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Influence of baffles on upstream passage of Brook Trout and Brown Trout in an experimental box culvert

By

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There is much to learn about improving baffle designs to increase successful fish passage through culverts. A fish’s motivation to attempt entry into the culvert is essential. Upon entry, successful passage will largely depend on the physiological ability of the fish to navigate the entire culvert length. In this study, the motivation of brook and brown trout to attempt ascent of an experimental flume which mimics a roadway culvert left bare (smooth) or fitted with either spoiler or weir baffles is assessed. Performance, measured as maximum distance of ascent within the flume is also quantified. The bare flume was the most motivating for brook trout, and the weirs for brown trout. As a rule, brown trout showed less motivation to stage attempts than brook trout, except within the weir baffle treatments. Performance was greatest for smaller trout in the weirs, and in the spoiler baffles for larger individuals. Our findings suggest that baffle form influences passage rates at road crossings in ways previously unknown and further stresses the importance of considering fish motivation and performance together when assessing the efficacy of baffle forms.

**Keywords:** culvert, baffles, fish passage, Salmo trutta, Salvelinus fontinalis

# 1 INTRODUCTION

Culverts are crucial elements of road and rail stream crossings. By providing adequate hydraulic conveyance, culverts protect supporting structural fill, prevent embankment overtopping and provide for passage of debris and sediment. Aside from respecting these engineering considerations and minimizing costs, culvert designers must also ensure hydraulic conditions do not impede movement of fish and aquatic organisms.

High velocity sections and shallow depths are well documented challenges to upstream
fish migration (Devkota et al. 2012; Olsen and Tullis 2013; Goerig et al. 2016). Culvert inlets can locally constrict the channel width leading to an increase in average cross-sectional velocities over the culvert length. Furthermore, even at relatively low grades (e.g. < 1.5 %), supercritical flow conditions are prone to develop over hydraulically smooth culvert materials such as prefabricated concrete and high-density polyethylene (HDPE). If flow transitions from subcritical to supercritical conditions, depths decrease and velocities increase. Currently, hydraulically rough, yet aging corrugated steel culverts are being retrofitted with smooth HDPE pipes (Syachrani et al. 2010). HDPE retrofitting threatens to impede access of species exhibiting anadromous, potamodromous and catadromous life cycles to spawning and feeding habitats upstream of the culvert. Installing hydraulic roughness elements such as baffles along the invert (‘floor’) of smooth culverts is one approach to mitigate these challenging hydraulic conditions.

A suite of baffle forms to use in culvert construction have been proposed over the last half century (Ead, Rajaratnam, and Katopodis 2002). Among these, two forms have received particular attention: weir and spoiler baffles. Weir baffles (WB) span the width of the culvert and protrude from the bed between 0.05 to 0.15 of the culvert diameter (D) and are spaced longitudinally at distances of 0.5D to 2D. Spoiler baffles (SPB) consist of isolated roughness elements patterned in rows along the invert of the culvert. Each baffle form generates a distinct flow field with the potential to influence how fish navigate the culvert.

A low velocity recirculatory zone develops in the lee of weir baffles (Ead, Rajaratnam, and Katopodis 2002). Fish are known to exploit this zone, taking advantage of the lower velocities as a refuge from the free stream (Liao 2007; Khodier and Tullis 2014). Yet, this benefit may be reduced by the presence of a laterally spanning shear layer at the interface of
the wake and free stream regions. Vortex shedding in this zone has the potential to provoke
instability in fish (Liao 2007; Tritico and Cotel 2010). For spoiler baffles, velocities relatively
lower than the free stream are expected to predominate at elevations less than the height of the
spoiler baffles. Even lower velocity recirculatory zones occur directly to the leeward side of
the spoilers. Ascending trout may benefit from reduced energy expenditures by slaloming
within the low velocity zones near the bed of the spoiler baffles while taking intermittent
refuge in their lees (Standen et al. 2002).

Fish proceeding quickly through a passage barrier incur lower migratory delays leading
to improved chances for reproduction (Castro-Santos and Haro 2003; Castro-Santos, Cotel,
and Webb 2009; Nyqvist et al. 2016). Spoiler baffles are thought to provide unimpeded
trajectories which fish may adopt to decrease transit times through culverts (Macdonald and
Davies 2007; Feurich, Boubée, and Olsen 2012). In contrast, fish have been observed to pass
considerable time in the lee of weir baffles (Feurich, Boubée, and Olsen 2012; Khodier and
Tullis 2014). Despite their potential benefit to reduce transit times, for equal baffle height,
spoiler baffles develop shallower depths and higher velocities than weir baffles. This is due to
the lower hydraulic roughness of spoiler baffles compared to weir baffles (Ead, Rajaratnam,
and Katopodis 2002). While the lower hydraulic roughness is beneficial for passing flood
waters, the resulting shallower depths and higher velocities may be a detriment to the passage
of weaker swimming fish.

Though swimming capacity plays an important role in culvert passage, a fish lacking
motivation to attempt entry (and possibly multiple attempts) is at risk of incurring migratory
delays (for both resident and anadromous forms; (Morinville and Rasmussen 2003) or failing
to pass altogether. The time it takes for fish to stage an attempt provides a quantifiable metric
for evaluating the motivating qualities of a given baffle form (Castro-Santos 2004; Goerig and Castro-Santos 2017). However, it is possible that a highly motivating baffle may also exhibit impassable hydraulic conditions. Or, conversely a baffle developing favorable hydraulic characteristics may incite little motivation. Thus, to obtain optimal passage rates through culverts, baffle designs should motivate multiple attempts and develop hydraulics conducive to the swimming ability of the target species. Despite some recent progress in this area (Enders et al. 2017), much remains to be learned on how baffle forms and the hydraulics they develop motivate fish to stage ascent attempts through culverts.

In this study, motivation and performance results from experimental trials of resident freshwater forms of wild brook and brown trout attempting ascents within an experimentally simulated culvert were analyzed. Trout volitionally staged attempts over the bare flume - mimicking a smooth culvert - and the same flume fitted with either one of two spoiler baffle arrangements or a weir baffle arrangement. Each flume bed configuration was tested at a low (0.10 m$^3$/s) and high discharge (0.15 m$^3$/s). We applied the methods of event analysis (also known as, survival or time-to-event analysis) to improve our understanding of how these common baffle forms influence motivation, performance and rates of movement of trout through baffle fitted culverts. The findings of this study should be of significant interest to fisheries managers and culvert designers.

2 MATERIALS AND METHODS

The flume

Experiments were performed in the fall of 2015 in the Aquatic Biomechanics and Kinematics Station (ABiKiS) flume facility at the S.O. Conte Anadromous Fish Research Center (U.S. Geological Survey) in Turners Falls, Massachusetts. The flume is 35 m long,
0.635 m wide, with a maximum full flow depth of 0.635 m (Fig. 1) and was set at a 1.5% slope. The floor, top, bottom and walls of the flume are constructed from transparent acrylic sheeting supported within aluminum framing to facilitate observations and videography. The downstream end of the flume is fitted with a 53 m² staging area with a maximum free surface depth of 1.5 m.

Flow was supplied by gravity to the flume by adjusting an intake valve connected to a supply pipe fed by the adjacent hydroelectric power canal. Flow entered the flume under an adjustable sluice gate then proceeded downstream over an 18.5 m section of smooth acrylic before reaching the 15 m long baffle test section. Within the staging area, flow established a dominant clockwise recirculatory pattern. The central region of the staging area contained low velocity zones providing adequate resting areas for fish. The design allowed fish to enter the flume under their own volition, thus no coercive tactics were used to incite fish to stage attempts. Flow exited the staging area through a semicircular wall (10.4 m²) of perforated steel plate (50% open) screens into a channel equipped with a weir. The motor-actuated weir adjusted the water surface level in the staging area. Flow rates were monitored with an HTTF Transit Time Ultrasonic flow meter (Racine, Wisconsin) with a manufacturer stated accuracy of ± 1% fitted to the supply pipe from the reservoir. Flume water temperatures were monitored using a HOBO Water Level Data Logger (ONSET, Bourne, MA) with a manufacturer stated accuracy of ± 0.44 % within the applied temperature range (0-50 °C). Water surface levels within the flume were manually recorded for each trial at 20 equidistantly spaced locations along the length of the flume.

Flume instrumentation

Fish movements within the flume were monitored using a passive integrated
transponder (PIT) system consisting of antennas fitted to the flume, a personal computer and other necessary data acquisition equipment. Antennas were located at 1.83 m intervals along the length of the flume, with the first antenna placed 0.49 m from the flume entrance. A total of 20 antennas were fitted to the flume, though only antennas 1-9 were required to cover the movements of fish over the baffle test section. Antennas were tuned to detect tags over a ±0.5 m buffer region and adjusted to charge and read tags at a rate of 10 Hz. At each detection, the antenna number, the time of acquisition to the nearest 0.01 s and the fish’s identification number were recorded onto a personal computer via in-house acquisition software. Further details of a similar PIT system to the one used here are available in (Castro-Santos et al. 2013).

