Notes
Flow-Control Plates to Manage Denil Fishways in Irrigation Diversions for Upstream Passage of Arctic Grayling

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Abstract

Small-stream irrigation diversions are key elements of many on-farm irrigation systems but can act as barriers to aquatic species. Denil fishways have been installed at irrigation diversion structures throughout the Big Hole River watershed in Montana to provide upstream passage for a population of Arctic Grayling *Thymallus arcticus*. When stream flows are low and irrigation demand is high, irrigators look for ways to maintain adequate diversion, but doing so may reduce the effectiveness of the fishways. In response, agencies and irrigators have proposed flow-control plates placed at the upstream end of fishways. We conducted laboratory-based fishway efficiency experiments with Arctic Grayling placed in an open-channel flume fitted with a Denil fishway and three flow plates. Of the total 200 fish that we used, the fishway entrance attracted 154 fish and we counted these fish as participants. We operated the fishway under varying flow conditions using three flow-control plate treatments and a control to investigate 1) the extent to which each treatment reduced flow compared to the control, and 2) the extent to which each treatment impacted passage success of Arctic Grayling relative to the control. We measured passage success as the ratio of the number of fish that fully ascended the fishway treatment to the number of participant fish attracted to the fishway treatment. One of the three plates, the Denil slot treatment, showed no evidence of reducing either flow or passage success. Another plate, the standard treatment, showed no evidence of reducing flow but moderate evidence of reducing passage success ($P = 0.03$). The only treatment to significantly reduce water flow rate was the narrowed Denil slot treatment and there was no evidence this treatment reduced passage in comparison to the control. Over all trials, water flow rate through the Denil fishway had a strong positive influence on fish passage success.

Keywords: fish passage; Arctic Grayling; Denil fishway; irrigation diversion; ecohydraulics

Received: July 2022; Accepted: January 2023; Published Online Early: January 2023; Published: June 2023


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Introduction

Recent conservation efforts in the Big Hole River valley in southwestern Montana offer an interesting example of cooperative efforts between irrigators, recreationalists, and conservation agencies to support Arctic Grayling Thymallus arcticus recovery while preserving traditional farming and ranching activities. The Big Hole River and its tributaries form a network of blue-ribbon trout streams that is home to five species of game fish: Brook Trout Salvelinus fontinalis, Brown Trout Salmo trutta, Cutthroat Trout Oncorhynchus clarkii, Rainbow Trout Oncorhynchus mykiss, and the last population of native fluvial Arctic Grayling in the contiguous United States, making it a popular angling destination for locals and tourists. The valley also boasts over 50,000 ha of crop-producing farms (Montana Department of Agriculture 2019), largely devoted to forage production, either alfalfa hay or pasture, and small grains.

Much of the water that supplies valley streamflow comes from winter snowfall in the surrounding mountains. In some years snowfall is abundant and there is gradual melt and release to surface waters through the spring and summer such that conflicting demands on summer stream flow are minimal. In other years the opposite occurs, low snowfall and early runoff, resulting in conflicting water demands for irrigation and in-stream flow. To address this potential water use conflict, conservation agencies worked with irrigators to implement actions that increased instream flows, a key strategy outlined in a voluntary Arctic Grayling Candidate Conservation Agreement with Assurances, or CCAA (Montana Fish, Wildlife and Parks and U.S. Fish and Wildlife Service 2006). Development and implementation of the CCAA in the Big Hole River valley was primarily to address concerns about the status of Arctic Grayling in the watershed, a species of concern in Montana (Montana Natural Heritage Program and Montana Fish, Wildlife and Parks 2022). Ancillary benefits to stream ecosystem function and the trout fishery were a desirable by-product of the CCAA activities.

Irrigators in the valley have adopted or refined many activities to seek a sustainable balance between agricultural production and the health of the fishery because of the CCAA. These activities included enhancing riparian and stream habitat, stock-water facility improvements, advances in irrigation scheduling, enhancements to on-farm irrigation delivery systems, and in-stream diversion management to improve migration routes throughout the watershed (Lamonthe 2009). The CCAA participants were particularly interested in ways to design and operate in-stream irrigation diversions that provided sufficient water for irrigation demands while providing for fish mobility. Fish mobility and stream connectivity is essential to meet life history needs such as spawning, seeking thermal refuge, or pursuing food (Silva et al. 2017).

