

DESIGNING AND ASSESSING THE EFFECTIVENESS OF DENIL FISHWAYS
USING HYDRAULIC MODELING-BASED APPROACHES

by

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DEDICATION

To Megan
and the 404,
much love to the community.

To Alan and Joan,
for valuing education and making it all possible.

To Ben,
this project would not be what it was without him.

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ABSTRACT

Man-made, instream structures can pose barriers to fish movement. Fish move about river systems to reach habitats associated with various stages of their life histories. If access to required habitat is blocked, it can cause detrimental effects to fish populations. Removing barriers to fish movement is often socio-economically infeasible so fishways are used to promote fish passage around barriers. Denil fishways consist of a chute for water to flow through and baffles to slow water velocities; they are a relatively cheap solution for promoting upstream fish passage over low-head barriers. The Big Hole River basin is home to the last fluvial population of Arctic Grayling in the continental United States. Per an agreement between landowners and several government organizations, Denil fishways were installed at irrigation diversions in the Big Hole Valley to provide fish volitional routes to navigate irrigation diversions. Eleven Denil fishways at irrigation diversions were evaluated for their effectiveness at passing grayling by using hydraulic modeling techniques coupled with biologic data. Hydrologic data was applied to hydraulic models to estimate water surface elevations about the Denils over time. A passage index was developed which inferred passage efficiency of the fishway based on depths at the upstream and downstream ends and assigning a "passage condition." Passage windows were developed which describe times when the fishways functioned to "allow", "limit", or "prevent" upstream passage. Across all sites fishways were predicted to "allow" passage 6.4% of the time, "limit" passage 17.2% of the time, and "prevent" passage 10.3% of the time. The modelled depth combination at fishways was "out of range" of the passage index 66.1% of the time. A hydraulic design process was proposed with the goal of designing Denil fishways at pin-and-plank irrigation diversions to promote upstream passage at low flows. Design criteria were established, explained, and presented. One-dimensional hydraulic modeling techniques for diversions and fishways was presented and used to determine design parameter values that optimize fish passage efficiency over a broad range of instream flows. We attempted to develop a novel method of assessing Denil structures using hydraulic models; our method is useful to managers because the effectiveness of fishways was assessed by considering how they functioned over a range of instream flows and at times associated with fish movement.

INTRODUCTION

The research presented within this thesis was a product of an interdisciplinary study into upstream fish passage, through Denil fishways, in the Big Hole Valley, Montana. This collaborative project involved a diverse set of partners and stakeholders including Montana State University, the United States Fish and Wildlife Service (USFWS), the Montana Department of Fish, Wildlife, and Parks (MFWP), and the Big Hole Valley community. The project was motivated by the need to assess the effectiveness of Denil fishways installed to promote habitat connectivity and conserve a population of Arctic Grayling (*Thymallus arcticus*) in the Big Hole River and its tributaries. Direct and indirect methods were used to evaluate the fishways for effectiveness at promoting upstream passage of grayling and other fish species. Upstream passage efficiency of wild fish and hatchery reared grayling was directly evaluated using Passive Integrated Transponder (PIT) arrays during discrete experiments at irrigation diversions. The effectiveness of 11 fishways was indirectly evaluated by using numeric hydraulic modeling coupled with biologic data to estimate fish passage efficiency over time. This thesis details the indirect investigations into fishway effectiveness and proposes a hydraulic design process utilizing hydraulic modeling methods.

The indirect assessment of fishway effectiveness in the Big Hole combined hydraulic models, hydrologic data, and biologic data to estimate upstream fish passage efficiency over time at 11 Denil fishways retrofitted onto irrigation diversion structures. This analysis is presented in Chapter 3. Passage windows (i.e. time periods when

upstream passage through the fishways was allowed, limited, or prevented) were estimated for each study site during summer-fall 2017/2018. To determine if the fishways were efficient connectors of habitat upstream and downstream of the diversions at a given time, modelled hydraulic conditions were compared to conditions known to facilitate or hinder fish passage based on experiments conducted in a laboratory setting with hatchery reared Arctic Grayling (Blank et al. forthcoming). Effective fishways exhibit high passage efficiencies over a wide range of instream flows, particularly at instream flows that correspond to time periods when fish move to seek habitat for spawning, feeding, or refuge. Denil fishway efficiency over time was estimated through hydraulic modeling, physical and hydrologic monitoring, and incorporating biologic data; the effectiveness of the fishways was inferred using the results of this analysis.

A hydraulic design procedure for Denil fishways at pin-and-plank irrigation diversions is presented in Chapter 4 of this thesis. This design procedure will promote sound engineering decision-making and inform practitioners in the use of Denil fishways to connect habitat between stream reaches upstream and downstream of pin-and-plank irrigation diversions. Fishway slope and the combination of depths at the upstream and downstream ends control the hydraulic grade and hydraulic conditions (i.e. depth, velocities, and turbulence) within Denil fishways (Rajaratnam 1984; Towler et al. 2015). A Denil fishway can be designed to promote favorable hydraulic conditions for fish passage over the widest possible range of instream flows by orienting the fishway such that it has an appropriate slope and the invert elevations are set to sustain minimum depth thresholds at low flows. Each fishway design is species and site-specific, based on the

physical layout of the site, target species, and the site hydrology. During field investigations, fishway installations which promoted and hindered passage were observed; this design procedure was inspired by the need to design Denil fishways in a consistent manner to optimize fish passage efficiency through time.

The author applied hydraulic modeling techniques, biologic data, and hydrologic data to the design and assessment of Denil fishways. This research is novel because, to date, the effectiveness of Denil fishways in the Big Hole River and its tributaries have not been extensively evaluated, nor has hydraulic modeling been used to infer the effectiveness of existing Denil fishways as presented. While others have proposed design criteria for Denil fishways (MDNRC Conservation Districts Bureau 2001; Axness and Clarkin 2013; USFWS 2017) the design process presented herein details the use of one-dimensional hydraulic modeling for designing fishways that operate effectively at desired instream flows. The objective of the research presented herein is to evaluate site-specific fish passage effectiveness of existing Denil fishways and create a procedure for the hydraulic design of Denils which maximizes their upstream passage effectiveness.

LITERATURE REVIEW

The Big Hole and Grayling

The headwaters of the Big Hole River begin in the Beaverhead Mountains south of Jackson, Montana. It flows north through the Big Hole Valley, then trends east between the Pioneer Mountains and Anaconda Range before turning south to round the eastern front of the Pioneers. The Big Hole then flows east towards its confluence with the Beaverhead River near Twin Bridges, Montana. The Big Hole River drains about 2,800 square miles and has United States Geological Survey (USGS) 8-digit Hydrologic Unit Code (HUC) 10020004 (Flynn et al. 2009). The 12 inches of average annual precipitation in the Big Hole Valley come mainly as snow (Vatland 2015). Peak flows generally occur early in July then decrease throughout the summer (Sladek 2013). The lowest annual flows are generally observed between mid-August and mid-September (Sladek 2013). Average instream temperatures rise as the discharge falls throughout July, temperatures peak towards the end of the month then cool through September (Sladek 2013). The Big Hole River is home to many fish species native to Montana including Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*), Mountain Whitefish (*Prosopium williamsoni*), Mountain Suckers (*Catostomus platyrhynchus*), White Suckers (*Catostomus commersonii*), Longnose Suckers (*Catostomus Catostomus*), Longnose Dace (*Rhinichthys catatactae*), Mottled Sculpin (*Cottus bairdii*), Burbot (*Lota lota*), and Arctic Grayling.