**Fish collection and manipulation**

All animal care and handling was performed in accordance with the US Geological Survey Institutional Animal Care and Use Committee (Protocol # LSC-116). Fish were collected in late September 2015 by electrofishing over various stream reaches on the Connecticut River watershed within a 20 km radius of Turners Falls, Massachusetts. A total of 167 fish were captured: 108 brook trout (*Salvelinus fontinalis*) and 59 brown trout (*Salmo trutta*). Though efforts were made to capture equal numbers of each species, brown trout were far less numerous in the streams fished. Electrofishing was performed using a Smith Root model 12 (Vancouver, WA). In each stream the voltage was regulated to the minimum required to solicit rollover responses of the trout. The voltage required varied as a function of the conductivity of the stream being fished and varied between 400- 700 V (frequency: 45/ 60 Hz, duty cycle range: 0.9%–72%). Fish were transported to the laboratory in tanks filled with water collected from the fished stream. Upon arrival, fish were anesthetized (0.4g MS-222 and 0.4g NaHCO3 were added to 4 L of water to prepare the anesthetic solution), weighed, measured, identified for species and tagged. The fish length was measured as the length
between the apex of the snout to the end of the middle caudal fin rays of the fish (i.e. fish length). Fish were surgically fitted with uniquely coded 12 mm half-duplex PIT tags (Oregon RFID, Portland, OR) following the intraperitoneal method outlined in Castro-Santos et al. (2013b). Both species of fish were then segregated for size and split into two interior holding tanks with a flow-through feed of river water, cooled to maintain temperatures between 14 and 16 °C. During the maintenance drawdown of the hydroelectric canal that supplied this flow, fish were held in de-chlorinated city water maintained at the same temperature. The drawdown lasted 8 days, at which time the fish were moved to two different exterior holding tanks with a flow through river water system. Fish were fed a mixture of manufactured feed pellets and earthworms. Held fish were monitored at least twice daily during the scheduled feeding and maintenance periods of the holding tanks. Any fish observed to demonstrate signs of illness were removed from the tanks.

**Trial treatments**

Mixed groups of individuals from both species were exposed to the flume fitted with one of the following four bed configurations; (1) bare, (2) SPB-212, (3) SPB-333 and (4) weir baffles (Figure 2). The bare flume consisted of only the smooth transparent polycarbonate onto which the baffle configurations were installed. Spoiler baffles (SPB) with heights and widths of 0.05 m were arranged in either rows of three (SPB-333) or in a repeating pattern of rows of two baffles followed by a row with only a single baffle (SPB-212). Weir baffles spanning the width of the flume with a height of 0.05 m were also tested. Regardless of baffle type, spacing between rows was set at 0.41 m. All baffles were fabricated from 4 mm thick 90° white PVC angle stock.

A total of 18 trials were performed from October 2 to October 20, 2015. Each of the 18
trials tested a combination of two discharges: low $Q = 0.10 \text{ m}^3/\text{s}$ and high $Q = 0.15 \text{ m}^3/\text{s}$, with one of the three baffle configurations or the bare flume. Four bed conditions and 2 flow conditions made for a total of 8 treatments. Each treatment was performed twice, except for the bare flume which was performed three times (at the beginning, near the middle and the end of the experiment). Trials lasted from 2-3 hours, contingent on operational constraints at the laboratory. The order of appearance of the baffle configurations was chosen at random. Details of the treatments tested in each of the 18 trials are presented in Table 1.

Two trials were performed each day, with fish from the morning trials being reused in the afternoon trials. Before each trial, fish were randomly removed from the holding tanks, identified and placed within the staging area. For the majority of the trials, fish were removed from the staging area at the end of each day and returned to the holding tanks. The number of fish placed in the staging area varied as the trials progressed due to a number of practical reasons, mortalities, and laboratory logistics. For the last 4 trial days, fish were left overnight in the staging area with an appropriate amount of flow provided. This was done to reduce handling stress on the experimental animals. At the end of the last trial, fish were removed and counted. Four fish were not accounted for. Since we cannot be sure which trials these four fish were in, we were not able to adjust the numbers of fish present in the last eight trials (four days) in Table 1. The implications of these missing fish on the experimental results are treated in the Discussion.

**Flow conditions**

Regardless of baffle treatment, supercritical flow ($Fr > 1$, where $Fr$ is the Froude number) was established upstream of 15 m (antenna 9) from the entrance of the flume. With spoiler baffles installed, flow conditions remained supercritical or near critical within the
baffled section. The increased hydraulic roughness of the weir baffles developed a subcritical normal depth within the baffled section. Nominal velocities in the weir baffle treatments were markedly lower compared to the bare and spoiler baffle treatments. Froude numbers and nominal velocities within the baffled section for each trial are presented in Table 1.

**Analysis**

Raw data acquired from the PIT system were treated and analyzed to understand the influence of flume bed and flow rate treatments on motivation (time-to-attempt, $t_a$), performance ($D_{\text{max}}$), and the transit time required to reach $D_{\text{max}}$. The data were first treated to delineate individual attempts. An ascent attempt was defined as a gap in detection of more than 40 seconds at the antenna placed at the entrance of the flume (the most downstream antenna). This threshold was determined using interval analysis (Castro-Santos and Perry 2012). Brief detections by only the first antenna (nose-ins) were retained as valid attempts for analysis of time-to-attempt and $D_{\text{max}}$, but were not included in estimates of transit time. This is because detections by a minimum of two antennas are required to determine transit times. The detection efficiency of the antennas was estimated by determining the proportion of missed detections to valid detections for each antenna in the baffled section. The efficiency was 94.7%, meaning 5.3% of fish arriving at a given antenna may not have been detected.

The data were used to form life tables for event analysis, demonstrated by (Castro-Santos and Haro 2003; Haro et al. 2004) to be an insightful tool for the analysis of PIT data in fish passage studies. One of the strengths of this approach is its ability to quantify covariate effects on any continuously distributed response variable (e.g. distance of ascent up a flume or fishway). Event analysis also robustly handles partial (censored) observations caused by limitations in the experimental apparatus not permitting a complete measure of the response.
variable (e.g. limited flume length for $D_{max}$ or limited trial duration for $t_a$). Details on event analysis methods can be found in (Allison 2010; Kleinbaum and Klein 2005). To study covariate effects on $t_a$ and $D_{max}$, we employed parametric Weibull accelerated failure time (AFT) models with the R package survival (version 2.41-2, (Therneau 2015)). The two parameter Weibull survival function takes the form of Eq. 1. The survival function gives the probability of an event occurring after time $t$ given the event has not already occurred before $t$. The coefficients $\beta_p$ in Eq. 1 are estimated using maximum likelihood estimation (MLE), $z_p$ denotes the components of the covariate vector $z$ and $p$ denotes the shape parameter (Kleinbaum and Klein 2005).

$$S(t) = e^{-e^{(\beta_0 + \beta_1 z_1 + \cdots + \beta_p z_p) t^p}} \tag{1}$$

$$t = \left[ -\ln S(t) \right]^{1/p} e^{(\beta_0 + \beta_1 z_1 + \cdots + \beta_p z_p)} \tag{2}$$

Note that $t$ in Eq. 1, normally indicating time until death in medical literature, can represent any continuous or sequential variable at which an event of interest may occur. For time-to-attempt analysis, $t$ in Eq. 1 is replaced by $t_a$. In the study of $D_{max}$, the event is a fish attaining its maximum distance of ascent within a given treatment. Therefore, $t$ in Eq. 1 is replaced by $D_{max}$.

Equation 1 solved for $t$ is shown in Eq. 2. In this form, the event $t$ is calculated for any value of $S(t)$. For example, substituting $S(t)=0.5$ in Eq. 2 gives the median event time. The exponential terms are the acceleration factor (AF). Acceleration factors allow the (MLE) coefficients to be interpreted as stretching-out or contraction factors on the time-to-event compared to the baseline treatment. Therefore, an AF > 1 indicates the covariate stretches the time-to-event (increasing $D_{max}$ and slowing $t_a$) compared to the covariate’s base level.
Conversely, AF < 1, reduces the time-to-event and indicates a decrease in $D_{\text{max}}$.

The lapse of time between contiguous attempts or the start of the trial and the first attempt is denoted as the time-to-attempt ($t_a$). Time-to-attempt is an appropriate method to quantify motivation of fish as they attempt to pass a barrier. Shorter time-to-attempt intervals indicate higher motivation. For the analysis of $t_a$, fish not staging attempts during the trial were right censored (Kleinbaum and Klein 2005) at trial duration. To reduce the bias introduced from highly motivated individuals in the study of $t_a$, the maximum number of attempts considered within each day for each individual was five. Attempts exceeding the fifth attempt within the day were removed from the dataset. Fish present but not staging an attempt within a two hour trial, were censored at 2 hours and retained in the dataset to contribute to fitting the model. Within each treatment, $D_{\text{max}}$ was calculated as the distance corresponding to the farthest antenna attained by each individual within all the trials of that treatment. For the analysis of $D_{\text{max}}$, trials were truncated at 2 hours to not introduce a bias potentially caused by fish having a longer period of time to maximize their ascent distances. Fish that ascended upstream of the baffled section were included in the $D_{\text{max}}$ analysis as censored observations at 15 m. Transit time ($T_{D_{\text{max}}}$) was calculated as the time elapsed between the last detection of the fish at the first antenna and the first detection at the maximum antenna attained during the attempt. No further calculations or modeling was performed on transit time.

