg/L), weighed to the nearest 0.1 g, and measured to the nearest millimeter (fork length; FL). All fish were then implanted with half-duplex PIT tags according to protocols from the Columbia Basin Fish and Wildlife Authority (CBFWA 1999). After tagging, fish were held in one of four 210-L holding tanks with flow-through rates of approximately 38 L/min. Water temperature in each tank was monitored and recorded throughout the pretrial holding period. Elapsed times between field capture and the start of passage trials varied from 28 to 35 h for individual fish.

Passage trials.—Each trial was performed over a 2-d period during June and July 2010. A trial began with the placement of test fish into the containment cage in the late afternoon of the first test day. The detection system was activated at that time and no coercive actions were taken to induce movement of fish. Care was taken not to introduce light into the test facility during evening hours, and all overhead or other external stimuli were avoided. Fish remained in the test facility for two evenings (a minimum of 36 h). On the morning of the second day, the water source was shut off and the headwater and tailwater tanks were drained to collect the fish. All fish were scanned using a handheld reader to assure tag retention. Air and water temperatures, as well as headwater and tailwater surface elevations, were recorded both before and immediately after each passage trial. Hydraulic conditions for each trial were set 3 to 4 h prior to placement of fish into the containment cage to allow the system to equilibrate.

Passage performance was summarized by reviewing the information recorded from each RFID antenna. Each individual fish was first identified as either a participant or a nonparticipant. Participants included all fish that were detected at a minimum on the most downstream antenna, indicating that they at least made an attempt to enter the culvert. A rate of participation for each trial was calculated by dividing the participants by the total number of individuals tested. Nonparticipants included fish that were never recorded on any of the antennas, and these fish were dropped from further analysis. Participants were classified as successful or unsuccessful in passing through the entire length of the culvert based on detections at the uppermost antenna. Elapsed time of ascent and the location of the fish midculvert (left or right) were recorded for each successful passage attempt. A rate of successful passage for each trial was calculated by dividing the number of successfully passing fish by the total number of participating fish in the trial.

Water velocities for testing ranged from 0.6 to 2.4 m/s, while depths ranged from 0.12 to 0.28 m. A standard-step model of gradually varied flow (J. Cahoon, Montana State University, personal communication) was used to determine the combination of culvert slopes and flows required to produce velocities in 0.15 m/s increments. The model was set to calculate distance-averaged bulk velocity (hereafter “average velocity”) and output the discharge required to achieve a target velocity, representing the average cross-sectional velocity across the entire longitudinal distance of the pipe. Due to facility constraints on slope (0–10%) and discharge ($\leq$0.57 m^3/s), three slopes (0.52%, 3.14%, and 8.6%) were required to achieve the range of average velocities for testing (Table 1). Tabular model outputs were used to set up the CTB for each trial (i.e., a discharge value was selected from the output table to achieve the test velocity for any given slope the CTB was set on). Test velocities tended to increase with testing date because the CTB was set at an increasingly steeper slope, but within a slope setting we varied test velocity randomly to avoid potential temporal bias.

Discharge was recorded both from the in-line flowmeter and through the use of two sharp-crested weirs developed to provide an independent measure of flow. The in-line electromagnetic flowmeter was inspected and certified during the course of the study to provide assurance of accurate readings. Several methods were used to validate modeled velocities during each trial and provide assurance that actual test velocities comported with model predictions. Velocities were hand measured using a Global Water velocity meter at three locations in the cross section of the pipe. These included the assumed locations near the left and right (looking downstream) sides of the waters’ edges that fish were likely to occupy, plus a measurement in the

TABLE 1. Hydraulic characteristics and passage performance rates for the 11 passage trials (velocities and water depths derived from model output; Q = discharge; FL = fork length in mm; SE = standard error). Rates of success may be higher than participation due to the use of participants as the quotient rather than total *N*.