The Big Hole River is home to the last remaining, purely fluvial population of Arctic Grayling in the contiguous United States (Peterson and Arden 2009; Vatland 2015). Arctic Grayling currently inhabit waterways in northeast Eurasia, Alaska, and Canadian Provinces between Hudson Bay and the Gulf of Alaska (Northcote 1995; Cahill 2015). Historically, glacial relic populations of Arctic Grayling occupied drainages in Michigan (extirpated in the 1930's) (Litkes 1981) and much of the Upper Missouri River basin of Montana and Wyoming upstream of Great Falls, Montana (Cayer and McCullough 2013). Presently, Arctic Grayling occupy less than 5% of their historic range in the Upper Missouri basin (MFWP and USFWS 2006; Cayer and McCullough 2013), surviving in at least three locations: the Big Hole River, Red Rocks lakes in the Centennial Valley, and the Ennis Reservoir on the Madison River (Peterson 2009). The Upper Missouri grayling are genetically distinct from their Canadian and Alaskan relatives (Peterson 2009). Arctic Grayling in the Upper Missouri River basin are considered a Species of Special Concern by MFWP, the American Fisheries Society Montana Chapter, and the Montana Natural Heritage Program (Cayer and McCullough 2013).

Decades of legal battles debating whether to list the Upper Missouri River Arctic Grayling populations under the Endangered Species Act (ESA) have occurred. The first legal actions taken to protect the Upper Missouri grayling occurred in December 1982, when they were declared a "Category 2" species; this means that listing as endangered or threatened was "possibly appropriate" (MESO 2014). In October 1991 the Biodiversity Legal Foundation petitioned to list Montana's Arctic Grayling on the ESA (MESO 2014),

but recognition of this population as a subspecies was not widely accepted until July 1994 when the Upper Missouri River population was declared a Distinct Population Segment (DPS) and a Candidate Species whose listing under the ESA was “warranted but not precluded” (MESO 2014). In 2004 the Upper Missouri River grayling listing priority level was upgraded to the highest level of priority that can be considered for a DPS (Cayer and McCullough 2013). In April 2007, the Candidate Species classification was repealed because it was decided that the Upper Missouri River grayling were not a DPS (MESO 2014). During the time period Arctic Grayling were considered a Candidate Species for listing, a Candidate Conservation Agreement with Assurances (CCAA) was agreed upon between several government agencies and local landowners to promote management actions to conserve this population (MFWP and USFWS 2006). In 2010 the Upper Missouri River grayling were again categorized as a DPS and upgraded to the highest priority level a DPS can attain (MESO 2014). In August 2014 it was decided that the Upper Missouri grayling DPS was not warranted for listing, but this was appealed and remanded for further consideration in 2018 (USCANC 2018). The ESA listing status of Arctic Grayling in the Upper Missouri basin has been changed several times over the last few decades, currently their listing is “not warranted.” Despite listing status this DPS currently inhabits less than 5% of its historic range and management actions are being taken at this time to protect the Big Hole grayling.

In 2006 a CCAA was agreed upon by the Montana Department of Fish, Wildlife, and Parks (MFWP), the USFWS, the USDA Natural Resources Conservation Service (NRCS), the Montana Department of Natural Resources and Conservation (MDNRC),

and local landowners with the goal of securing and enhancing the population of Arctic Grayling in the Big Hole River and its tributaries (MFWP and USFWS 2006). The CCAA promotes management actions that conserve the population of Arctic Grayling in the Big Hole and protects landowners enrolled in the program from additional regulations being leveled upon them if the population of grayling were to get listed under the ESA (MFWP and USFWS 2006). The CCAA (2006) addresses the following major threats to grayling in the Big Hole: reduced instream flows, degraded and non-functioning riparian habitats, barriers to grayling movement, and entrainment in irrigation ditches. Per the CCAA, enrolled landowners agreed to remove barriers to grayling movement or modify instream structures to permit grayling movement within 5 years of joining the program (MFWP and USFWS 2006). Through this initiative 63 Denil fishways were installed throughout the Big Hole Valley for promoting upstream passage of grayling over pin-and-plank irrigation diversion structures (2017 email from Jim Magee, USFWS Biologist). A sample of these fishways were the subject of the present research; they were monitored for two years with the goal of assessing their effectiveness and proposing design and management recommendations.

Hydraulic Modeling Applied to Fish Passage

Hydraulic models are used to estimate hydraulic conditions (i.e. velocity, depth, turbulence) within lotic waterways, about barriers, and within fishways for fish passage and habitat suitability projects. Hydraulic modeling can be categorized into one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) techniques which

solve different forms of fundamental governing equations (i.e. continuity, conservation of momentum and energy) using numerical methods yielding estimations of fluid motion in one, two, or three directions. Computational Fluid Dynamics (CFD) is a type of hydraulic modeling which solves the Saint-Venant or Navier-Stokes equations to provide estimations of hydraulic parameters for flowing fluids in two or three dimensions (Coulthard and Van De Wiel 2012). Three-dimensional CFD models have been used in conjunction with agent-based decision making or energetics frameworks to predict fish passage success through fishways or culverts (Goodwin et al. 2006, Blank 2008, Plymesser 2014). Two-dimensional models have been utilized to predict fish passage or habitat suitability based on species specific biologic criteria associated with depth and velocity preferences or thresholds (Katopodis 2003, Grantham 2013). One-dimensional hydraulic analysis is the basis of FishXing (FishXing User Manual 2006), a software that has been extensively used to model whether culverts are barriers to fish passage (Hendrickson et al. 2008, Burford et al. 2009). In applications of hydraulic modeling to fisheries projects, fish abilities or preferences are compared to the results of hydraulic models to draw inference about how fish may react to the hydraulic environment they inhabit.

Three-dimensional CFD modeling can estimate hydrodynamic properties at a scale relevant to fish perception, so this technique has been applied to fish passage investigations. Three-dimensional models require detailed topographic/geometric data within the model domain (Blank 2008; Plymesser 2014). Through Eulerian-Lagrangian-Agent Method (ELAM) modeling, movements of individual fish in response to the

surrounding hydraulic environment are predicted based on a 3D CFD model coupled with a decision-making framework (Goodwin et al. 2006). ELAM models are named as such because an Eulerian framework is used to govern the physical and hydrodynamic aspects of the model, a Lagrangian framework is used to govern the sensory perception and movements of an individual specimen, and an agent framework is used to model decision making of the specimen (Goodwin et al. 2006). Using an approach like ELAM modeling, Khan (2006), Plymesser (2014) and Blank (2008) used 3D hydraulic models to describe the hydraulics within vertical-slot fishways, Alaska Steeppass fishways, and culverts respectively. They conducted energetics analyses based on fish swimming speeds, drag forces, and swim paths (Khan 2006; Blank 2008; Plymesser 2014). Blank (2008) observed fish passage paths through a culvert, created a 3D hydraulic model, and analyzed the energy required to ascend low energy, high energy, and observed fish paths. Plymesser (2014) used American Shad swimming speeds and durations to determine passage proportions of simulated agents through an Alaska Steeppass style fishway. Fish passage models utilizing 3D CFD models have only recently emerged as practical tools (Blank 2008); simpler one- and two-dimensional hydraulic modeling techniques have been used more extensively to date.