Irrigation diversions are in-stream structures used to control the water surface elevation near a ditch or canal to maintain flows necessary for irrigation. These diversion structures vary in size and government agencies, irrigation user groups, or individual irrigators may regulate them. In the Big Hole Valley, the diversions are typically manmade structures less than 2 m tall that are regulated by individual irrigators and span the width of the stream (Figure 1). Irrigators can add or remove cross-boards in the weir, or planks, to increase or lower the water surface level in the upstream pool. This adjustability allows the irrigator to respond to stream flow variation while maintaining adequate canal flow. The diversion shown in Figure 1 also has a Denil fishway installed to facilitate upstream movement of fish. CCAA participants have installed 63 Denil fishways at irrigation diversions throughout the Big Hole River watershed as part of the CCAA.

Denil fishways are a type of technical fishway that have closely spaced baffles to reduce water velocity and redirect flow by exerting a retarding shear stress on the fluid moving through the fishway (Katopodis 1992). The resulting flow is highly turbulent but has a lower average velocity than an un baffled chute. Denil fishways exhibit a low water velocity near the floor of the fishway that increases vertically. Engineers and fisheries personnel believe that the low-velocity zone, which occupies a larger area at higher flow rates, provides an ideal passage route for fish travel in the upstream direction. Research-
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Facility

The BFTC open-channel flume that we used was approximately 18.3 m in length and 0.9 by 0.9 m in cross-section (Dockery et al. 2019) with a 3.7-m-long Denil fishway installed in the flume at a 12(H):1(V) slope; this drop resulted in a slope of 8.2%, which has effectively passed Arctic Grayling in previous laboratory tests (Blank et al. 2021; Plymesser et al. 2022) and is consistent with design standards used by fish passage practitioners in the Big Hole River watershed (Montana Fish, Wildlife and Parks and Natural Resources Conservation Service, personal communication). Design guidance for Denil fishways recommends maximum slopes of 16.7% (USFWS 2019). Pumps moved fresh water from a nearby spring into the upstream end of the flume and recirculated it at the prescribed flow rate for each trial. The flume design allowed flexible placement of a passive integrated transponder (PIT) antenna system and temperature and water depth data loggers; the flume had a tarp cover to prevent disturbance of test fish and maintain uniform lighting. A detailed description of the research flume that we used for the experiments is in Dockery et al. (2019).

Fish handling and history

The Arctic Grayling embryos were the offspring of brood stock collected from Red Rock Creek in southwestern Montana, in May 2014. Fisheries personnel transported the embryos to the BFTC where they hatched in a vertical, flow-through incubator and then moved to a 150-L tank supplied with 10–12°C spring water (Davis 2016). A belt-fed system delivered a starter diet to the fry. Once weaned off the starter diet, the fish received 3.5 mm floating feed Classic Trout diet (Skretting USA, Tooele, UT) daily. At age 0+: fisheries personnel transferred the fish to a 20-m-circumference artificial river (fabricated by Hydro Composites, LLC, Stockdale, TX). The oval-shaped artificial river was composed of two 6.42-m-long, 1.56-m-wide straight sections that connected two simulated channel bends with an outside diameter of 5.81 m and a center wall separating the channels. Water was circulated in the tank and velocities varied spatially from 0 to 0.9 m/s. The water source was a natural spring with water tempera-

Methods

Our research team carried out a series of experiments in an open-channel flume at the U.S. Fish and Wildlife Service (USFWS) Bozeman Fish Technology Center (BFTC) in Bozeman, Montana, from July through September of 2017. We tested three different flow-control-plate treatments and a control (Figure 3). Our conversations with representatives of Montana Fish, Wildlife and Parks, USFWS, and the Montana Department of Natural Resources and Conservation who worked with irrigators in the project area informed design of the flow-control plates. We selected the standard (S) plate because irrigators and agency personnel had installed these plates at a few of the Denil fishways in the Big Hole River valley. The Denil slot (DS) plate has the same open-area geometry as a standard Denil fishway baffle and we selected it as a plate that may have a small reduction in flow but retain the fundamental hydraulics of the fishway. We chose the narrowed Denil slot (NDS) plate because there was potential for a marked reduction in flow while retaining some elements of the Denil baffle slot geometry.