Velocity (m/s)	Q (m^3/s)	Slope (%)	Water depth (m)	*N*	FL (SE)	Participation	Success	Trial sequence
0.6	0.06	0.5	0.15	21	123 (20.2)	1.0	0.86	1
0.8	0.12	0.5	0.21	20	130 (20.1)	0.95	0.89	3
0.9	0.21	0.5	0.28	26	122 (25.8)	0.96	1.0	2
1.4	0.14	3.1	0.15	23	123 (25.8)	0.78	0.61	7
1.6	0.22	3.1	0.18	23	117 (19.9)	0.96	0.77	4
1.7	0.30	3.1	0.21	29	111 (18.0)	1.0	0.83	6
1.8	0.41	3.1	0.25	27	121 (24.0)	0.67	0.39	5
1.9	0.14	8.6	0.12	22	115 (28.1)	0.82	0.33	9
2.2	0.23	8.6	0.15	26	122 (25.2)	0.77	0.75	8
2.3	0.28	8.6	0.16	28	117 (16.6)	0.79	0.27	11
2.4	0.34	8.6	0.18	26	120 (21.5)	0.62	0.31	10

inferred maximum velocity zone (culvert midline). These measurements were taken at three longitudinal stations (1, 8, and 11.5 m from the downstream end of the pipe). As a secondary check on average velocity, a neutrally buoyant object was timed as it floated along the midline of the culvert prior to each trial. Finally, the accuracy of the modeled depth profile through the entire length of the culvert was assessed at 15 locations for the 1.9-m/s trial conditions. These measured depths were averaged to calculate an expected velocity for comparison with the modeled velocity. The 1.9-m/s trial conditions were also selected for fine-scale velocity mapping using 36 equally spaced point measurements to better understand the cross-sectional variability in velocity. Use of an acoustic Doppler velocimeter proved impossible due to the excessive amount of noise in the data produced by entrainment of air within the highly turbulent water column (addressed by Mori et al. 2007). Instead, a Swoffer meter (Model 2100) was used for these measurements, which were taken at a cross section located at the longitudinal center of the culvert following the protocol established by Richmond et al. (2007).

Statistical analysis.—The effect of fish size was evaluated with several tests. Since the distribution of fish lengths was strongly right skewed, a log transformation ($\log_e$) was applied to these length data. Differences in mean fish lengths between trials were compared using a one-way analysis of variance (ANOVA). Testing for differences in mean length between successful and unsuccessful fish passage across trials was evaluated through a two-way ANOVA. Where trial factor was slightly statistically significant in the two-way ANOVA test results, 10 individual two-way *t*-tests were used for within trial comparisons of mean length for successful and unsuccessful fish passage using a Bonferroni adjusted significance level of 0.005.

Passage performance data were used to fit a logistic regression model predicting the probability of passage success. In addition to velocity, average fish length (by trial group) and water depth were added in initial model runs. However, these covariates were not a significant determinant in the passage model. An additional model was developed that included a two-way interaction between velocity and depth that yielded a significant effect for the velocity depth interaction and insignificant main effects. While there does appear to be some dependence between velocity and depth, the interaction term and depth were dropped from the final model. Depth was not a targeted variable in this set of experiments and a full range of depth levels were not reflected across the targeted velocities. As a result, interpretation of the two-way interaction is difficult and any observed results may not reflect the true dynamics of the two variables across a full range of velocity and depth combinations. In turn, target velocity was the only independent variable used in the subsequent model reported here. All model fitting was conducted using R version 2–12.0 on Mac OS X. The 11 data records were used to find $\hat{\beta}_0$ and $\hat{\beta}_1$, estimates of the parameters β_0 and β_1, respectively. Once the parameters were estimated, a fitted logistic curve was generated by estimating passage probabilities calculated over a set of target velocities ranging from 0.0 to 3.0 m/s. A wider range of target velocities was used when fitting the logistic curve in order to better extrapolate the shape of the curve for 0% and 100% passage. It is possible that the shape of the curve would be somewhat different if target velocities below 0.6 and above 2.4 m/s had been included in the trials. Pointwise 95% confidence bands were added to the logistic curve using procedures outlined in Hosmer and Lemeshow (1989).

RESULTS

A total of 271 Coastal Cutthroat Trout were captured from seven tributaries of the upper Skookumchuck River for the 11 passage trials. The median size of all captured fish was 114 mm (range = 85–207 mm). The age groups and the size structure of the test population was representative of resident Coastal Cutthroat Trout populations in headwater streams of western Washington. Test groups for each passage trial varied in number (range 20–29) based on the number of fish sampled from the watershed, but mean fish size did not significantly differ across trials (one-way ANOVA: $F_{10,216} = 1.33$, $P = 0.21$).