Two-dimensional hydraulic modeling techniques coupled with biologic data (i.e. habitat preferences, depth requirements, locomotive abilities) can be used to model habitat suitability (Katopodis 2003; Stewart et al. 2005; Lee et al. 2010; Chou and Chuang 2011) and assess fish passage (Reinfelds et al. 2010; Grantham 2013; Ryan 2015). Two-dimensional hydraulic models use depth-averaged simplifications of the

Navier-Stokes equations, called shallow water or Saint-Venant equations (Coulthart and Van De Wiel 2012). These models use finite element, finite difference, or finite volume numerical methods for solving the equations (Coulthart and Van De Wiel 2012; USACE 2016; Deal et al. 2017). Two-dimensional models spatially describe mean water column velocity and depth within streams (Wright et al. 2017) and model hydraulics about complex stream features that are important for fish habitat like braids and boulders (Katopodis 2003, Hardy and Addley 2003). Katopodis (2003) presents several examples of using results from a 2D hydraulic model and a habitat suitability index to estimate species specific suitable habitat areas over a range of instream discharges. The United States Geologic Survey (USGS) developed a software package, called Physical Habitat Simulation System (PHABSIM), that models the relationship between stream discharge and fish habitat or recreational river space with the goal of balancing the value of water removed from streams versus instream flows (USGS: Science... 2012). River2D is another software package that incorporates 2D CFD modeling with fish habitat suitability to quantify fish habitat given instream flow and channel geometry (River2D manual). Depth and velocity data extracted from 2D hydraulic models has been used to predict fish passage at natural stream features (Reinfelds et al. 2010; Grantham 2013) and constructed ones (Ryan 2015). Grantham (2013) used a 2D hydraulic model to estimate depths at riffle crests in three California streams used by salmon and/or steelhead for spawning habitat over a range of instream flows. He compared the results from 2D models to depth criteria along possible fish swimming paths to determine instream discharge thresholds corresponding to successful fish navigation of riffle crests (Grantham 2013). Two-

dimensional hydraulic models can provide quantitative estimates of hydraulic parameters relevant to fish habitat or passage assessment, but these models require detailed topographical data (Deal et al. 2017); therefore, 1D models may be preferred for projects where obtaining such data is not feasible.

The research presented within this thesis, and a well-known software package called FishXing, utilize biologic passage criteria and 1D hydraulic modeling techniques to estimate fish passage at barriers over a range of instream flows. FishXing is a software package developed by the United States Forest Service (USFS) that performs 1D hydraulic analysis through culverts and compares depths, velocities, and outlet drop height to known fish locomotive abilities to determine if culverts are barriers to fish passage (Furniss et al. 2000). FishXing includes a compilation of fish swimming abilities, leaping abilities, and estimates of fish body depth that are compared to results from the 1D hydrodynamic analysis (FishXing User Manual 2006). The output is a barrier classification of the culvert of interest at the specified flow for a target species (Furniss et al. 2000). Burford et al. (2009) and Mahlum et al. (2014) found barrier classifications using FishXing to be conservative compared to direct assessments of fish passage at existing road/stream crossings. Culverts, like Denil fishways, should be designed with aquatic organism passage in mind, during the design process the hydraulics within and about the culvert under various design scenarios should be modelled and compared to hydraulic conditions associated with successful fish passage (Kilgore et al. 2010). The research presented herein expands on the FishXing legacy by applying 1D

hydraulic modeling and biologic data to answer fish passage questions and inform the hydraulic design process of Denil fishways at irrigation diversions.

MODELING UPSTREAM ARCTIC GRAYLING PASSAGE THROUGH DENIL
FISHWAYS IN THE BIG HOLE VALLEY, MONTANA

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Introduction

The United States Fish and Wildlife Service (USFWS) estimates that there are over 6 million barriers to fish movement within rivers of the United States (USFWS 2012) including 74,000 dams (USFWS 2013). Physical barriers to fish movement include: irrigation diversions (Schrank and Rahel 2004), low and high head dams (Jackson and Moser 2012; Brink et al. 2018), road-stream crossings (Warren and Pardew 1998; Taylor 2000; Burford et al. 2009), natural waterfalls or cascades (Bryant et al. 1999, Reiser et al. 2006), and man-made barriers designed to inhibit fish movement (Fausch et al. 2009). Fish move about river systems in search of habitat for spawning, feeding, and refugia; barriers can prevent, or delay required migrations causing detrimental effects (Katopodis 1992; Gosset et al. 2006; Sheer and Steel 2006; Morita et al. 2009). Fish barriers that cause habitat fragmentation have been shown to negatively affect the persistence of fish populations and increase their risk for extirpation and extinction (Dunham et al. 1997; Morita et al. 2002; Sheer and Steel 2006; Letcher et al. 2007). Barrier removal and connectivity restoration can improve fish population productivity (Roni et al. 2002). Removal of barriers may be socio-economically impractical because of societal benefits realized by these structures (Brink et al. 2018) so fishways are often used to abate negative effects of habitat fragmentation (Katopodis 1992).

Fishways are used to provide fish with a path to navigate barriers and restore longitudinal habitat connectivity. The USFWS (2017) defines a fishway as: “the combination of elements necessary to ensure the safe, timely, and effective movement of

fish past a barrier.” Many technical fishways are designed to slow water velocities to within the swimming ability range of a target fish species with the goal of providing volitional passage routes (NMFS 2008). Types of technical, volitional fishways include: baffled chute fishways (e.g. Denil, Alaska Steeppass), vertical-slot fishways, pool-weir/orifice fishways, and culvert fishways (e.g. baffled, arch culverts) (Katopodis 1992; Noonan et al. 2012; Brink et al. 2018).

Denil fishways are a type of technical, volitional fishway consisting of a rectangular chute with baffles spaced throughout to reduce flow velocities and dissipate energy (Katopodis et al. 1997; Towler et al. 2015). An advantage of using Denil fishways for promoting fish passage at barriers is that they are often the cheapest option (Noonan et al. 2012). Passage and attraction efficiencies for Denil fishways can vary greatly and have not been shown to differ significantly from vertical-slot, nature like, or fish elevator fishways (Bunt et al. 2012, Noonan et al. 2012). Denil fishways have been implemented to provide passage for a variety of fish including: grayling, trout, salmon, whitefish, Alewife, bass, and suckers (Fulton and Bair 1953; Bryant et al. 1999; Bunt et al. 1999; Schmetterling et al. 2002; Bunt et al. 2012). The hydraulics within Denil fishways and the physical parameters that affect them have been studied extensively in laboratory settings (Rajaratnam and Katopodis 1984; Katopodis et al. 1997; Odeh 2003; Towler et al. 2015). The USFWS (2017) recommends maintaining depths of at least 0.61 meters throughout the fishway, but in arid watersheds and small streams this may not be feasible. While some work has been done to investigate how depth throughout Denil fishways affects fish passage (Castro-Santos et al. 1996; Haro et al. 1999), more research

is required to set species-specific depth thresholds that promote favorable hydraulic conditions within the fishway.