Figure 2. An example of a diversion weir and Denil fishway in the Big Hole River valley, Montana, in 2015, operating under conditions where water is limited. A Denil fishway at this site facilitates upstream fish migration when the planks are in use. The water does not cascade over the adjustable planks and the flow in the fishway is shallow. Photo by Nolan Platt.
tures between 8.0 and 13.1°C. Between hatching in 2014 and the restrictor-plate experiments in 2017, researchers used the Arctic Grayling in two other experiments; one in 2015 to quantify swimming performance (Dockery et al. 2019) and another in 2016 to determine passage success through a standard Denil fishway (Blank et al. 2021). The researchers held any Arctic Grayling not actively participating in a research study in the artificial river. BFTC technicians conducted all care and feeding of the Arctic Grayling. In 2017 the Arctic Grayling were age 3+ hatchery fish and represented an adult-size wild counterpart; wild Arctic Grayling are rare and not available for laboratory research purposes. Arctic Grayling reared and exercised in captivity have been swim tested and demonstrated abilities like their wild counterparts (Cahoon et al. 2018; Dockery et al. 2020).

In May 2017 we transferred approximately 400 Arctic Grayling to a 3-m-diameter outdoor tank near the open-channel flume. The holding tank was equipped with external pumps to maintain water velocities that varied spatially from 0 to 0.9 m/s; we maintained water temperature at approximately 12°C and kept feed rations unchanged. To identify and track individual fish, we inserted 12-mm PIT tags (HDX12 Pre-load; Biomark, Boise, ID) into the peritoneal cavity through a small needle incision located just anterior to the anal fin in 2015. During the tagging process, we used MS-222 to lightly anesthetize subject fish. We identified individual subjects using a Destron Fearing 601 Handheld PIT tag reader (Destron Fearing, DFW Airport, TX) prior to each trial.

**Fish passage observations**

Prior to each trial we randomly selected 10 fish from the holding tank, recorded the individual PIT tag identification numbers, and transferred them to the staging area. We omitted and replaced subjects from the

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**Figure 3.** We placed Arctic Grayling *Thymallus arcticus* in an open-channel flume fitted with a Denil fishway and a flow treatment in Bozeman, Montana, in 2017, and allowed fish to attempt to enter and traverse the fishway volitionally. The figure shows the geometry and dimension of the three flow plates and a control (no plate); we used the four treatments to investigate 1) the extent to which each plate treatment reduced flow compared to the control, and 2) the extent to which each plate treatment impacted passage success of Arctic Grayling relative to the control. We measured passage success as the ratio of the number of fish that fully ascended the fishway treatment to the number participant fish attracted to the fishway treatment.
Table 1. A summary of the fish, hydraulic conditions, and fish passage trial data for fish passage experiments conducted at the Bozeman Fish Technology Center, Bozeman, Montana, in summer of 2017.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Plate type (treatment)</th>
<th>Notch depth (m)</th>
<th>Water flow rate (m³/s)</th>
<th>Average water temperature (°C)</th>
<th>Average fish fork length (mm)</th>
<th>Average fish mass (g)</th>
<th>No. of fish participating (attracted)</th>
<th>No. of fish fully ascending</th>
<th>Rate of participants that fully ascended</th>
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<td>0.101</td>
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<td>390.6</td>
<td>10</td>
<td>0</td>
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<td>332.0</td>
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<td>11.5</td>
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<td>381.5</td>
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<td>0.011</td>
<td>12.3</td>
<td>325.0</td>
<td>394.0</td>
<td>5</td>
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<td>10</td>
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<tr>
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<td>325.0</td>
<td>389.3</td>
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<td>323.5</td>
<td>421.5</td>
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<td>316.0</td>
<td>373.1</td>
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</tr>
</tbody>
</table>

C = control; DS = Denil slot plate; NDS = narrowed Denil slot plate; S = standard plate.