Water temperature during the holding periods and passage trials ranged from 9.0°C to 13.5°C, similar to the water temperature within the streams where the fish were captured (range = 8.0–13.5°C). Temperatures were not regulated during passage trials and reflected a range commonly found in many Pacific Northwest stream environments during the early summer season. One tag shed occurred over the course of the study (during the 1.6-m/s trial). Trial-related mortality included one fish during the 1.8-m/s trial and four fish during the 1.7-m/s trial. Causes of death were unknown, although impingement on the downstream screen was suspected.

Actual slope and discharge values deviated from those targeted in the initial hydraulic modeling exercise due to facility-related constraints on the fine-scale adjustment of both parameters. Actual water velocities were calculated using actual slope and discharge values and are reported in Table 1. Validation of modeled velocities using point measurements of the inferred maximum velocity and float tests indicated that a consistent pattern between modeled and measured velocities existed across the entire range of conditions tested. Both validation techniques recorded consistently higher velocities than the modeled average velocity by a similar magnitude, which was to be expected because both validation methods targeted above-average velocity locations within the culvert. In addition, the accuracy of the modeled depth profile along the longitudinal axis of the culvert was found to be highly accurate based on point measurements taken during the 1.9-m/s trial. The calculated bulk average velocity using these point measurements was within 0.31% of the modeled result. Fine-scale velocity mapping indicated cross-sectional asymmetry in velocity values (range 1.1–3.5 m/s), with a reduced-velocity region (approximately 60% of maximum velocity) located along the left flow margin in the culvert (looking downstream; Figure 1).

The dominant period of passage activity occurred at dusk with scattered activity throughout the night. Daytime activity generally increased with higher test velocities, especially ≥1.6 m/s. Rates of participation ranged from 62% to 100% and were generally lower for trials testing higher velocities, especially ≥1.8 m/s. Similarly, rates of successful passage by participants ranged from 27% to 100% and followed a pattern of generally lower success rates for trials testing higher velocities (Table 1). The two-way ANOVA testing for differences in mean length between successful and unsuccessful fish passage across trials indicated that trial was slightly statistically significant (F_{10} = 1.73, P = 0.08), while passage versus no passage was highly statistically significant (F_1 = 11.61, P = 0.0008). Although successful individuals were larger on average in 9 of the 10 trials where a comparison could be made, it was only statistically significant for the 1.9-m/s trial (t = 3.55, df = 12, P = 0.004). It is noteworthy that fish of all sizes, even the smaller individuals in the test population, successfully navigated the culvert over the entire range of trial velocities (Figure 2).

Multiple ascents by at least one fish were recorded in all but a single trial (2.3 m/s). Overall, 37% of the fish that successfully passed through the culvert did so more than once, and for some trials and individuals multiple-pass behavior was common. For example, the 12 fish transiting the culvert more than once during the first trial (0.6 m/s) averaged 14 ascents, with two fish passing 22 times each (FL 114 mm and 132 mm). Fewer multiple ascents occurred as trial velocities increased, with a noticeable drop between 1.4 and 1.6 m/s velocities (average of 1.4 ascents per fish for trials ≥1.4 m/s versus 5.2 for trials ≤1.4 m/s). The fish making more than one ascent were larger than those making a single ascent for all but two trials (0.6 and 1.6 m/s), though sample sizes were too small for statistical comparison.

The duration of ascent for successful passage attempts ranged from 12 s to 47 min. Larger fish tended to ascend more quickly than smaller fish in all trials, although this pattern was highly variable. Passage times generally decreased as velocity increased, especially for the five test velocities at or above 1.8 m/s (Figure 2). For the three lowest velocities (0.6–0.9 m/s), long passage times were recorded for fish of all sizes (105–207 mm). However, long passage times for the next three trials (1.4–1.8 m/s) were recorded only for fish below 120 mm long (Figure 2). Duration of passage became relatively uniform across all fish sizes during the four trials testing the highest velocities (Figure 2).