Hydraulic modeling has been used by the fish passage community to determine passage flow thresholds (Reiser et al. 2006), identify barriers (Blank 2008; Reinfelds et al. 2010; Ryan 2015), quantify habitat suitability (Stewart et al. 2005; Wright et al. 2017), and determine instream ecological flow requirements (Hardy and Addley 2003; Katopodis et al. 2003). Hydraulic modeling can be utilized in conjunction with biologic information regarding how fish react to specific hydraulic environments to infer fish passage effectiveness at potential barriers or through fishways. For example, FishXing is a fish passage model used in the design of culverts or evaluation of fish passage through existing culverts at road-stream crossings (Furniss et al. 2000). Whether a culvert is a barrier to fish passage is estimated based on results of a one-dimensional (1D) hydrodynamic analysis and known swimming/leaping abilities of fish species (Furniss et al. 2000). FishXing has been extensively used by government agencies and others to evaluate whether existing culverts are barriers to fish passage at various flows (Taylor 2000; Clarkin et al. 2005; Hendrickson et al. 2008). The accuracy of FishXing at identifying fish passage barriers has been evaluated and compared to results from field studies; model predictions tend to be conservative compared to observed passage as field studies observed passage through conditions identified as impassable by the model (Burford et al. 2009; Mahlum 2014). Grantham (2013) used two-dimensional hydrodynamic modeling to infer passage success of spawning salmon and steelhead in several California streams. Depth criteria defining passage success thresholds for target

species was compared to the modelled depths at shallow riffle crests, which were believed to limit movement to spawning habitat, to infer whether fish could successfully navigate the riffle crests (Grantham 2013). Diverse applications of hydraulic modeling to fish passage projects have proven its effectiveness as a fishway design and barrier assessment tool.

Arctic Grayling (*Thymallus arcticus*), hereafter referred to as grayling, inhabit waterways in northeastern Eurasia, Alaska, and Canadian provinces between Hudson Bay and the Gulf of Alaska (Northcote 1995; Cahill 2015). One fluvial, disjunct population historically inhabited the Upper Missouri River basin upstream of Great Falls, Montana (Liknes 1981; Northcote 1995; MFWP and USFWS 2006). The present distribution of the Upper Missouri River basin population has decreased by more than 95% compared to historic distribution; the last known fluvial population inhabits the Big Hole River and its tributaries (MFWP and USFWS 2006; Cayer and McCullough 2013). This population is genetically distinct from other populations further north in Canada and Alaska (Peterson and Ardren 2009) and are considered a “Species of Special Concern” by the Montana Department of Fish, Wildlife and Parks (MFWP) (Cayer and McCullough 2013).

The Big Hole Valley is nicknamed the “Land of 10,000 Haystacks,” as it is mostly comprised of private land used for production of hay and beef cattle (BHCW 2012). Irrigation has a significant impact on the surface water hydrology, especially during early summer (MFWP and USFWS 2006; Flynn et al. 2009); water is typically diverted into unlined canals and applied to the fields using flood-irrigation practices. The Big Hole River is considered a world-class fishery, many tourists visit the area every year

to fish, contributing a significant amount of money into the local economy (Duffield et al. 1992; Davis 2015). Fish species that inhabit the Big Hole River include: Brook Trout (*Salvelinus fontinalis*), Brown Trout (*Salmo trutta*), Rainbow Trout (*Oncorhynchus mykiss*), Westslope Cutthroat Trout (*Oncorhynchus clarkia lewisi*), Mountain Whitefish (*Prosopium williamsoni*), Mountain Suckers (*Catostomus platyrhynchus*), White Suckers (*Catostomus commersonii*), Longnose Suckers (*Catostomus Catostomus*), Longnose Dace (*Rhinichthys catatactae*), Mottled Sculpin (*Cottus bairdii*), Burbot (*Lota lota*), and grayling. Attempts at conserving the population of grayling in the Big Hole River has required collaboration between government agencies and private landowners as litigation concerning their listing under the Endangered Species Act (ESA) have been ongoing for decades (Cayer and McCullough 2013). In 2006, a Candidate Conservation Agreement with Assurances (CCAA) for fluvial grayling in the Big Hole River basin was reached between the USFWS and other organizations to balance conservation of the population of fluvial grayling within the Big Hole drainage with agricultural practices in the area (MFWP and USFWS 2006).

Immediate, human-influenced threats to grayling in the Big Hole are identified in the CCAA (2006) as: reduced streamflow, degraded and non-functioning riparian habitats, barriers to movement, and entrainment in irrigation ditches. Barriers to movement are detrimental to grayling because they move between winter refuge habitat and summer foraging habitat (Heim et al. 2015), while sexually mature fish additionally migrate to spawning habitat in the late spring/early summer (Shepard and Oswald 1989; Northcote 1995). In the Big Hole, grayling migrate into tributaries or cooler reaches

when the main stem exceeds preferred temperatures (Vatland 2015; 2019 email from Jim Magee, USFWS Biologist). The CCAA proposed a conservation measure to remove or modify all movement barriers to grayling in the Big Hole project area (MFWP and USFWS 2006). In order to make irrigation diversions more passable for moving fish, 63 Denil fishways were installed at diversions (2017 email from Jim Magee, USFWS Biologist). Modeling and evaluating a sample of these fishways is the focus of the research presented herein.

The research presented herein was inspired by the need for a field study as part of a progressive line of research aimed at investigating grayling passage using Denil fishways. In 2015, researchers conducted a study to determine the swimming ability of grayling in an open channel flume (Dockery et al. forthcoming 2019). This study produced the highest swim speed documented for grayling (3.32 m/s) and had sustained swimming speed results that agreed with literature values (Dockery et al. forthcoming 2019). During summer 2016, a study was conducted to evaluate how grayling passage success using Denil fishways was affected by hydraulic conditions like depths at the upstream and downstream ends of the fishway, velocity within the fishway, and discharge through it (Blank et al. forthcoming). The 2016 study found passage generally increased with discharge and the combination of depths at each end of the fishway was an accurate predictor of upstream passage success (Blank et al. forthcoming). Research into grayling swimming ability and passage using fishways is important to inform managers about the effectiveness of past and future management actions.

The objective of this study was to develop a model which predicts passage windows at Denil fishways within the Big Hole Valley and use model results to assess the effectiveness of the fishways at providing upstream passage for grayling. Passage windows are defined as periods of time when fishways allow, limit, or prevent passage. A fishway is effective if it provides passage opportunity over a wide range of instream flows and during times associated with target species movement.

Methods

During this investigation into upstream grayling passage through Denil fishways, 1D hydraulic modeling was used to predict depth at the upstream and downstream ends of Denil fishways based on physical, hydraulic, and hydrologic data. Biologic information describing combinations of upstream and downstream depths associated with favorable hydraulic conditions for grayling passage was superimposed on hydraulic modeling results to predict upstream passage efficiency over time. Based on analyzing modelled passage windows, the effectiveness of the fishways can be inferred.

Study Area and Sites

Eleven Denil fishways mounted onto pin-and-plank style irrigation diversion structures throughout the Big Hole River and its tributaries were investigated (Figure 3.1). The selection of the subset of fishways included in the study was guided by USFWS and MFWP biologists, considering presence of fish, proximity to Big Hole main stem, landowner permission, and ease of access.