Cohorts of candidate terms were formed from combinations of main effects deemed reasonable to influence $t_a$ and $D_{\text{max}}$. Common main effects to the candidate terms for both $t_a$ and $D_{\text{max}}$ were: flume configuration, discharge, fish length, species, flume water temperature, and holding time. Over the duration of the trials, holding times of the fish varied between 6 and 28 days, with an average of 19 days. Water temperature varied between 16 °C and 12°C,
dropping 4 °C over the study period. Consequently, holding time and temperature were also included as main effects in the candidate terms for both $t_a$ and $D_{max}$. Because temperatures were declining throughout the study period, there was a strong correlation between temperature and holding time ($r = -0.86$). Because not all fish were captured on the same day, however, there was partial decoupling of temperature and holding time. This means that we can meaningfully test these as independent variables. Nevertheless, the presence of a strong correlation means that any interpretation of either of these variables should be viewed with caution.

Because fish were reused over trials, previous experience in the flume is thought to have affected both $t_a$ and $D_{max}$. Therefore, an additional term, exposures, was considered for inclusion to account for the number of trials individuals had previously been exposed to. However, exposure was found to be strongly correlated with holding time and was consequently dropped from the set of candidate main effects. This means that the influence of prior exposure is confounded within holding time and the interpretation of holding time should be viewed with caution. For only $t_a$, the term attempt number was included to investigate possible dependency of time-to-attempts on the number of previous attempts staged on the same day. An additional term, order, was included in the study of $t_a$ to account for whether the attempt occurred on the first or second trial of the day.

For both $t_a$ and $D_{max}$, five two-way interaction terms constructed from main effects were included to form the complete sets of candidate terms. We hypothesized that both $t_a$ and $D_{max}$ varied among flume bed configurations for different fish sizes, hence the inclusion of configuration:fish length. Interactions between species and configuration were also deemed reasonable. Likewise, discharge was hypothesized to impact motivation and performance in
certain configurations more than others. Accordingly, configuration:discharge was included. The term fish length:discharge was introduced to reveal whether discharge had more of an influence on smaller fish than larger fish. Finally, discharge:species was included to reveal if either species exhibited a preference or aversion to either of the two discharge treatments.

Within the models, configuration, discharge, species and order are categorical variables with the following levels - configuration: bare, SPB-212, SPB-333 and WB; discharge: 100 and 150 (0.10 and 0.15 m3/s); species: brook (0) and brown (1); order: first (1) and second (2). Fish length is treated as a continuous variable modeled in increments of 1 mm. Temperature and holding time are continuous variables incremented in °C and days of holding time, respectively.

Main effects that are not included within a two-way interaction are interpreted as having a universal effect on the response variable independent of treatment. The coefficients of a main effect and its two-way interaction are additive, and so must be considered together. The two-way interaction will either strengthen or diminish the influence of the main effect depending on the sign of the interaction. Interpreting a lone main effect that is also included in a two-way interaction, reveals how the considered level of the main effect affects the response variable compared to the base level. The base levels for each covariate are: configuration = bare, discharge (Q) of 0.10 m3/s, fish length (FL) 56 mm, species brook trout of 0 (brown trout=1), temperature of 12 °C, holding time of 6 days, attempt number of 1 and order of 1.

The predictive power of the resulting models were assessed by ranking them using the Akaike Information Criterion (AIC) (Eq. 3), where L is the model’s likelihood estimation and K is the number of modeled covariates. Lower values of AIC indicate a better fitting model. Plots of \( \ln[-\ln S(t)] \) versus \( \ln(t) \) for each of the main effects were inspected for parallelism to validate
the accelerated failure time assumption. The straightness of the lines was also assessed to verify the applicability of the Weibull distribution.

\[
AIC = -2 \log L = 2K
\]  

(3)

RESULTS

Time-to-attempt

For the study of \( t_a \), a total of 1151 candidate Weibull accelerated failure time models were formed from possible combinations of candidate terms. Each main effect and two way interaction within the cohort of candidate terms is considered to potentially describe the response variable to an unknown degree and therefore all possible combinations of the cohort terms were evaluated. The eight lowest AIC models are presented in Table 2. The most parsimonious model (Model 1, AIC = 6745.92) includes the following main effect terms: order, temperature, holding time, attempt number, fish length, configuration, species and discharge. The following two-way interactions were also retained: fish length:configuration, configuration:species and species:discharge. Model 1 has a \( \Delta \text{AIC} \) of 1.26 from Model 2. With an Akaike weight (w) of 0.47, Model 1 is interpreted as having a 47% probability of being the best model given the data. Many of the models presented in Table 2 share common terms with those in Model 1. Inspection of the coefficients of the common terms between Models 2 to 8 revealed they were all of similar sign and magnitude to those presented in Model 1. This reinforces the finding that these common terms contribute the most towards maximizing the likelihood function. For models containing uncommon terms with Model 1, the uncommon terms have \( p \)-values > 0.5 and standard errors greater than the value of the term; indicating they are not significantly improving the fit of the model. In particular, between Model 1 and Model 2, the only difference is the term fish length:discharge. Yet the significance of this term
is questionable given it presented a standard error (0.00235) larger than the coefficient (0.00203) and a \( p \)-value of 0.37. The evidence presented supports Model 1 as the best choice for further analysis of \( t_a \).

The proportions of trout staging attempts within each of the treatments are presented in Table 4. Approximately 20% to 30% of brook trout available staged at least one ascent attempt in each treatment. Smaller proportions were observed for brown trout compared to brook trout in all treatments, except in the weir baffles where greater than 38% of brown trout available staged at least one attempt. For attempt numbers > 2, larger proportions of brook trout continued to stage attempts within the bare and spoiler baffles, and brown trout continued to stage more attempts within the weir baffles. Within the spoiler baffles, the proportions of trout staging > 1 were generally less than 10% and were as low as 1% for brown trout. The observed variations in the proportion attempting across treatments demonstrates that motivation is highly influenced by baffle configuration and discharge treatments. To study how covariates influence motivation, time-to-attempt \( (t_a) \), defined as the time elapsing between the start of the trial and the first attempt or the time elapsed between any two successive attempts, was modeled using parametric survival methods. A cohort of candidate covariates were used to form potential models (see Materials and Methods). The results of the best fitting \( t_a \) model (Model 1, Table 2) are presented here.

Of the eight main effects of Model 1 (Table 2), order, attempt number, temperature and holding time do not appear within interactions and are interpreted as having a universal influence on \( t_a \) independent of treatment. The acceleration factor (AF) of 2.16 \( (p < 0.001) \) for order suggests fish staged attempts 2.16 times slower in the second trial of the day compared to the first. The within day attempt number, with an AF of 0.546 \( (p < 0.001) \), suggests fish
staged their second attempt in about half the time as their first. Subsequent attempts occurred
at even shorter intervals. However, this is a general trend for attempts > 2; further examination
of the data revealed $t_a$ intervals do not forcibly become shorter with each successive attempt
beyond 2. Time-to-attempt quickened at higher water temperature ($AF = 0.59, p < 0.001$) and
with increasing holding time ($AF = 0.96, p = 0.017$). However, the contributions of temperature
and holding time should be interpreted with caution, for reasons detailed later in the
discussion.

The remaining main effect terms (configuration, fish length, species, discharge) all
appear within at least one two-way interaction. Since two-way interaction coefficients
additively modify the main effect, both main effect and interactions must be interpreted
together. In Table 5, the main configuration terms reveal how the baffle treatments affect $t_a$
compared to the bare culvert. Both SPB-212 and the weir baffle incited faster time-to-attempts
than the bare flume (AR of 0.52 and 0.63 respectively). Conversely, SPB-333 caused slower
time-to-attempts. Yet, the two-way interactions between configuration:fish length and
configuration:species demonstrate that motivation within each configuration was strongly
dependent on species and fish length. Fish length stimulated 1.5% faster times-to-attempt per
mm compared to a 56 mm fish in the bare flume, indicating that larger fish demonstrated a
higher level of motivation within the bare flume than smaller fish. The coefficients for the fish
length:configuration interaction are of opposite sign to the main effect fish length,
demonstrating a reduced motivation within the baffles compared to the bare flume with fish
length. The species term suggests that brown trout staged attempts more slowly than brook
tROUT ($species$) in the bare flume ($species AF = 1.664, p = 0.039$). Yet, interestingly, the
$species$:configuration interaction reveals that brown trout demonstrated faster time-to-attempt
within the weir baffles than brook trout.