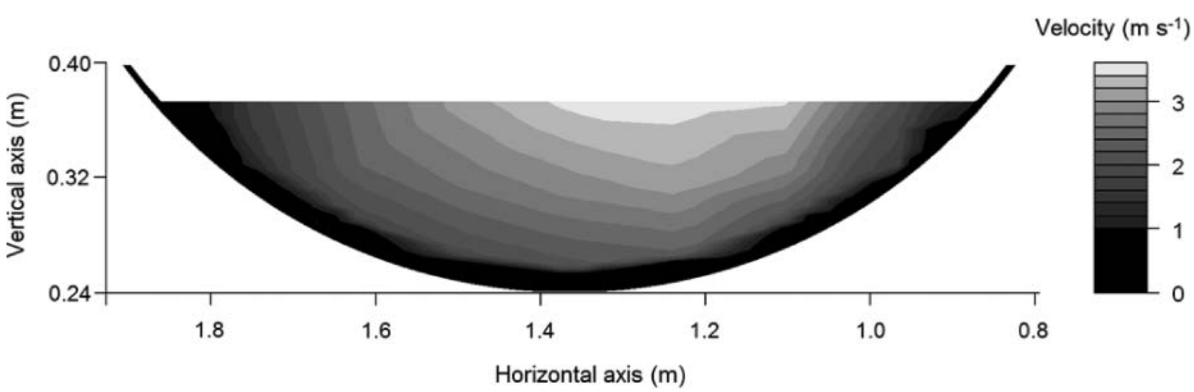

FIGURE 1. Velocity contour profile at a modeled average velocity of 2.4 m/s (Q = 0.34 m^3/s; slope = 8.6%) at the center of the culvert looking downstream; the vertical axis is exaggerated to provide greater resolution of the variation in velocities.

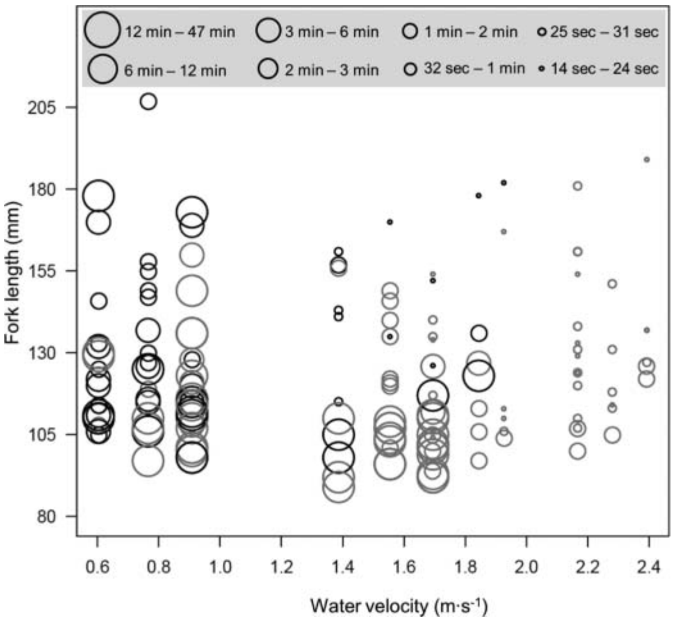

FIGURE 2. Duration (circle size) and culvert side (black = right; grey = left) of successfully passing fish by fork length and trial velocity. For fish exhibiting multiple passes, duration was averaged across all successful passages. If fish with multiple passes used the middle or right side of the pipe during at least one ascent, the resulting data point was chosen to reflect this with a black circle.

Four transit paths were identified for fish ascending the culvert: left, right, both sides, and midline pathways. Low-velocity trials had roughly even passage distributions between left and right sides, but a notable shift occurred to the left side of the culvert at velocities > 1.4 m/s (Figure 3). At test velocities of 2.2 m/s and above, no fish were detected successfully passing on the culvert's right side. Few fish occupied both left and right sides of the culvert during a single successful ascent and this occurred only in velocities at or below 1.7 m/s (Figure 3). Even fewer fish

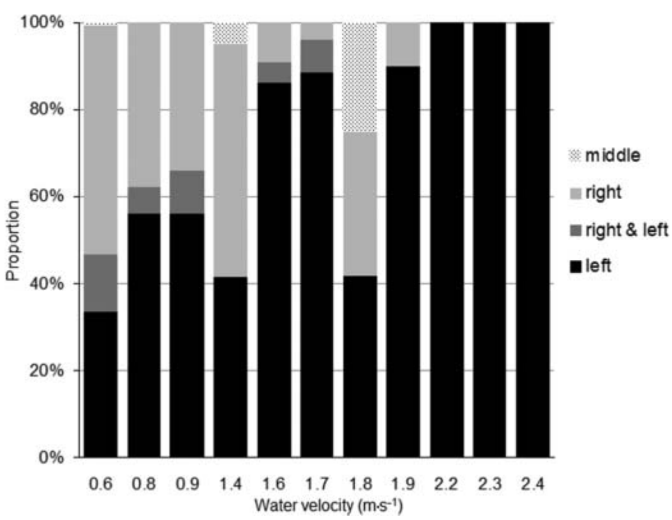

FIGURE 3. Proportion of fish choosing the middle, the right, the right and left, and only the left sides of the culvert during passage trials.