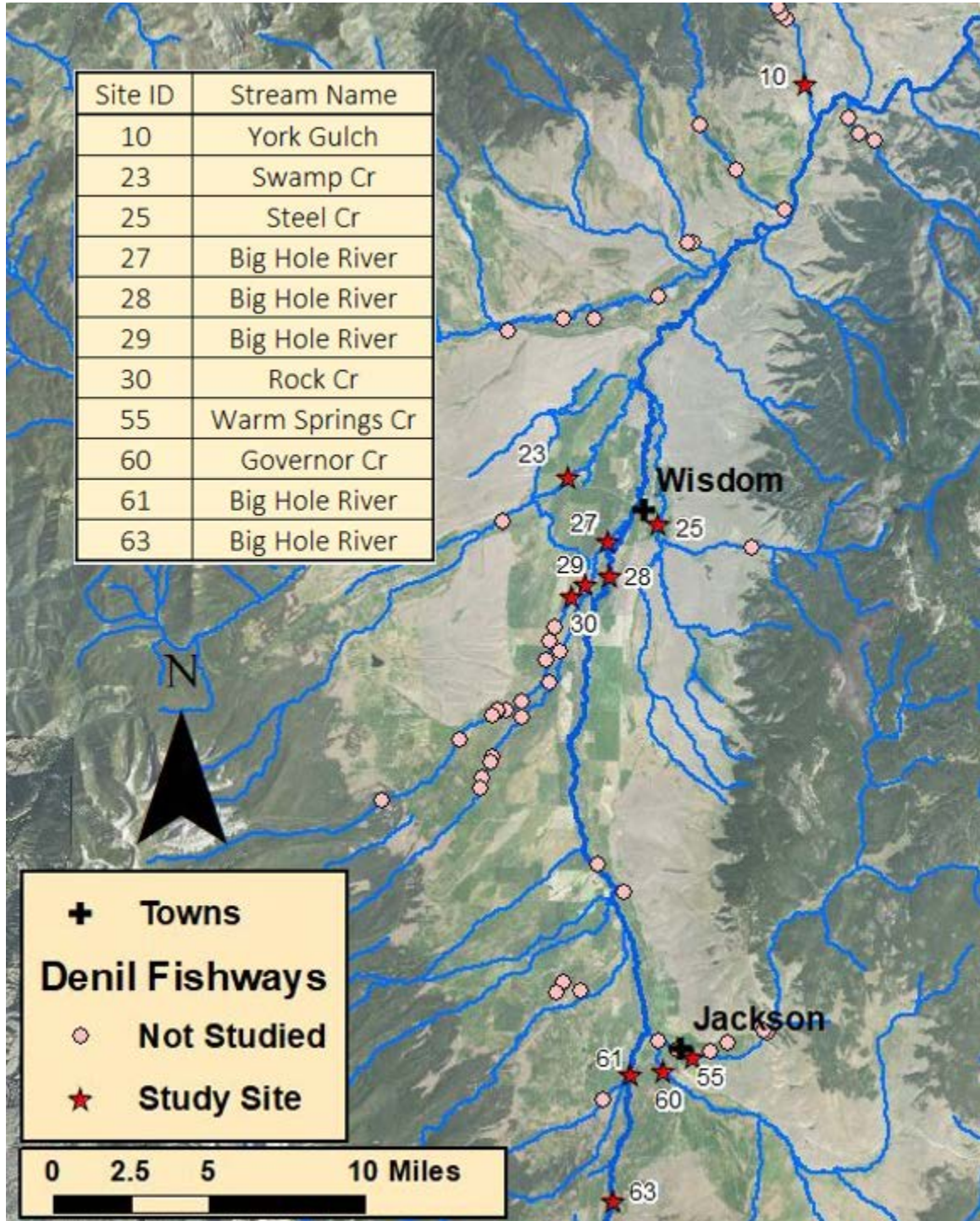


Figure 3.1. Map of the Big Hole Valley showing Denil fishways in the study area and indicating study sites. Study sites are labelled with identifying numbers, the streams each site are located on are summarized in the table towards the top-left of the map.

The study sites were located on the Big Hole River and its tributaries in the Big Hole Valley, Southwest Montana. The headwaters of the Big Hole River begin in the Beaverhead Mountains south of Jackson, Montana. The Big Hole flows north through the Big Hole Valley, then east/southeast before trending south through the towns of Melrose and Glen reaching its confluence with the Beaverhead River near Twin Bridges, Montana (Vatland 2015). The climate in the Big Hole watershed is classified as inter-montane continental with marked seasonality (Flynn et al. 2009). Precipitation falls mostly as snow and averages about 30 centimeters in the lower valley area at elevation 1,980 meters (Vatland 2015). Surface water hydrology is snowmelt dominated with peak flows usually occurring in June, the late summer months often bring irrigation water shortages and high in-stream temperatures (Flynn et al. 2009).

Denil fishways in the Big Hole Valley are mounted onto pin-and-plank style irrigation diversions to facilitate upstream fish passage when the diversions are operated as weirs and pose a barrier to moving fish (Figure 3.2). These diversion structures can be operated open (i.e. no planks) so that they do not back up additional water and debris, or planks can be inserted to create a low-head weir controlling stage at the point of diversion (MDNRC Conservation Districts Bureau 2001). The fishways are typically mounted on the opposite side of the river from the lateral headgate structure, which connects the stream to the irrigation ditch and controls flow into the ditch by sluice gate or other mechanisms.



Figure 3.2. Photo of a pin-and-plank irrigation diversion retrofitted with a Denil Fishway, on Swamp Creek in the Big Hole Valley. Note that the diversion is being operated with planks inserted and the fishway is the only route up for moving fish. On the right, the top of a sluice gate which controls the discharge that flows into the irrigation ditch can be seen.

Data Collection

Hydraulic, hydrologic, and physical data was collected May 31, 2017 through November 11, 2017 and April 24, 2018 through October 9, 2018.

The discharge (Q) downstream of each diversion structure was estimated at hour intervals by monitoring stage continuously and applying discharge-rating curves. Stilling wells were constructed, each was about 1.5 meters long and made of 5-centimeter diameter polyvinyl chloride (PVC) pipes with holes drilled along them. Inside the stilling wells HOBO® U20L water depth loggers (model U20L-04, Onset, Bourne, MA, USA) were suspended using small steel chains; these loggers measure temperature and pressure at specified frequencies. The stilling wells were in a pool just upstream of a hydraulic-

controlling riffle crest, out of the main current, and downstream of the diversions. Staff gauges were positioned next to the stilling well and at the upstream and downstream ends of the fishway. Staff gauge 1 (SG1) was used to determine the water surface elevation (WSE) at the downstream boundary of the hydraulic model and for reading water surface elevations associated with the stilling well location. Staff gauge 2 (SG2) was used to measure WSE at the downstream end of the fishway and staff gauge 3 (SG3) was used to measure WSE at the upstream end of the fishway. Staff gauges were read during each site visit. The elevations of the stilling well along with staff gauges were surveyed by level looping using an automatic level (model B2-A, Sakkisha, Tokyo, Japan) several times throughout the two field seasons. The repeated elevation surveys were used to confirm that each well and staff gauge position had not changed. If subsequent measurements indicated a well's position had shifted, the survey data was used to adjust depth/stage measurements. Figure 3.3 shows an example site layout and shows where the staff gauges were installed relative to the diversion, fishway, and hydraulic control.