The main effect for discharge suggests that the 0.15 m³/s discharge treatment considerably slowed $t_a$ over the low discharge ($Q$, AF = 1.49, $p = 0.015$). This is a general trend common to all baffle configurations, with the exception that brown trout staged attempts quicker in the high discharge compared to brook trout ($species: WB$, AF 0.43, $p = 0.019$).

Figure 3 illustrates how the two-way interactions influence time-to-attempt. The curves are predictions from the Weibull regression coefficients of Model 1. The grey curves in Fig. 3 represent the proportion of a fictive population of fish that have staged an attempt between the start of the trial and time ($t$) into the trial. The black curves represent the proportion of fish staging a third attempt after the time elapsed since the end of their second attempt. Higher percentages attempting indicate higher motivation. The curves were modeled from coefficients in Fig. 5 using an average fish length (125 mm) exposed to average trial conditions ($temperature = 14.6 ^\circ C$, holding time = 19 days, $order = 1.5$) with an attempt number of either 1 (grey) or 3 (black lines).

From Fig. 3 generally less than 30 – 40% of fish staged at least one attempt by the end of the trial, which agrees with the empirical values presented in Table 4. Successive attempts occurred at faster $t_a$ as observed by the black lines in Fig. 3. Brook trout were most attracted to the bare flume (quickest attempt times), whereas the weir baffles were the most attractive for brown trout. Both spoiler baffle configurations stimulated lower percentages of entry than the bare culvert. The interaction between species and discharge is also apparent, where slight reductions in the percentages attempting are seen for brook trout between low and high discharge and a more substantial increase is visible for brown trout.
Maximum distance of ascent

For the study of $D_{\text{max}}$, 575 models were run on the full dataset from the possible combinations of the cohort of candidate terms. The eight lowest AIC models are presented in Table 3. Of the twelve candidate terms, the most parsimonious model (Model 1, AIC = 1006.44) include configuration, fish length, species, discharge and the interaction terms fish length:configuration, configuration:species and fish length:discharge. Model 1 has a nearly two point $\Delta$AIC (1.66) from Model 2. With an Akaike weight ($w$) of 0.29, Model 1 is interpreted as having a 29% probability of being the best model given the data. Considering $w$, Models 2 and 7 have between 13% and 11% probabilities of being the best model. Given their relatively high Akaike weights, both Models 2 through 7 cannot be neglected outright.

For all eight models presented, configuration, fish length, discharge, fish length:configuration and fish length:discharge are common terms. Comparing coefficients of these common terms reveals they are nearly identical across all eight models and likewise for standard errors and $p$-values, reinforcing their important contributions to the MLE. For models where temperature, holding time appear, these terms have $p$-values $> 0.5$ and standard errors greater than the value of the term, indicating the terms are not significantly improving the fit of the model. Between Model 1 and Model 2, the only difference is the term configuration:species. Yet, inspecting the coefficients for this term in Model 1 reveals it contains an important interaction of interest between species and the weir baffles. The similarity of coefficient values among the common terms in the models, the insignificant contribution of uncommon terms and the weight of evidence supports Model 1 as the best choice for further analysis of $D_{\text{max}}$.

Results for the retained maximum distance of ascent ($D_{\text{max}}$) model (Table 3) are presented in Table 6. For the study of $D_{\text{max}}$, acceleration factors (AF) $< 1$, indicate treatment
decreased maximum distances of ascent. Considering only the main effects for configuration without interactions, all three baffles configurations increased $D_{\text{max}}$ ($AF > 1$). Both SPB-212 and SPB-333 increased $D_{\text{max}}$ by a factor of 2.32 and 2.02 respectively, yet these terms were only marginally significant ($p \approx 0.01$), suggesting benefits over the bare flume may be partly due to chance. Weir baffles in contrast, increased $D_{\text{max}}$ with a significant acceleration factor of 13.6 ($p < 0.001$). The increase in discharge reduced $D_{\text{max}}$ ($AF = 0.290$) and brown trout generally under-performed brook trout ($species$, $AF = 0.640$). $Fish$ $length$, with an $AF = 1.01$, increased $D_{\text{max}}$ in the bare flume by 1% for each mm in fish length compared to a 56 mm trout.

The three main effect terms ($fish$ $length$, $species$, $discharge$ and $configuration$) appear within one or more two-way interactions. The additive effect of interaction coefficients on main effects reveal many interesting insights. Figure 4 displays survival curves derived from $D_{\text{max}}$ Model 1 stratified by $species$, $discharge$ and $fish$ $length$. The median maximum distance of ascent ($D_{50}$) -- the distance at which 50% of the population of attempting fish are able to attain or surpass -- provides a convenient indication of how treatment affects performance.

Though brown trout generally attained lower $D_{\text{max}}$ than brook trout, brown trout out-performed brook trout in the weir baffles by a factor of 2 as witnessed by the interaction term $WB:Species$ in Table 6 (AR = 1.996). This is evident in Fig. 4(a,d), where $D_{50}$ for 100 mm brook trout within the weirs was 7.9 m and 10.1 m for brown trout in low flow, and 4.0 m and 5.1 m respectively at high flow. Interactions between $fish$ $length$ and $configuration$ demonstrate a reduction of 1.2% in $D_{\text{max}}$ per additional mm of fish length in the weir baffles (Table 6, $AF = 0.988$), suggesting larger fish under-performed smaller fish in the weir baffles. This effect is observed in Fig. 4, where 100 mm brown trout attained a higher $D_{50}$ than 150 mm and 200 mm brown trout in the weir baffles. Similar results are seen for brook trout. Large
individuals from both species \((\text{fish length} = 200 \text{ mm}, \text{Fig. 4c and e})\) benefited the most in the SPB-333 condition, with \(D_{50} > 15 \text{ m}\) for brook trout and approximately 11.8 m for brown trout at low discharge, substantially surpassing the \(D_{\text{max}}\) values attained by larger trout in the weir baffles. Regardless of species and fish length, SPB-333 improved \(D_{50}\) over SPB-212, suggesting that doubling the number of baffles resulted in better performance.

The interaction term between fish length and discharge produced a 0.6% increase in \(D_{\text{max}}\) with each 1 mm increase in fish length in the high flow treatment. This result suggests the performance of larger fish was impacted less during the high flow than smaller fish which can be explained by the offsetting effect that the fish length coefficient has on the lone discharge term. As an example, a 100 mm brook trout in the bare flume at low discharge has a \(D_{50}\) of 2.0 m, and 1.02 m at high discharge (a 49% decrease). In contrast, a 200 mm brook trout in the bare flume at low flow has a \(D_{50}\) of 5.44 m, and 4.79 m at high flow (a 12% decrease).

**Transit time to \(D_{\text{max}}\)**

The transit time \((T_{D\text{max}})\) required to attain \(D_{\text{max}}\) for each of the eight treatments, both species and three fish length classes are presented in Figure 5. Points in Fig. 5 correspond to the \(D_{\text{max}}\) attained by each attempting fish for each of the eight tested treatments. Attempts ending with \(D_{\text{max}}\) at the first antenna (0.5 m) could not be used to determine \(T_{D\text{max}}\) and were therefore excluded from Fig. 5. For the bare flume, \(T_{D\text{max}}\) was in all cases less than 15 s in both the 0.10 m\(^3\)/s and 0.15 m\(^3\)/s conditions. Mean \(T_{D\text{max}}\) were 5.4 s and 4.8 s in the 0.10 m\(^3\)/s and 0.15 m\(^3\)/s conditions respectively. Within the SPB-212 configuration, a single point from a large brown trout was recorded (lone red square right in Fig. 5C) with a long \(T_{D\text{max}}\) (469 s). During its ascent, this fish held station behind a spoiler baffle at mid-length of the flume for a considerable period of time. For the SPB-212, mean \(T_{D\text{max}}\) were 10.6 and 7.5 s (with the
aberrant point removed) for low and high discharge. Within SPB-333 further increases were observed, with mean $T_{D_{\text{max}}}$ of 13.7 and 12.5 s for low and high discharges respectively. With the exception of the large brown trout, these rapid values for $T_{D_{\text{max}}}$ within the spoiler baffle configurations suggest fish were not significantly exploiting velocity refugia in the lee of the spoiler baffles. $T_{D_{\text{max}}}$ was considerably higher in the weir baffles compared to the other flume bed treatments. Interestingly, for $Q=0.10 \text{ m}^3/\text{s}$ within the weir baffle, numerous small brown trout spent considerable time (>1000 s) reaching $D_{\text{max}}$. This behavior was not observed for brook trout, who demonstrated similar $T_{D_{\text{max}}}$ as in the SPB-212 and SPB-333 treatments.