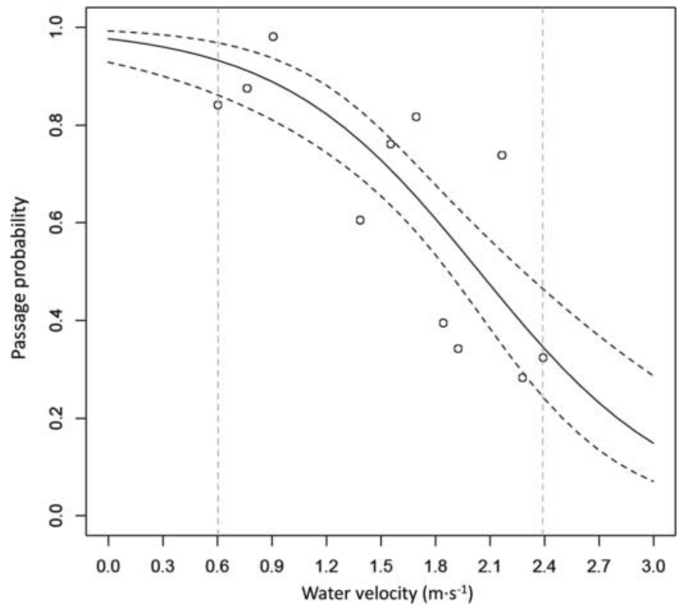

FIGURE 4. Fitted logistic regression curve (solid line) giving average culvert passage probabilities for various target velocity values and pointwise 95% lower and upper confidence bands (dashed lines).

ascended the culvert midline (i.e., not detected on either the left or right antenna: 6 of 473 successful passage records).

The estimated regression line for the logit of passage probability indicated a linear decreasing logit with increasing target velocity (Figure 4). The curve represents the average culvert passage probability over the domain of target velocities, and the confidence bands are for the expected response. Although the logistic curve was fit over target velocity values ranging from 0 to 3 m/s, the observed velocities ranged from 0.6 to 2.4 m/s.

DISCUSSION

Observed passage performance during volitional trials provided sufficient data to describe a passability likelihood function based on average velocity for CMPs with dimensions similar to the test culvert. This probability function describes the capability of Cutthroat Trout to pass through similarly sized corrugated metal culverts with no outfall drop over a range of flow conditions and is broadly applicable to resident Coastal Cutthroat Trout populations. Caution should be taken in attempting to extrapolate passage probabilities beyond the observed velocities in the study (0.6–2.4 m/s). Despite an apparent pattern between water depth and fish passage across trials grouped by slope (Table 1), depth was not a significant determinant in the passage model. While there did appear to be some dependence between velocity and depth based on the additional model run including a two-way interaction between velocity and depth, interpretation of the two-way interaction was difficult because of the narrow range of depths tested across the targeted velocities. Depth was not a target variable we intended to control but rather the product of the discharge and slope combinations selected for targeted trial velocities. Thus a full range of depth levels was not reflected across the targeted velocities, and observed results may not reflect the true dynamics of the two variables across a full range of velocity and depth combinations. While this study did not handle other aspects of culvert passability (e.g., outfall drops) or different culvert dimensions, these are fruitful areas for future research that would deepen the themes addressed in this study.

Passage participation and success of Coastal Cutthroat Trout decreased as average velocity increased, especially >1.7 m/s. We expected fish size to play a more significant role in the performance of test individuals across all passage trials because fish size is positively correlated with swimming capability (Bainbridge 1958; Webb et al. 1984). However, overall, fish length was not significant in the logistic model, and successful individuals were statistically larger than their failed counterparts in only one trial when analyzed separately. Successful and failed attempts were recorded for fish across the entire size range during all trials, including the most challenging ones. This general lack of size-specific passage performance and success may be an artifact of the relatively limited size range of the test fish (85–207 mm). However, this size range is common for headwater populations of Coastal Cutthroat Trout (excluding young of the year), making our results directly applicable to natural populations.