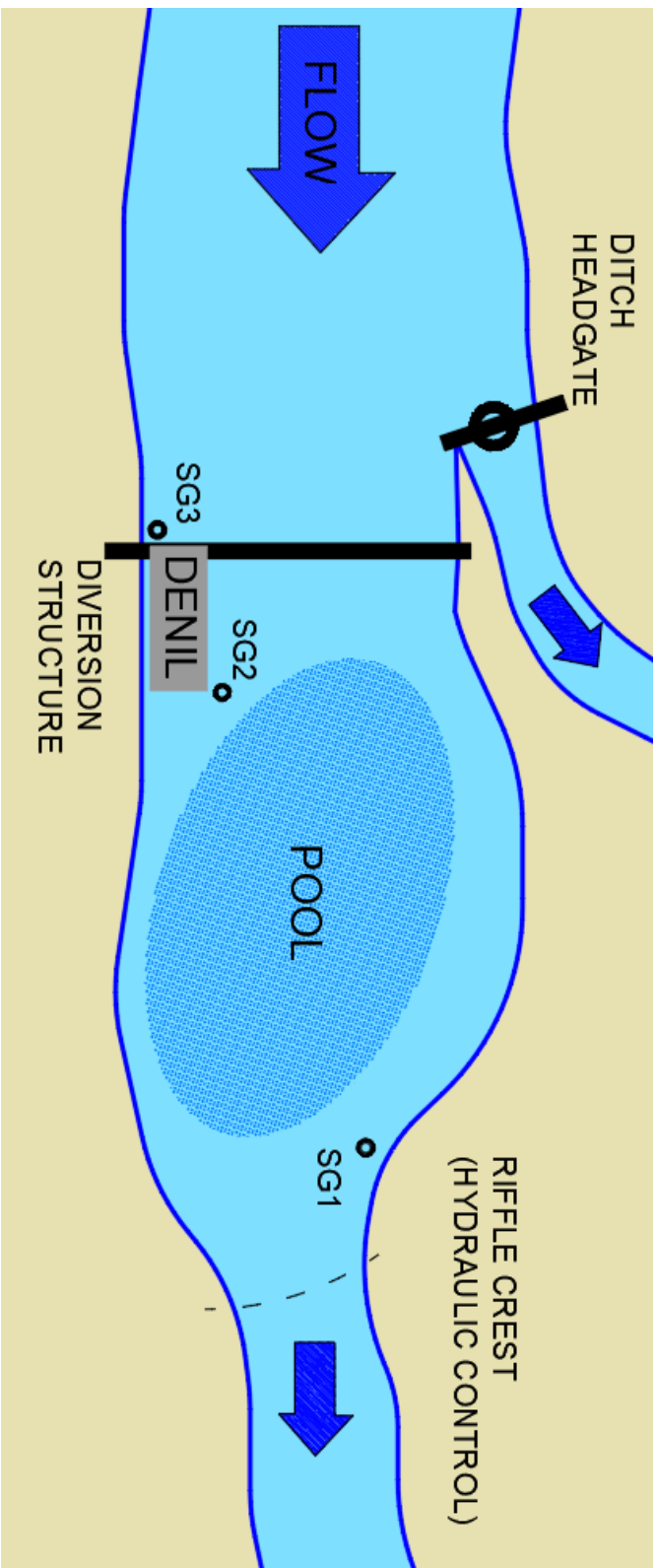


Figure 3.3. A plan-view schematic showing a typical site layout of the Denil fishway, diversion structure, and ditch headgate in relation to the stream and irrigation ditch. Staff gauge locations are shown as SG1, SG2, and SG3.

Rating curves were created using between six and eight stage-discharge data pairs for the stream cross sections corresponding with the SG1 location. Discharge was determined using a hand-held flow meter (model FH950, Hach, Loveland, CO, USA) per the USGS Midsection Method (Turnipseed and Sauer 2010). The rating curves were used as predictive models to infer discharge based on the WSE at SG1/stilling well locations. All rating curves utilized power function relationships, regressed using non-linear regression, with the form

$$Q = a (WSE - c)^b$$

where a , b , and c are regression coefficients and WSE is the water surface elevation at the stilling well. Compound rating curves (different stage-discharge relationships for different ranges of stage), were employed when appropriate. Components of the compound rating curves were combinations of power functions and linear functions. The rating curves were applied to the continuous stage data to create seasonal hydrographs and used to describe downstream boundary conditions for hydraulic models.

Physical data concerning the diversion structure and Denil fishways were collected at each site. The diversion structures were surveyed using a total station (model TS06-Plus, Leica Geosystems, Heerbrug, Canton St. Gallen, Switzerland), and their dimensions measured. The length, number of baffles, cross section dimensions, and slope were recorded for each fishway. The operating condition of the diversion was also recorded by measuring the height and number of planks inserted into each pin gap during each visit. Operating condition is defined as the configuration of planks inserted into the diversion, this dictates the dimensions of the assembled weir and how the diversion

influences hydraulics. The operating condition was designated as “no planks” if there were no planks inserted, plank configurations at each site were named designating the year it was observed and a letter (“a” or “b”) specifying different configurations observed during the same year. The exact dates and times the weir configurations were changed by the irrigators were not known but inferred from jumps or drops in the hydrograph corresponding with the removal or addition of planks and changes in the operation of the ditch headgate structure. If change in the operating conditions could not be inferred from the hydrograph the change date and time were assumed to be halfway in between site visits when different operating conditions were observed.

Information required to develop 1D Hydraulic Engineering Center River Analysis System (HEC-RAS) hydraulic models was collected at each of the study sites. One-dimensional HEC-RAS models require input data concerning: cross section geometry, reach lengths, roughness data, boundary conditions, stage-discharge relationships at the cross sections, and qualitative observations of ineffective flow areas, obstructions and levees (USACE 2016). The bathymetry and topography of each site was surveyed using a total station. Surveyed cross sections were oriented perpendicular to the dominant stream lines observed throughout the water year. Reach lengths between the cross sections were measured along the thalweg and both banks. Manning’s n was determined for the channel and left/right overbank areas for the reaches between cross sections based on descriptions in Chow’s Open-Channel Hydraulics (1959). Ineffective flow areas and levees were noted during site visits with attention paid to how these hydraulic features changed with discharge.

Hydraulic Modeling

One-dimensional, steady flow hydraulic models were constructed using HEC-RAS (USACE 2016). In HEC-RAS, water surface profiles are computed from one cross section to the next utilizing the energy equation and the standard-step method for gradually varied flow (USACE 2016). The sites were modelled over the range of observed discharges assuming subcritical flow and a user specified rating curve for the downstream boundary condition (DSBC). While three-dimensional flow fields are present about these irrigation diversions, 1D modeling is appropriate because velocity heads (and thus energy loss) are low and water surface elevations are the only desired output. HEC-RAS, one-dimensional modeling has been applied to more complex water diversion scenarios with success (Sanford et al. 1998). The purpose of the hydraulic models was to predict WSEs at the upstream and downstream ends of a Denil fishway depending on discharge through the diversion structure and the operating condition of the structure.

Locations of cross sections within the model domain were selected strategically to facilitate extraction of important WSEs from the model output at key locations. The downstream-most cross section was placed at the hydraulic control downstream of the stilling well. The rating curve associated with the DSBC was the same used to infer discharge based on stage at the stilling well. Cross sections were placed within a few feet of the upstream and downstream ends of the fishway so water surface elevations at these key locations could be extracted from the model. The cross section just upstream of the diversion was placed between the diversion structure and the ditch headgate; this was

done because a flow change occurred between this cross section and the next upstream resulting from discharge extracted for irrigation. In addition to the three key cross sections mentioned above, one or two more cross sections were placed between the DSBC and the cross section just downstream of the fishway, and one to three more cross sections were placed upstream of the cross section just upstream the fishway.

The diversion structure was represented in the model as an inline structure. The pin-and-plank structure was modelled as a “weir/embankment.” The Denil fishway was modelled as a “user-defined gate.” The rating curve specified for the gate was based on an average of the rating curves presented in several papers reporting results of hydraulic investigations into Denil fishways (Katopodis 1992; Rajaratnam and Katopodis 1997; Katopodis et al. 1997; FAO/DVWK 2002; Odeh 2003). These rating curves are based on the slope and dimensions of the fishways. For some of the models an extra “user-defined gate”, called a “leaky gate”, was added to represent hyporheic flow and water flowing through the gaps in the diversion structure planks if such flow was observed at the site. In some situations, boards had been placed to block the upstream end of the fishway and divert more water for irrigation purposes. For calibration purposes, the Denil (when blocked) in the model took the shape of a representative orifice or was completely blocked off to best represent what was observed during data collection. Once calibrated with these irregularities, the fishways were modelled as if they were free of debris and upstream blockages for the passage window analysis.