**DISCUSSION**

**Effects of temperature, holding time and hydraulic jump**

To increase the number of ascent attempts, trials were performed during the fall spawning period of the wild non-anadromous freshwater trout used in the experiment. Mid-study, an unexpected delay of eight days ensued from a rescheduling of an annual maintenance drawdown of the adjacent hydroelectric reservoir. This delay caused a considerable drop in temperature between the first and last trials and prolonged holding times beyond what was originally planned. Consequently, the effects of temperature and holding time on the health and the swimming capacity of our fish were a concern for the study of $D_{\text{max}}$ and $t_a$. For $D_{\text{max}}$, the retained model (Model 1, Table 3) did not include either temperature or holding time. Further, these terms appear only with low significance in Models 3, 6 and 7 in Table 3. This provides evidence that temperature and holding time did not meaningfully increase the MLE of the model and consequently had little influence on $D_{\text{max}}$. For $t_a$, temperature and holding time appear in both of the two lowest AIC models. Times-to-attempt became substantially shorter with increasing water temperature. Also, $t_a$ was found to slightly quicken with holding time (during which temperatures dropped). The reasons for these reactions are unclear.
Possible explanations include; the warmer water at the beginning of the study stimulated fish to stage quicker ascent attempts to return to their origins in the cooler headwaters and; the decrease in $t_a$ with holding time may be explained by a progressive onset of behaviors to locate favorable spawning habitat upstream. Both temperature and holding time were found to have had a significant effect on $t_a$ and should be considered when interpreting time-to-event results.

During the bare flume trials a hydraulic jump was present at the downstream end of the flume. Though efforts were made to reduce the intensity of the jump by adjusting the water level in the staging area, its presence was unavoidable. The jump was confined downstream of the detection buffer of the first antenna to ensure fish were exposed to approximately 0.3 m of supercritical flume conditions before detection. Hydraulic jumps were not observed in the baffled trials. The jump may have played an important role in attracting fish to stage attempts in the bare flume. The increased attraction may be caused by the high levels of turbulence generated within the jump (Coutant 2001) or attraction to another mechanism such as locally elevated levels of dissolved oxygen or the sound generated within the jump. All of these possibilities are attractive hypotheses for future study.

**Effects of trial order, density and reuse of fish**

Our time-to-attempt and performance analyses provide useful insights towards understanding how the baffles influenced passage at culverts. However, a number of difficulties and operational constraints occurred during the experiments which may have introduced various levels of bias into the results. The following discussion presents these difficulties and describes the potential biases they may have introduced within the models.

In Table 1 the percentage of attempting fish wanes during the last eight trials. Consequently, a large number of time-to-attempt observations censored at the end of the trial.
were recorded during the last eight days. The numerous prolonged times to first attempt in the
last four days contained within the dataset mean the coefficients presented in Model 1 (Table
5) likely underestimate the true motivation of fish to stage attempts to some degree that is not
fully controlled for by the *holding time* term. Analysis of models run on the same dataset (not
presented here), yet truncated to include only observations occurring over trials 1 to 12,
demonstrated modeled coefficients of identical sign, yet with slightly lower magnitudes to
those in Model 1 for $t_a$, suggesting that including the last eight trials did indeed reduce the
modeled levels of motivation. Due to various practical constraints, fish were left in the staging
area overnight during the last eight trials. This is a change from the procedure during the first
10 trials, in which the fish were removed overnight and replaced with a new random group the
following day. Leaving the fish in the staging area may have been partly responsible for the
observed decrease in motivation over the last four days of the experiment. The reader should
be aware of this potential bias while interpreting the time-to-attempt results.

In our experimental design the order of appearance of discharges was reversed in the
repeat treatments. This was done to control for any effect that experience gained by the fish
during the first trial of the day may have had on motivation and performance in the second
trial. However, due to human error, the discharges were not reversed for the repeat trial of the
SPB-333 configuration. Instead, the high discharge was tested in the second trial of both days.
Since time-to-attempts were found to generally slow down within the second trial of the day
independent of treatment (Table 5, order, $AF = 2.16$, $p < 0.001$), the modeled coefficients for
the SPB-333 configuration likely predict faster time-to-attempts than what occurred, because
fish were generally more motivated in the first trial. For $D_{max}$, in analysis not presented here,
the order variable was found not to appear within the eight lowest AIC models (e.g. Table 2).
Meaning $D_{\text{max}}$ was not affected by whether it occurred in the first or second trial of the day. Therefore, both high discharges occurring in the afternoon for the SPB-333 trial should not affect the interpretation of $D_{\text{max}}$ results.

Due to mortalities and operational constraints, each day we had to reevaluate an appropriate number of fish for the trials. As a result, unequal densities of fish were present within the staging area from trial to trial. Densities varied between 0.7 fish per m$^3$ to 1.5 fish per m$^3$.

Little research has been done to examine whether fish density affects motivation. Goerig et al. (2016) and Goerig and Castro-Santos (2017) provide some insight on the potential effects of density on motivation. Goerig et al. (2016) found brook trout caged at a density of 5.5 fish per m$^3$ staged more upstream attempts into an in-situ culvert than un-caged brook trout released freely downstream. Goerig and Castro-Santos (2016) suggest the increased motivation of the high density caged fish may have been due to an escape response. Since the uncaged fish of Goerig and Castro-Santos (2016) were free to move downstream, it is difficult to determine the density of un-caged fish that were available to stage an attempt. However, it was likely substantially lower than the 5.5 per m$^3$ density in their cage. It is unlikely that the small differences in densities that occurred over our trials was sufficient to introduce an escape or “crowding” response that stimulated more attempts per trial.

The varied number of fish available in the staging area may have resulted in more observations (i.e. attempts) to have been collected in the denser trials compared to less dense trials. Since event analysis is an observation-based modeling method, where each observation is treated as independent from the number of other individuals in the test, not having equal numbers of fish in the trials does not undermine the validity of the approach. Variable density, however, does mean that some treatments may have had a greater number of observations for
model fitting than others (Kleinbaum and Klein 2005). Aside from density, it should be mentioned that the number of observations is also dependent on the motivating effects of the treatments in question. Therefore, even with equal numbers of fish available to stage entry, the number of observations is expected to vary across treatments. However, treatments with more observations provide more data for model fitting, helping to lower standard errors and higher confidence in the results.

A tally done during the removal of the fish at the end of the last four days indicated that four fish went missing during this period. It is possible that these fish were not present in some or all of the last eight trials. The missing fish were kept in the dataset of available individuals for the study of $t_a$. Because only four fish are at question within the group of available fish present in the last four days, we are not concerned that this introduced a significant bias into $t_a$ or $D_{max}$ modeling. However, the reader should keep in mind that the numbers used to quantify attempt rate during the last four days may exceed the actual number available by as many as four fish.

The reuse of fish over multiple trials was unavoidable given the limited quantity of wild trout we were able to acquire. Prior experience gained during previous exposures to the flume may have influenced time-to-attempt and maximum distances of ascent. Since fish were randomly reused in different treatments, it was impossible for us to decouple the effects of reuse from that of the treatment. However, for the study of $D_{max}$, reusing fish should not have introduced a bias within the model, since we are interested only in the highest $D_{max}$ attained by each fish within each treatment. For the study of motivation, however, our study and others (Goerig and Castro-Santos 2017) strongly suggests that motivation is a function of the number of prior attempts within the same trial. At this point, it is unclear how long any experience
gained is retained within wild trout and whether or not it might introduce a significant bias over multi-day experiments.

Motivation, performance and transit times

The motivation of fish to quickly stage multiple attempts at crossing a hydraulic challenge is essential for successful passage (Castro-Santos 2004; Goerig and Castro-Santos 2017). In this study we quantified motivation by modeling covariate effects on the time elapsed between attempts, with the assumption that shorter intervals correspond to increased motivation. From this standpoint, passage through baffled culverts can only be evaluated as the product of a baffles’ capacity to stimulate attempts while also improving passage performance. A successful configuration should also reconcile the attraction-performance paradox recently discussed by others (Castro-Santos 2004; Goerig and Castro-Santos 2017). The paradox can be stated as: passage conditions favorable to motivation are often also coincidentally detrimental to performance. Our results indicate that this paradox is strongly at play in some treatments and not at all in others.

In terms of $D_{max}$, our results indicate that baffles always improve performance compared to the bare flume. Yet, true to the attraction-performance paradox, the bare flume enticed faster times-to-attempt compared to all other treatments. The one exception to this was among brown trout, which demonstrated their quickest attempts in the presence of weir baffles. This suggests that brown trout preferred to stage attempts into the deeper, lower velocity fluvial conditions characteristic of the weir baffle trials. For smaller juveniles, and especially brown trout, weir baffles significantly improved $D_{max}$ while simultaneously being the most motivating configuration. Weir baffles developed the lowest nominal velocities and largest depths of all the flume bed treatments. These qualities are likely responsible for much
of the observed improvements in $D_{\text{max}}$ for smaller fish. Interestingly, larger fish attained lower $D_{\text{max}}$ in the weir baffles compared to smaller fish. It is doubtful that larger trout attained physiological limits when traversing the weir baffles, rather an alternative hypothesis is that larger fish were repelled by hydraulic characteristics of the weirs. Many smaller trout were observed bounding between weirs, refuging in their lees as they progressed upstream.