At the beginning of an experimental trial, we moved fish from the staging tank to the tail-water box at the downstream end of the fishway. We then covered the flume–fishway system with a tarp and left the test subjects to move volitionally for 2 h. During experimental trials we monitored fish movement using a Multi-Antenna HDX Reader (Oregon RFID, Portland OR) attached to two antennas at the upstream and downstream ends of the Denil fishway. Upon completion of the 2-h trial, we inserted screens to restrict further movement of the Arctic Grayling, removed the tarp, and recorded the physical location of the subjects as upstream, downstream, or inside of the Denil fishway. We then removed the fish from the flume and measured, weighed, and placed them into a separate holding tank (Table 1; Data S1, Supplemental Material).

In summary, we selected 200 fish from a holding tank of 400 and swam them in 20 trials, with 10 fish placed in the raceway simultaneously for each trial. We used 10 fish in the trials based on our experience with Arctic Grayling research (Blank et al. 2021) that showed adequate participation while allowing us a reserve number of fish for repeating an interrupted trial or removing fish that appeared unhealthy. We performed five trials for each of the three flow-restrictor plates and the control at replicated depths measured at the notch of the flow plate or first baffle in the case of the control.

Hydraulic observations

In each trial we set a prescribed upstream fishway depth by adjusting the flow rate into the system. The depth of water flowing over the first baffle notch or flow-plate notch at the Denil fishway entrance was the concern; the height of the boards in relation to the Denil fishway placement regulated notch depth. Thus, placement of boards regulates notch depth in the case of the flume research or in an irrigation diversion application; water will back up on the dam boards and fill the Denil fishway and the boards will shunt it to the diversion canal. Flow will pass over the boards once it exceeds the Denil height entrance or volume. Noteworthy is the coupling of depth over the first baffle notch and flow rate through the Denil fishway, in that they increase or decrease in relationship. Researchers have observed Denil ladders placed in irrigation diversions under conditions varying from no water passing over the notch to completely submerged (Triano et al. 2022; Figures 1 and 2). The study notch depth test conditions varied from ~0.1 to ~0.35 m. The range of test conditions represent field conditions varying from optimal to suboptimal hydraulics for fishway operation (Katopodis 1992); the minimum tested notch depth provided enough water depth to allow a fish to ascend the fishway without leaping or air exposure, while the maximum depth represented a full-
Flowing Denil ladder functioning near optimal hydraulic conditions. We measured the notch depth vertically from the lowest point in the open space of the most upstream baffle or flow-control plate to the water surface. We set the prescribed downstream fishway depth using backwater weir boards inserted at the downstream end of the flume. Water depth data loggers (WT-HR, TruTrack; GEO Scientific Ltd., Vancouver, Canada) in the headwater and tail-water boxes provided continuous depth and temperature measurements over the duration of each trial. Note that the upstream depths were similar within the trials for each flow-control-plate treatment but do not match the control where the zero-flow inlet water surface elevation is slightly lower because the first baffle opening within the Denil is recessed into the sloping fishway (Table 1). We used the U.S. Geological Survey midsection method to determine the flow rate in the flume (Rantz 1982; Rantz and Peck 1982) after each trial.

**Observations of passage success**

We defined passage success as the ratio of the number of fish that fully ascended the fishway to the number of fish attracted to the fishway and participating in the study (Table 1). We considered fish to be participants if they registered on the PIT antenna at the downstream end of the fishway and considered them to be passage successes if they registered on the upstream PIT antenna. There was only one instance in which we observed a fish upstream of the fishway that did not register on the upstream PIT antenna. Because of its location at the end of the trial we counted it as a successful pass.