Fish in trials >1.8 m/s displayed a more focused swimming behavior, as evidenced by shorter and less variable transit time. These findings are consistent with the weak relationship of measured transit times versus average velocity for adult Westslope Cutthroat Trout *Oncorhynchus clarkii lewisi* described by Solcz (2007). While we can only report the average ground speed of the test fish as measured by detections at exit and entrance antennas, the most rapid ascents suggest swim speeds in excess of the critical speed of 0.6 m/s for juvenile Coastal Cutthroat Trout reported by Hawkins and Quinn (1996). Ascending fish displayed a noticeable preference in culvert side only when the velocity exceeded 1.5 m/s. The reduced-velocity zone on the culvert's left side that has been noted for helically wound CMPs (Silberman 1970) was the preferred passage route for fish at these higher velocities, as only 14% of successful ascents above 1.5 m/s occurred on culvert right.

Despite the wealth of information available on fish swimming capability, its effective application to determine passage performance through engineered structures remains elusive. Swimming performance has usually been studied in a laboratory apparatus such as a Blazka-type swim chamber (e.g., Smith and Newcomb 1970), with performance characterized in metrics normalized for fish size and classified by a swimming behavior keyed to sustainability (e.g., Hawkins and Quinn 1996). Models designed to assess fish passage through high-velocity zones in engineered structures are parameterized with this type of swimming performance data, though their output is often unreliable due in part to assumptions of uniform velocities within structures and the swimming behavior of fish when confronted with challenging water velocities (Castro-Santos 2006). A more realistic approach, based on actual fish observations, is needed to evaluate the complex hydraulic environments of engineered structures and the correspondingly complex swimming responses of fish to these settings.

Observed passage performance of Coastal Cutthroat Trout in our study could provide valuable information for both simulation and expert system approaches to passage assessment. An assessment of our experimental conditions using the model FishXing (Version 3.0.17; Furniss et al. 2008) indicated all test trials contained passable conditions. Two user-defined parameters in particular were found to be very sensitive (leveraging pass or fail determinations) to user input in the current beta version of FishXing, including minimum depth and a velocity reduction factor. We populated these fields with data derived from our experiments and, using the guidance in FishXing, input factors of 3.7 cm and 0.6 m/s for the depth and velocity factor fields, respectively. Modest deviations from these values failed some of our trials for both depth and velocity, suggesting that FishXing is calibrated realistically if these two parameters are used. We also assessed how passable the experimental conditions were using the expert-based Washington State protocol, which assumes culvert slopes in excess of 4% slope are unacceptable for passing trout >150 mm (WDFW 2009). Our slope of 8.6% documented successful rates of passage ranging from 27% to 71% for fish, 76% of which were smaller than 150 mm. While the Washington State protocol indicates that maximum culvert velocities >1.8 m/s represent nearly insurmountable barriers for trout >150 mm (WDFW 2009), a third of the participants were successful in ascending the pipe where maximum velocity was doubled (3.7 m/s), with five of the six fish in this trial being <150 mm long. Our results were expected to exceed Washington State fish passage design criteria because they are intended to pass the weakest and smallest individuals of each species requiring passage (WDFW 2003), though criteria for trout are based on individuals >150 mm (WDFW 2009).

The consideration of empirically based data such as those presented here could further refine the protocols most commonly used for passage assessments. For example, consideration of a reduced-velocity area when applying criteria could lead to a better understanding of passability, leading to improved prioritizations and cost savings. Such data also lay the foundation for developing new quantitative tools for describing passability through empirically derived functions. These functions could address difficult management questions such as partial passability (i.e., *how* passable a crossing structure is) and better inform managers faced with making decisions. Recent studies have focused on constructing passability models that are based on observed fish passage values. Cahoon et al. (2007) utilized RFID to assess fine-scale movements of Yellowstone Cutthroat Trout *Oncorhynchus clarkii bouvieri* through road culverts, while others have conducted volitional movement trials through test culverts and flumes that accurately emulate velocity profiles of stream crossing structures (Powers et al. 1997; Haro et al. 2004; Pearson et al. 2005). This study contributes to this body of empirically based research, developing a probabilistic model describing the likelihood of successful passage of wild-caught fish through bare CMPs similarly sized to the test culvert (no baffles or natural substrate) using average velocity as the explanatory variable. This model quantifies the occurrence of partial passage, characterizing passage in a more realistic way. The consideration of these data in culvert assessments will generate conclusions that more accurately reflect the risk to passability and provide greater certainty to potential population-level benefits from remedial actions.

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