Our observations of smaller fish holding station in the lee of the weirs for extended periods agrees with similar observations by Feurich et al. (2012) and Khodier and Tullis (2014). It seems because of their size, larger trout adopted a direct route above the baffles instead of performing the bounding/refuging behavior observed in smaller fish. This stands in contrast to the larger brown trout (approximately 275 mm fork length) in Khodier and Tullis (2014), which were observed to hold station in the lee of their weir baffles. The weir baffle heights of Khodier and Tullis (2014) where nearly double ours (91.5 mm compared to 50 mm). The expected additional vertical space of the recirculation zone in the lee of Khodier and Tullis (2014) weir baffles may have been sufficient to accommodate the larger brown trout used in their study.

Recent work (Enders et al. 2017) has demonstrated that $D_{\text{max}}$ improved within vertically oriented baffles compared to horizontally orientated baffles in a similar open-channel flume to ours. Enders et al. (2017) hypothesized that the presence of strong laterally orientated roller vortices shedding off the crests of the horizontal baffles may have been an important factor in reducing $D_{\text{max}}$. Work by Tritico and Cotel (2010) provides strong evidence that laterally orientated vortices can cause postural instability in fish detrimental to passage metrics (e.g. energy use, increased transit times, abandoned attempts, lower performance). It is possible the larger fish in our study were avoiding zones characterized by strong laterally
orientated vortices shedding off the upper edge of the weir baffles. Future work performing
fine scale hydraulic characterization in these zones would be beneficial to understand if
laterally orientated vortices impedes upstream movement of fish within baffled culverts.
Considering the same species and FL class in Fig. 5, numerous fish are seen to have spent
more time reaching the same $D_{\text{max}}$ in the weir baffle than in the spoiler baffle configurations.
This supports anecdotal evidence of Feurich et al. (2012) suggesting fish navigate spoiler
baffle arrays with greater ease than weir baffles. Indeed, our fish were observed to generally
adopt a direct unimpeded trajectory between the side wall and the outside baffle (from
unpublished video data). On rare occasion, fish opted for a partial trajectory within the spoiler
baffles. Partial because, they were often observed to exit after a few rows to seek a path along
the side wall. Similar behaviors have been observed by Macdonald and Davies (2007) and
Feurich et al. (2012). Goerig et al. (2016) also mention fish exploited trajectories within the
low velocity regions near the edges of the flow of their circular culverts. The increased transit
times in the weir baffles is likely a consequence of station holding behavior in the lees of the
weir baffles. In field application, these prolonged transit times may lead to increased exposure
of fish to predation. In some contexts, this risk could potentially offset the benefits accrued
from employing weir baffles.

Fish demonstrated marked improvements of $D_{\text{max}}$ in the spoiler baffles, especially for
larger trout from both species, with a slight advantage to brook trout. Additionally, transit
times through spoiler baffles were low, indicative of quick passage. However, in terms of
absolute passage success, these benefits may have been offset by the relatively prolonged
times-to-attempt observed within the spoiler baffles and also because spoiler baffles only
marginally improved the performance of smaller fish compared to the bare flume.
Feurich et al. (2012) mention their 0.12 m SPB baffle height was sufficient to provide passage for fish with lengths less than 100 mm through a 16 m long culvert. Here, however, trout within the first size class (< 100 mm, Fig. 5) were only rarely observed above 5 m for both spoiler baffle configurations (Fig. 5). This difference may be due in part to differences in experimental variables (e.g. average cross-sectional velocities, spatial density of baffles, flow rates, depths) or by variations in swimming capacity between the studied species. Peake et al. (1997) found 100 - 150 mm brown and brook trout maintained prolonged swimming in velocities up to 0.6 m/s for brook trout and 0.8 m/s for brown trout. Mitchell (1989) showed jollytails (Galaxias maculatus) with a FL of 52-73 mm (20-50 mm smaller than those used by Macdonald and Davies (2007) and about equal to those studied by Feurich et al. (2012)) could maintain a prolonged swim speed in velocities less than 0.3 m/s. Despite these results suggesting brook and brown trout have at least a slightly superior or similar swimming capacity to jollytails of the same fish length, the jollytails were able to attain greater ground distances. To achieve this, it is likely that the fish in Macdonald and Davies (2007) and Feurich et al. (2012) where able to improve ground distances by exploiting velocity refugea within their spoiler arrangements. In our study, station holding near spoiler baffles was not observed with the sole exception of a single mature brown trout.

The following reasons may help explain why our trout were not observed holding station within the spoiler baffle arrays: (1) in contrast to the 2D plastic angles used here, the 3D SPB forms (blocks) of Macdonald and Davies (2007) and the streamlined forms of Feurich et al. (2012) likely generated a horseshoe vortex originating at the upstream face of the baffle (Lacey and Rennie 2012) aiding in developing a larger low velocity wake zone suitable for station holding in the baffle’s lee; (2) the flow regime through their spatially denser baffles
likely produced a wake interference flow regime (Morris 1955), contributing to reduced velocities within the arrays compared to the isolated roughness flow regime expected around our SPB; (3) the baffles used in Macdonald and Davies (2007) and Feurich et al. (2012) were generally larger than those studied here, which would have produced wider wake zones and lower velocities in the baffle’s lee; and (4) variations in responses to hydraulic cues between Galaxias truttaceus, Galaxias maculatus and the trout used in our study may have also played an important role.

The increase in discharge slightly decreased motivation for brook trout and caused higher motivation in brown trout. A number of other studies, employing a similar definition of motivation as used here, have also investigated the effects of discharge on motivation of brook and brown trout. Castro-Santos et al. (2013) came to the opposite conclusion of ours, instead providing evidence that motivation in brown trout decreased with increased discharge and motivation increased for brook trout with discharge. Similarly, Goerig and Castro-Santos (2017) found that brook trout attempt rates increased with higher discharge in their culverts. Yet, for brook trout Enders et al. (2017) came to a similar conclusion as ours – that attraction decreased with increased discharge. One possible explanation for this difference is that in both Enders et al. (2017) and the current study, motivation may have been adversely affected by turbulence caused by the roughness elements placed along the floor of the flume. In contrast, the studies by Castro-Santos et al. (2013) and at least some of the culverts studied by Goerig and Castros-Santos (2017) were in smooth channels, which likely exhibited lower levels of turbulence compared to our roughened flume. Also, much of the conflicting observations noted across these studies may be due to random errors introduced by limited sample sizes, regional differences between study populations or influences of study specific conditions.
Consequently, it is difficult to draw conclusions on the influence of discharge on attempt rates for brook or brown trout species.

**Engineering considerations**

Aside from their influence on fish passage, baffles reduce the hydraulic capacity of culverts (Ead, Rajaratnam, and Katopodis 2002; Wang, Uys, and Chanson 2017) and increase the risk of debris blockage and sediment deposition. These are important engineering considerations, especially for slipline retrofitting applications where reductions in cross-sectional area pose risks to hydraulic capacity (Duguay and Lacey 2015). In open-channel flow, additional bed roughness reduces velocities and increases depth, both favorable for fish passage yet detrimental to hydraulic conveyance. Thus, an important research question arises: can baffle form be optimized to respect engineering requirements and provide for effective fish passage?

For the baffle geometries studied here, free surface Manning’s coefficients ($n$) were approximately 0.016 for SPB-212, 0.022 for SPB-333 and 0.037 for the weir baffles compared to approximately 0.010 for the smooth flume bed which is comparable to a smooth plastic culvert (calculated using depth and discharge values in 1). For comparative purposes, a corrugated steel culvert generally presents a Manning’s value of 0.024 at full flow and upwards of 0.04 at shallower depths. Manning’s $n$ varies non-linearly with depth in partially full flowing pipes (Akgiray 2004). Therefore, the Manning’s coefficients we observed are expected to decrease with increasing depths brought on by higher flow rates through the culvert. Duguay and Lacey (2015) found weir baffles with similar relative roughness heights ($h^*$) and spacings ($\lambda^*$) to those studied here (this study: $h^* = 0.08, \lambda^* = 0.63$; Duguay and Lacey 2015) $h^* = 0.10, \lambda^* = 0.6$) had a fully pressurized $n$ of 0.018. The relative height of the weir...
baffle studied here was nearly half that of those used in similar studies (e.g. $h^* = 0.15$; Olsen and Tullis 2013; Khodier and Tullis 2014). Despite the low relative roughness height of our weir baffles compared to these previous studies, our weir baffles were still capable of greatly improving $D_{\text{max}}$ compared to the bare flume. This is encouraging for applications requiring low roughness baffles and the passage of juvenile trout. Additional work may demonstrate that weir baffles with even lower values of $h^*$ (e.g. 0.05) may prove equally effective and develop lower values of $n$.