**Statistical analyses**

We examined the effect of our flow-control treatments on the relationship between flow rate and inlet water depth using multiple linear regression on the log-transformations of the observed data (equation 1). We performed this analysis in Microsoft Excel (Microsoft Corporation, Redmond, WA). Hydraulic rating relationships that are theoretically linked to the gradual hydraulic drop are known to behave as power functions and are appropriate for linearization using a log-log transformation (Chow 1959). The model was as follows:

$$\log(Q) = \beta_0 + \beta_1 \log(h) + \beta_2 DS + \beta_3 NDS + \beta_4 S + \epsilon,$$

(1)

where $Q$ is the flow rate ($\text{m}^3/\text{s}$); $h$ is the notch depth (m); DS, NDS, and $S$ are binary indicator variables indicating the presence (1) or absence (0) of a treatment; the control treatment is the reference level; $\beta$ values are regression coefficients; and $\epsilon$ is the normally distributed random error.

We did not intend water temperature and size of the fish as indicated by the fish mass and the fish length (Table 1) to be variables in this experimental design. However, due to random sampling of fish for each trial and the imperfect method of controlling water temperature over a month-long experiment, we checked for lack of homogeneity of these observations using ANOVA as part of the model-building process. We completed this analysis using SigmaPlot (Systat Software, San Jose, CA). The mean water temperature failed the equal variance test, so we used ANOVA on ranks. There was no evidence for differences in water temperature between the control and the DS treatment ($P = 0.265$), between the control and the S treatment ($P = 0.786$), and between the control and the NDS treatment ($P = 0.841$). There was no evidence for difference in fork length ($P = 0.265$) or fish mass ($P = 0.091$) from a standard ANOVA. Within trials, we noted no trends in the size of successful fish compared to unsuccessful fish. Based on this analysis we discounted water temperature, fish length, and fish mass as candidate model variables.

We used a mixed effect binomial logistic regression to examine the relationship between trial passage success and the variables flow rate ($\text{m}^3/\text{s}$) and plate treatment. We defined the inferential mixed effects logistic regression model in the following way:

$$Y_i \sim \text{Binomial}(n_i, p_i)$$

$$\text{logit}(p_i) = \beta_0 + \beta_1 \text{Flow} + \alpha_i$$

$$a_i \sim \mathcal{N}(0, \sigma^2_a)$$

where $Y_i$ denotes the number of fish that successfully passed through the Denil on the ith trial ($i = 1, 2, \ldots, 20$). The model assumes $Y_i$ follows a binomial distribution ($n_i, p_i$), with $n_i$ equal to the number of participants in trial $i$ and $p_i$ representing the constant probability of passage success for all fish in trial $i$. The variables DS, NDS, and $S$ are binary indicator variables indicating the presence (1) or absence (0) of a treatment; the control treatment is the reference level; and $\beta$ values are regression coefficients. We assumed the random intercept for trial ($a_i$) to be normally distributed with a mean of 0 and variance $\sigma^2_a$ (Zuur et al. 2009). A random intercept term for trial was included to account for a potential lack of independence among fish within a trial due to group swimming behavior. Due to strong correlation among all measured hydraulic variables, it was not appropriate to have more than a single hydraulic variable in the model. A two-way interaction between the flow and plate variables was included in the initial regression model and evaluated with a likelihood ratio test (Ramsey and Schafer 2002; Zuur et al. 2009). Residual diagnostics did not indicate severe violations of model assumptions, although a sample size larger than 1 for each flow by plate treatment would allow for a more thorough investigation of the appropriateness of this model for predicting passage success probabilities. We performed this analysis in the program R, version 4.03 (R Core Team 2020) using the lme4 package (Bates et al. 2015).
Results

All treatments exhibited a nonlinear relationship between flow rate and inlet water depth (Figure 4; Table 2). Examining the $P$ values for the coefficients in equation (1), there is no evidence that the DS ($P = 0.305$) and the S ($P = 0.961$) treatments effectively reduced flow when compared to the control. Confirming the visual presentation (Figure 4) there was strong evidence that the NDS treatment had a significantly lower flow capacity than the control ($P = 0.005$).