The hydraulic models were calibrated using stage and discharge data collected during site visits. Stage at each end of the fishway and SG1 location (see Figure 3.3) was

determined from staff gauge readings. Discharge was either measured manually or estimated using the water surface elevation at the SG1 location and a discharge-rating curve. For each observed operating condition, a HEC-RAS model “geometry” was constructed. Geometry files in HEC-RAS represent the physical shape, roughness, and structures present within a stream reach. Each model geometry was calibrated using stage-discharge data collected while the associated operating condition was observed. Therefore, geometries were calibrated using varying amounts of observed versus modelled water surface elevation data points. Calibration was performed manually by iteratively running the model and adjusting the following parameters: weir coefficient of the inline structure, Manning’s n (within realistic bounds), “leaky gate” rating curve or size, or adding ineffective flow areas or levees. Mean Absolute Error (MAE) was used as a metric to determine agreement between modelled and observed WSEs for each model geometry. MAE was calculated as:

$$MAE = \frac{\sum_{i=1}^n |e_i|}{n}$$

Where n is the number of modelled and observed water surface elevations compared and e_i is the error between a given observed and modelled water surface elevation. The model was run, and calibration parameters were adjusted until MAE was minimized in a trial-and-error manner.

Water surface elevations at the upstream and downstream ends of the fishway, based on discharge through the site and operating condition of the diversion structure, were predicted using the calibrated HEC-RAS models. Select discharges spanning the range of gauged discharges were modelled through geometries at each site. In order to

infer WSEs over a continuous range of discharges the modelled stage-discharge results were linearly interpolated between selected points. HEC-RAS results were used to calculate WSEs over time at the upstream and downstream ends of the fishways for every recorded discharge data point (collected hourly) during the stream gauging periods.

Passage Index Application

A passage index, a tool used to describe passage success based on a combination of upstream and downstream depths, was developed using laboratory grayling passage data (Blank et al. forthcoming). Upstream and downstream depths were related to fishway passage efficiencies because they were shown to correlate to passage success (Blank et al. forthcoming), are simple to measure, and are often used when designing and constructing fish passage structures. Upstream depth is defined as the depth of the water over the “V-notch” on the upstream-most baffle of the Denil. Downstream depths were measured from the downstream invert of the fishway. A laboratory study was conducted summer 2016 at the Bozeman Fish Technology Center that investigated the effect of upstream and downstream depth, among other hydraulic variables, on the passage efficiency of laboratory reared grayling up 1.83-meter and 3.66-meter-long Denil fishways (Blank et al. forthcoming). Fifteen trials consisting of combinations of depths were tested on both 3.66-meter and 1.83-meter fishways, the proportion of passed fish for each trial was determined using PIT tag antennae (Blank et al. forthcoming).

Laboratory observations were compiled into an index by associating depth combinations with passage efficiencies and defining four passage condition categories. Table 1 is a matrix that shows binned upstream and downstream depths (above and to the

left of the matrix respectively), the associated passage efficiency, and assigned passage condition. To create the index, divisions were made halfway between laboratory tested depths to create the binned-depth intervals. The 2016 laboratory assessment tested upstream depths of 0.038, 0.064, 0.102, 0.152, 0.254, and 0.356-meters so divisions were made at 0.025, 0.051, 0.083, 0.127, 0.203, 0.305, and 0.407-meters. Likewise, laboratory tested downstream depths were 0.152, 0.305, and 0.457-meters so divisions were made at 0.076, 0.229, 0.381, and 0.534-meters. The passage efficiencies associated with binned depth combinations result from averaging passage efficiencies for 1.83-meter and 3.66-meter length fishways. The passage efficiency is read from the passage index by reading the value of the cell which is located at the intersection of the row and column associated with the depth combination. For example, an upstream depth of 0.130 meters paired with a downstream depth of 0.305 meters would result in a predicted passage efficiency of 0.30. Passage conditions are defined as follows: passage efficiencies between 0.75-1 were said to “allow” passage, efficiencies between 0.25-0.75 were said to “limit” passage, and efficiencies less than 0.25 were said to “prevent” passage. For any depth combination that does not fall within the ranges of binned upstream and downstream depths tested in the laboratory study, an “out of range” passage condition was assigned. Passage efficiencies and conditions were predicted over time by superimposing the passage index upon depth combinations extracted from the hydraulic models.

Table 1. The passage index used to determine passage efficiency and condition given the depth combination. The top row consists of ranges of upstream depths and the left column consists of downstream depth ranges. The numbers in the colored boxes correspond to estimated passage efficiencies and the colors are associated with passage condition predictions (green = "allows", yellow = "limits", red = "prevents").

DS Depth	US Depth									
	< 0.025m	0.025-0.051m	0.051-0.083m	0.083-0.127m	0.127-0.203m	0.203-0.305m	0.305-0.407m	>0.407m		
<0.076m	?	?	?	?	?	?	?	?	?	?
0.076m-0.229m	?	0.15	0.60	1.00	0.85	0.90	0.00	?	?	?
0.229m-0.381m	?	?	0.00	0.40	0.30	0.75	1.00	?	?	?
0.381m-0.534m	?	?	0.00	0.00	0.50	0.75	0.90	?	?	?
>0.534m	?	?	?	?	?	?	?	?	?	?

Note: "?" denotes depth combination ranges out of range of the passage index.

Results

Hydraulic Models

The hydraulic model was calibrated using an iterative process until the MAE between WSEs at the staff gauge locations was minimized for each geometry. The MAE across all staff gauge locations, operating conditions, and sites was 0.013 meters. The site where the model had the highest average MAE was site 28 (MAE = 0.020 meters) and the site with the lowest average MAE was site 10 (MAE = 0.007 meters). See Table 2 for a summary of MAE by site and operating condition.

Table 2. HEC-RAS calibration results by site and operating condition. The numbers on the left side of each cell are the MAE associated with the specified site and operating condition in meters, and the number in parenthesis is the number of observed stage-discharge pairs used for calibration. The right column “Total” presents the MAE across all operating conditions for each site. “NA” indicates that the associated operating condition was never observed at a site.

MAE by Operating Condition						
Site	No Planks	2017a Planks	2017b Planks	2018a Planks	2018b Planks	2017/2018 Planks
10	0.005 (24)	NA	NA	NA	NA	0.013 (6)
23	0.017 (21)	0.009 (18)	NA	0.023 (6)	NA	NA
25	0.013 (42)	NA	NA	NA	NA	NA
27	0.008 (24)	0.011 (6)	0.004 (3)	0.042 (3)	NA	NA
28	0.014 (18)	0.012 (9)	NA	0.048 (6)	NA	NA
29	NA	0.008 (15)	0.009 (6)	0.030 (9)	NA	NA
30	0.012 (12)	0.008 (21)	NA	0.015 (6)	NA	NA
55	NA	NA	NA	NA	NA	0.008 (33)
60	0.020 (33)	0.007 (6)	NA	NA	NA	NA
61	0.017 (39)	NA	NA	NA	NA	NA
63	0.018 (15)	0.014 (12)	NA	0.010 (6)	0.021 (9)	NA
						0.017 (42)

Operating Condition

Across all sites it was estimated that the diversions were actively diverting water (i.e. had planks installed) 48 percent of the time. Some sites never had planks inserted (25 and 61) while others had planks in for more than half of the observations (23, 28, 29, 30, 55, and 63). Site 29 had planks inserted for a total of 192 days during the duration of the study (70% of monitored days) and Site 55 had planks inserted during the entire period of observation.