The lees of weir baffles are prone to sediment deposition because of the low velocities and reduced bed shear in this zone. As sediment accumulates, the flow field in the lee may be altered to such an extent as to reduce or nullify the low velocity recirculatory zone. Spoiler baffles in contrast, because of the inter baffle voids, may improve sediment transport through the culvert since spoiler baffles provide unimpeded paths for the saltation of sediments downstream. Our SPB-212 configuration, despite developing a small $n$ of 0.016, still provided for exceptional performance improvements over the bare culvert for our larger fish (e.g. > 150 mm fork length), with even greater improvements observed in the SPB-333 baffle for only a small increase in $n$. In streams with high sediment bed load transport rates, spoiler baffles may present a significant advantage over weir baffles in this regard. At present, little is known on how sediment deposition within baffle arrays may affect the passage of fish and further research in this area is merited.

This study provides evidence that baffle form has important impacts on the motivation of brook and brown trout to attempt entry and successfully pass baffled culverts. The bare high velocity supercritical flow conditions of the smooth flume motivated brook trout the most to stage ascent attempts. In contrast, brown trout were most motivated to attempt ascent in the

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low velocity subcritical conditions developed over the weir baffles. Larger fish were much less
motivated to enter the weir baffles than smaller fish. Baffles significantly improved $D_{max}$
compared to the bare flume condition. Larger fish performed best in the spoiler baffles.
However, smaller fish of both species improved performance best in the weir baffles,
especially brown trout. Transit times within the bare and spoiler baffles were similar, yet
slowed drastically in the weir baffles, especially for smaller fish. Our results demonstrate that
the motivation of brook and brown trout to stage entry is influenced to a large extent by baffle
form, species, fish size and hydraulic conditions. Furthermore, our work suggests that passage
performance of brook and brown trout over smooth bottomed culverts can be greatly improved
with the addition of short, sparsely spaced baffles imposing minimal impact on the discharge
capacity of the culvert. These findings will be of interest for applications where maintaining
adequate hydraulic capacity is of prime concern such as in rehabilitated slip-line culverts.

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Bibliography

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TABLE 1: Baffle configurations, water temperatures, flow rates, average cross-sectional velocities and characteristics of groups of fish available for staging an attempt in each trial.

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<td>bare</td>
<td>0.10</td>
<td>16.0</td>
<td>0.055</td>
<td>2.9</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151003A</td>
<td>3</td>
<td>333</td>
<td>0.10</td>
<td>16.2</td>
<td>0.140</td>
<td>3.1</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151003B</td>
<td>3</td>
<td>333</td>
<td>0.15</td>
<td>16.0</td>
<td>0.180</td>
<td>4.1</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151004A</td>
<td>3</td>
<td>WB</td>
<td>0.15</td>
<td>15.6</td>
<td>0.250</td>
<td>1.1</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151004B</td>
<td>3</td>
<td>WB</td>
<td>0.10</td>
<td>15.6</td>
<td>0.200</td>
<td>0.8</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151005A</td>
<td>3</td>
<td>212</td>
<td>0.10</td>
<td>14.4</td>
<td>0.115</td>
<td>3.1</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151005B</td>
<td>3</td>
<td>212</td>
<td>0.15</td>
<td>14.7</td>
<td>0.140</td>
<td>1.7</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151006A</td>
<td>3</td>
<td>bare</td>
<td>0.10</td>
<td>14.0</td>
<td>0.070</td>
<td>3.4</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151006B</td>
<td>3</td>
<td>bare</td>
<td>0.10</td>
<td>14.4</td>
<td>0.055</td>
<td>2.9</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151007A</td>
<td>3</td>
<td>333</td>
<td>0.10</td>
<td>13.5</td>
<td>0.140</td>
<td>3.1</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151007B</td>
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<td>333</td>
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<td>14.1</td>
<td>0.170</td>
<td>1.4</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151008A</td>
<td>3</td>
<td>212</td>
<td>0.15</td>
<td>12.5</td>
<td>0.140</td>
<td>1.7</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151008B</td>
<td>3</td>
<td>212</td>
<td>0.10</td>
<td>12.9</td>
<td>0.115</td>
<td>1.4</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151009A</td>
<td>3</td>
<td>bare</td>
<td>0.10</td>
<td>11.8</td>
<td>0.055</td>
<td>2.9</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
<tr>
<td>151009B</td>
<td>3</td>
<td>bare</td>
<td>0.15</td>
<td>12.0</td>
<td>0.070</td>
<td>3.4</td>
<td>124 ± 47</td>
<td>18</td>
</tr>
</tbody>
</table>

Notes: Duration (dur.) is measured in hours, discharge ($Q$) in m$^3$/s, temperature ($T$) in °C, average depth ($h$) in m, $U_{nom}$ in m/s and fish length (fl) in mm. The trial identifier indicates the date (ymmmdd) followed by trial order with A preceding B, Fr is the non-dimensional Froude number. Please see Materials and Methods for discussion on the number of available fish for the last eight trials.

† Standing waves were present within the SPB and WB trials and could locally vary water surface levels by as much as ±5 cm.

†† $U_{nom}$ is calculated as the discharge divided by the average cross-sectional area of the flow.
TABLE 2: Model selection for time between attempts ($t_A$).

<table>
<thead>
<tr>
<th>model #</th>
<th>T</th>
<th>order</th>
<th>ht</th>
<th>attempt</th>
<th>fl</th>
<th>config</th>
<th>species</th>
<th>Q</th>
<th>fl:config</th>
<th>config:Q</th>
<th>species:Q</th>
<th>AIC_i</th>
<th>ΔAIC</th>
<th>w_i</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>6745.92</td>
<td>-</td>
<td>0.47</td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>6747.18</td>
<td>1.26</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>6749.68</td>
<td>3.77</td>
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</tr>
<tr>
<td>4</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>6749.79</td>
<td>3.88</td>
<td>0.07</td>
</tr>
<tr>
<td>5</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>6750.89</td>
<td>4.98</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>6750.90</td>
<td>4.99</td>
<td>0.04</td>
</tr>
<tr>
<td>7</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>6751.09</td>
<td>5.18</td>
<td>0.04</td>
</tr>
<tr>
<td>8</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>6752.54</td>
<td>6.63</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Note: Subset formed of the eight models producing the lowest AIC within a group of 1151 candidate models. Main effect explanatory variables include: temperature ($T$, continuous - °C), trial order (dichotomous categorical), holding time ($ht$, continuous - day), attempt number (continuous), fork length ($fl$, continuous - mm), configuration (config, polychotomous categorical), species (dichotomous categorical) and flow rate ($Q$, dichotomous categorical). Two-way interactions are separated by colons. ΔAIC is calculated as the difference between model_i and the lowest AIC model. Akaike weights ($w_i$) can be interpreted as the probability the model is the best model given the data (Burnham and Anderson 2002).
### TABLE 3: Model selection for maximum distances of ascent (performance, $D_{\text{max}}$) based on AIC.

<table>
<thead>
<tr>
<th>model#</th>
<th>config</th>
<th>fl</th>
<th>species</th>
<th>Q</th>
<th>ht</th>
<th>T</th>
<th>config:species</th>
<th>fl:Q</th>
<th>config:Q</th>
<th>species:Q</th>
<th>AIC_i</th>
<th>$\Delta_i$AIC</th>
<th>$w_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
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<td>1006.44</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>1008.10</td>
<td>1.66</td>
<td>0.13</td>
</tr>
<tr>
<td>3</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>1008.14</td>
<td>1.70</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>1008.26</td>
<td>1.82</td>
<td>0.12</td>
</tr>
<tr>
<td>5</td>
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<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>1008.39</td>
<td>1.95</td>
<td>0.11</td>
</tr>
<tr>
<td>6</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>1008.40</td>
<td>1.96</td>
<td>0.11</td>
</tr>
<tr>
<td>7</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>1009.59</td>
<td>3.16</td>
<td>0.06</td>
</tr>
<tr>
<td>8</td>
<td>x</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>1009.65</td>
<td>3.21</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Note: Subset of the eight lowest AIC models from a group of 575 candidate models. See notes of Table 2 for variable definitions.
### TABLE 4: Number of fish available and attempting within treatments