In all trials except one (Trial 10) at least 1 of the 10 fish introduced to the downstream pool participated in a passage attempt (Table 2). Over all trials the average participation rate was 77%. Trials 7, 11, 16, and 18 had participants but no successful passage. Over the entire experiment, including treatments and control, 42.2% of fish that participated successfully passed the Denil fishway. The passage rate, defined as the number of fish passing divided by the number fish participating, was 51.4% for the control, 57.4% for the DS treatment, 26.4% for the NDS treatment, and 28.9% for the S treatment. Passage success generally increased with flow for all plate treatments and was 0 for the lowest flow treatment in all plate treatments (flow $\leq 0.014$ m$^3$/s; Table 1; Figure 5).

We assumed the mixed effect binomial logistic regression random intercept for trial ($\alpha_i$) to be normally distributed with a mean of 0 with an estimated variance of 1.035. There was a lack of evidence for an interaction between plate and flow and the interaction term was not included in the inferential model ($\chi^2 = 2.32; df = 3; P = 0.51$). There was strong evidence (Figure 5; Table 3) that passage success was positively associated with flow ($P < 0.0001$). There was moderate evidence that the standard (S) plate had reduced passage in comparison to the control ($P = 0.03$). There was a lack of evidence that passage differed between the Denil plate treatment (DS) and the control ($P = 0.92$) and the narrowed Denil (NDS) and the control ($P = 0.49$). Given the limited sample size, lack of replication, large residual deviance, readers should view results cautiously.

Discussion

We conducted this study to determine if plates installed on the inlet of Denil fishways reduced the flow

Table 2. Estimated parameters for the multiple linear regression model describing associations among flow, notch depth, and plate treatments (control, standard, Denil slot, and narrow Denil slot) in 2017.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\beta$</th>
<th>SE</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$ intercept</td>
<td>-0.43</td>
<td>0.04</td>
<td>$&lt;0.0001$</td>
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<tr>
<td>$\beta$ log(h)</td>
<td>1.48</td>
<td>0.05</td>
<td>$&lt;0.0001$</td>
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</tr>
<tr>
<td>$\beta$ narrow Denil slot</td>
<td>-0.09</td>
<td>0.03</td>
<td>0.005</td>
</tr>
<tr>
<td>$\beta$ standard</td>
<td>-0.001</td>
<td>0.03</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Figure 4. We placed Arctic Grayling *Thymallus arcticus* in an open-channel flume fitted with a Denil fishway and three flow plate treatments and a control (no plate) in Bozeman, Montana, in 2017, and allowed fish to attempt to traverse the fishway voluntarily. The figure shows rating curves that describe the relationship between flowrate and notch depth for each of the plate treatments and the control (C = control; DS = Denil slot plate; NDS = narrowed Denil slot plate; S = standard plate). The research investigated 1) the extent to which each plate treatment reduced flow compared with the control, and 2) the extent to which each plate treatment impacted passage success of Arctic Grayling relative to the control. The measure of passage success was the ratio of the number of fish that fully ascended the fishway treatment to the number participant fish attracted to the fishway treatment.
of water through the fishway and if the plates affected passage success of Arctic Grayling moving in the upstream direction. We first note that it requires a dramatic restriction in cross-section for the flow-control plate to substantially reduce flow (Figure 4). Both visually and statistically it is evident that the control, the DS plate, and the S plate all had similar rating curves when evaluated from an irrigator’s standpoint, the flow rate as a function of inlet water depth. This alone may negate any interest in using the S or DS plates to regulate water flow through the fishway. The NDS plate noticeably and statistically reduced flow as would be expected with a weir having a slot width that is only 15.2 cm wide.

A desirable Denil restriction would be a plate that reduces flow through the Denil fishway while maintaining effective fish passage. If we consider the results of the logistic analysis, the S treatment passed fish less effectively than did the control but there was not evidence the DS and NDS treatments reduced passage compared to the control. When seeking ways to reduce water flow through the Denil without compromising fish passage, we recommend that the S plate not be used because it reduces fish passage and the DS plate not be used because it does not substantially reduce water flow. The NDS plate did reduce water flow and there was a lack of evidence that the NDS plate reduced passage in relation to the control. This type of plate design may warrant further research. Alternatively, a scaled Denil fishway is a possible replacement to standard-sized Denil fishways to enhance upstream mobility of Arctic Grayling in small, water-limited streams (Plymesser et al. 2022) to achieve balance between irrigation water needs and fish passage goals.