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Available</th>
<th>Number of fish staging at least n number of attempts</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>brook</td>
<td>brown</td>
<td>brook</td>
<td>brown</td>
<td>brook</td>
<td>brown</td>
<td>brook</td>
</tr>
<tr>
<td>bare-0.10 m³/s</td>
<td>125</td>
<td>82</td>
<td>42 (0.34)</td>
<td>21 (0.17)</td>
<td>30 (0.24)</td>
<td>15 (0.12)</td>
<td>24 (0.19)</td>
</tr>
<tr>
<td>bare-0.15 m³/s</td>
<td>125</td>
<td>82</td>
<td>38 (0.30)</td>
<td>22 (0.18)</td>
<td>27 (0.22)</td>
<td>14 (0.11)</td>
<td>18 (0.14)</td>
</tr>
<tr>
<td>S212-0.10 m³/s</td>
<td>67</td>
<td>48</td>
<td>12 (0.18)</td>
<td>5 (0.07)</td>
<td>9 (0.13)</td>
<td>4 (0.06)</td>
<td>7 (0.10)</td>
</tr>
<tr>
<td>S212-0.15 m³/s</td>
<td>67</td>
<td>48</td>
<td>10 (0.15)</td>
<td>7 (0.10)</td>
<td>9 (0.13)</td>
<td>6 (0.09)</td>
<td>6 (0.09)</td>
</tr>
<tr>
<td>S333-0.10 m³/s</td>
<td>76</td>
<td>47</td>
<td>19 (0.25)</td>
<td>7 (0.09)</td>
<td>13 (0.17)</td>
<td>1 (0.01)</td>
<td>7 (0.09)</td>
</tr>
<tr>
<td>S333-0.15 m³/s</td>
<td>76</td>
<td>47</td>
<td>19 (0.25)</td>
<td>8 (0.11)</td>
<td>11 (0.14)</td>
<td>3 (0.04)</td>
<td>7 (0.09)</td>
</tr>
<tr>
<td>WB-0.10 m³/s</td>
<td>52</td>
<td>49</td>
<td>18 (0.35)</td>
<td>20 (0.38)</td>
<td>6 (0.12)</td>
<td>11 (0.21)</td>
<td>2 (0.04)</td>
</tr>
<tr>
<td>WB-0.15 m³/s</td>
<td>52</td>
<td>49</td>
<td>16 (0.31)</td>
<td>25 (0.48)</td>
<td>5 (0.10)</td>
<td>14 (0.27)</td>
<td>1 (0.02)</td>
</tr>
</tbody>
</table>

Note: Available fish are the sums of all fish present across trials of the same treatments (bed configuration and discharge) presented in Table 1.
TABLE 5: Estimated parameters for time-to-attempt ($t_a$) from model 1 in Table 2.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\beta_i$</th>
<th>SE</th>
<th>AF</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>intercept</td>
<td>16.262</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>attempt number</td>
<td>-0.604</td>
<td>0.053</td>
<td>0.546</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>temperature (°C)</td>
<td>-0.526</td>
<td>0.110</td>
<td>0.590</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>holding time (days)</td>
<td>-0.044</td>
<td>0.019</td>
<td>0.956</td>
<td>0.017</td>
</tr>
<tr>
<td>order</td>
<td>0.771</td>
<td>0.140</td>
<td>2.163</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>fish length (mm)</td>
<td>-0.015</td>
<td>0.002</td>
<td>0.985</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Q</td>
<td>0.395</td>
<td>0.162</td>
<td>1.485</td>
<td>0.015</td>
</tr>
<tr>
<td>species</td>
<td>0.509</td>
<td>0.247</td>
<td>1.664</td>
<td>0.039</td>
</tr>
<tr>
<td>SPB212</td>
<td>-0.650</td>
<td>0.555</td>
<td>0.521</td>
<td>0.241</td>
</tr>
<tr>
<td>SPB333</td>
<td>0.145</td>
<td>0.502</td>
<td>1.157</td>
<td>0.772</td>
</tr>
<tr>
<td>WB</td>
<td>-0.458</td>
<td>0.440</td>
<td>0.631</td>
<td>0.297</td>
</tr>
<tr>
<td>fish length:SPB212</td>
<td>0.010</td>
<td>0.004</td>
<td>1.010</td>
<td>0.007</td>
</tr>
<tr>
<td>fish length:SPB333</td>
<td>0.005</td>
<td>0.003</td>
<td>1.005</td>
<td>0.159</td>
</tr>
<tr>
<td>fish length:WB</td>
<td>0.007</td>
<td>0.003</td>
<td>1.007</td>
<td>0.011</td>
</tr>
<tr>
<td>species:SPB212</td>
<td>0.277</td>
<td>0.407</td>
<td>1.320</td>
<td>0.494</td>
</tr>
<tr>
<td>species:SPB333</td>
<td>0.824</td>
<td>0.427</td>
<td>2.281</td>
<td>0.053</td>
</tr>
<tr>
<td>species:WB</td>
<td>-0.763</td>
<td>0.326</td>
<td>0.466</td>
<td>0.019</td>
</tr>
<tr>
<td>Q:species</td>
<td>-0.836</td>
<td>0.263</td>
<td>0.433</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Note: Standard errors are noted as SE. AF stands for acceleration factor. The covariates configuration, discharge, species and order are categorical variables with the following levels - configuration: bare, SPB212, SPB-333 and WB; discharge: 0.10 and 0.15 m$^3$/s; species: brook (0) and brown (1); order: first (1) and second (2). Fish length is treated as a continuous variable modeled in increments of 1 mm. Attempt number is continuous and increments in integers. Temperature and holding time are continuous variables incremented in °C and days of holding time.
### TABLE 6: Estimated parameters for maximum distance of ascent ($D_{max}$) from model 1 in Table 3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\beta_i$</th>
<th>SE</th>
<th>AF</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.098</td>
<td>0.002</td>
<td>1.010</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>FL</td>
<td>-0.446</td>
<td>0.157</td>
<td>0.640</td>
<td>0.005</td>
</tr>
<tr>
<td>Q</td>
<td>-1.237</td>
<td>0.331</td>
<td>0.290</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>SPB-212</td>
<td>0.841</td>
<td>0.530</td>
<td>2.319</td>
<td>0.113</td>
</tr>
<tr>
<td>SPB-333</td>
<td>0.704</td>
<td>0.437</td>
<td>2.023</td>
<td>0.107</td>
</tr>
<tr>
<td>WB</td>
<td>2.615</td>
<td>0.484</td>
<td>13.670</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>FL:SPB-212</td>
<td>-0.001</td>
<td>0.003</td>
<td>0.999</td>
<td>0.877</td>
</tr>
<tr>
<td>FL:SPB-333</td>
<td>0.003</td>
<td>0.003</td>
<td>1.003</td>
<td>0.418</td>
</tr>
<tr>
<td>FL:WB</td>
<td>-0.013</td>
<td>0.003</td>
<td>0.988</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>SPB-212:Species</td>
<td>0.148</td>
<td>0.312</td>
<td>1.152</td>
<td>0.650</td>
</tr>
<tr>
<td>SPB-333:Species</td>
<td>0.013</td>
<td>0.342</td>
<td>1.012</td>
<td>0.970</td>
</tr>
<tr>
<td>WB:Species</td>
<td>0.691</td>
<td>0.257</td>
<td>1.996</td>
<td>0.004</td>
</tr>
<tr>
<td>FL:Q</td>
<td>0.006</td>
<td>0.002</td>
<td>1.006</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Note: Parameterization of modeled terms is available in Table 5. Standard errors are noted as SE. AF stands for acceleration factor.
FIG. 1: Layout of the Aquatic Biomechanics and Kinematics Station (ABiKiS) flume facility at the S.O. Conte Anadromous Fish Research Center. River water is gravity fed from the adjacent power canal. Tagged fish were placed within the staging area and allowed to stage ascent attempts upstream within the antenna fitted flume operating under various baffle and flow rate treatments. Note - the non-baffled section of the flume extends farther in reality than depicted. Drawing approximately to scale.
FIG. 2: Relevant dimensions and layouts of the two spoiler baffle (a and c) and weir baffle (b) configurations studied. Baffles were actually white, but are dark gray here to improve contrast.
FIG. 3: Modeled time-to-attempt regression curves for brook and brown trout at low and high flows. Grey lines represent time to first attempts and black lines represent time to the third attempt. The third attempt was chosen to illustrate the effect of the covariate attempt number. Study average values were used for the other covariates: order=1.5, fish length=125 mm, temperature=14.6 °C, holding time=19 days.
FIG. 4: Curves are derived from regression coefficients ($\beta$) in Table 6. The expected percentage of trout attaining a given value of $D_{\text{max}}$ can be read from these curves. Black lines represent brook trout and grey lines indicate brown trout (see legend below figure). Fish length increases from left to right, $\text{FL} = 100$ mm (a & d), 150 mm (b & e) and 200 mm (c & f). The top row of plots presents the low flow condition of 0.10 m$^3$/s, the bottom row presents the high flow condition 0.15 m$^3$/s. Study average values were used for the modeling the following covariates: fish length = 125 mm, temperature = 14.6 degC, holding time = 19 days.
FIG. 5: Experimentally observed transit times (s) for fish to attain their farthest $D_{\text{max}}$ within each treatment. Subplots a-d are for low discharge, i.e. $Q = 0.10 \text{ m}^3/\text{s}$, whereas subplots e-h are for $Q = 0.15 \text{ m}^3/\text{s}$. Data points are further distinguished among FL class sizes, (1) 0-100 mm, (2) 101-200 mm, (3) 201-300 mm and brook (black) and brown trout (red).