We contend Figure 5 portrays the irrigation management implication of the study most strongly, where overall treatments there was a positive relationship between water flow rate and Arctic Grayling passage success. This relationship suggests that an adequate supply of water ensures that a Denil fishway is an effective fishway. In the overall analysis the plate treatment was not a significant indicator of passage success, but flow rate was; we contend that it is not prudent to reduce the flow in a Denil fishway using any of the plate geometries we evaluated. We recognize that our recommendation to maintain adequate flow in the fishway may leave some irrigators in low-flow situations with a compromised ability to divert their water. In response, we recommend first that irrigation managers examine the diversion structure itself for effectiveness. Diversion structures can leak or have substantial piping through the coarse streambed on which the diversion rests. Some diversions have flow paths that circumvent the weir by flowing around it as surface flow or have collected debris in a way that reduces the utility of the diversion.

**Figure 5.** We placed Arctic Grayling *Thymallus arcticus* in an open-channel flume fitted with a Denil fishway, in Bozeman, Montana, in 2017, and allowed fish to attempt to traverse the fishway volitionally. The fishway was operated with three flow-plate and control (no plate) treatments at a range of flows. The figure shows estimated logistic regression curves for the probability of success for flow for each of the flow plate treatments (C = control; DS = Denil slot plate; NDS = narrowed Denil slot plate; S = standard plate).

**Table 3.** Estimated parameters for the selected logistic model describing associations among passage success, flow, and plate treatments (control, standard, Denil slot, and narrow Denil slot) in 2017. Note: Flow is treated as a continuous variable and plate treatments are categorical. The reference level for the plate treatments is the control treatment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>β</th>
<th>SE</th>
<th>P</th>
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</thead>
<tbody>
<tr>
<td>β_intercept</td>
<td>−3.01</td>
<td>0.61</td>
<td>&lt;0.0001</td>
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<tr>
<td>β_flow</td>
<td>102.21</td>
<td>16.35</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>β_Denil slot</td>
<td>−0.06</td>
<td>0.62</td>
<td>0.92</td>
</tr>
<tr>
<td>β_narrow Denil slot</td>
<td>−1.15</td>
<td>0.64</td>
<td>0.07</td>
</tr>
<tr>
<td>β_standard</td>
<td>−2.86</td>
<td>0.83</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
these issues may lessen the need for flow reduction through the Denil and irrigation managers should consider this possibility. There are likely also cases where the diversion itself is well maintained and functional, but the standard-size Denil fishway requires too much flow to ensure adequate fish passage and irrigation flow. In this case modifications to the Denil inlet that allow any fish passage at all are preferable to blocking the inlet entirely. Use of a plate like the NDS treatment may be a good stopgap because it reduces flow and there is evidence that fish pass the plate as well as a lack of evidence that passage differed between the NDS plate and the passageway without a plate attached.

Supplemental Material

Please note: The Journal of Fish and Wildlife Management is not responsible for the content or functionality of any supplemental material. Queries should be directed to the corresponding author for the article.

Data S1. An archive of data observed in the study trials conducted at the Bozeman Fish Technology Center, Bozeman, Montana, in 2017. Available: https://doi.org/10.3996/JFWM-22-041.S1 (19 KB XLSX)


Acknowledgments

We extend thanks to Bill Rice and Jim Magee with the U.S. Fish and Wildlife Service for their help in establishing this project. Jacqueline Knutson (Natural Resources Conservation Service), Mike Roberts (Montana Department of Natural Resources and Conservation), and Austin McCullough (Montana Fish, Wildlife and Parks) were integral in developing the objectives of the project. Our thanks to Erin Ryan, Jason Ilgen, and Matt Toner and all the BFTC staff for the instruction, assistance, and guidance. Undergraduate assistance from Maddie Moyness, Audrey Jones, and Brianna Bowman during trial data collection was essential in the completion of this study. Funding for this project was provided by the USFWS. We would also like to thank the reviewers and the Associate Editor at the Journal of Fish and Wildlife Management for improving this manuscript through their constructive feedback and encouragement.

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