Passage Windows

Including all 11 sites studied there were 69,923 hourly discharge observations analyzed using the hydraulic model to estimate passage efficiency. Of these observations, 23,703 (33.9%) corresponded to a depth combination within range of the passage index. Of the predicted depth combinations within range of the passage index, 4,494 (19.0% of within-range predicted depth combinations) were determined to “allow” passage, 11,994 (50.6% of within-range predicted depth combinations) were determined to “limit” passage, and 7,215 (30.4% of within-range predicted depth combinations) were determined to “prevent” passage. Table 3 summarizes the passage window predictions. The left four columns of percentages include the “Out of Range” predictions. The right three columns of percentages exclude the “Out of Range” predictions. For example, the percentage of time the “Allow” passage condition was predicted across all sites, excluding “Out of Range” predictions, was calculated by dividing the number of “allow” passage condition predictions by the number of modelled depth combinations within range of the passage index.

Table 3. The percentage of monitored time at each site different passage conditions were predicted by the fish passage model, including and excluding “Out of Range” predictions. The bottom row shows the percentage of time passage conditions were predicted across all sites. For sites where 100% of the passage condition predictions were “Out of Range” of the passage index, “NA” is written in the cells corresponding to the analysis that excluded the “Out of Range” predictions.

	Passage Condition (% of Time Observed) By Site						
	Including "Out of Range"				Not Including "Out of Range"		
Site #	Out of Range	Allow	Limit	Prevent	Allow	Limit	Prevent
10	44.6%	0.0%	16.0%	39.4%	0.0%	28.9%	71.1%
23	100.0%	0.0%	0.0%	0.0%	NA	NA	NA
25	26.5%	26.7%	37.7%	9.1%	36.4%	51.3%	12.3%
27	100.0%	0.0%	0.0%	0.0%	NA	NA	NA
28	25.6%	6.1%	51.6%	16.8%	8.2%	69.3%	22.5%
29	100.0%	0.0%	0.0%	0.0%	NA	NA	NA
30	99.2%	0.0%	0.0%	0.8%	0.0%	0.0%	100.0%
55	26.0%	9.1%	64.9%	0.0%	12.3%	87.7%	0.0%
60	91.6%	0.0%	0.0%	8.4%	0.0%	0.0%	100.0%
61	71.8%	2.0%	10.9%	15.4%	7.0%	38.5%	54.5%
63	46.5%	26.9%	3.2%	23.4%	50.3%	5.9%	43.8%
All Sites	66.1%	6.4%	17.2%	10.3%	19.0%	50.6%	30.4%

Results can be presented and analyzed on an individual site basis. For example, site 63 exhibited the highest proportion of observations with the “allows” passage condition: 26.9% on 1,668 hourly occurrences. However, site 25 had more hourly occurrences of this passage condition with 1,740 (26.7% of observations). Site 55 had the most combined hourly occurrences of “allows” and “limits” passage condition with 4,941 (74.0% of observations). Sites 25 and 28 also showed many occurrences of “allows” and “limits” passage conditions with 4,194 (64.4% of observations) and 3,859 (57.7% of observations) occurrences respectively. Site 10 had the most occurrences of “prevents” passage condition with 2,875 (39.4% of observations). Graphical

representations of passage efficiency and discharge through the site over time can be helpful for interpreting site-specific results (Figure 3.4). Graphical representations, like Figure 3.4, for each site and year monitored can be found in the Appendix.

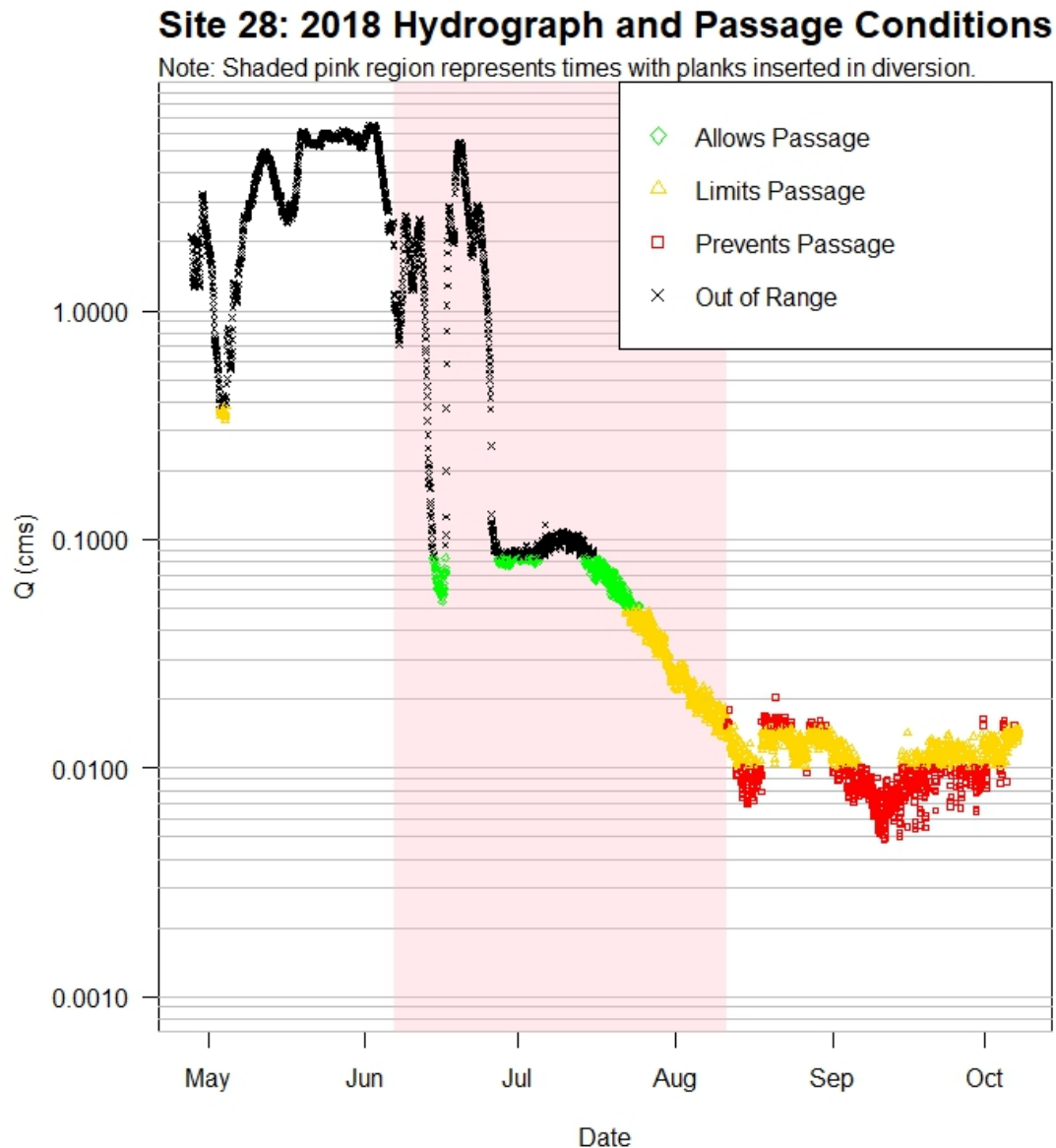


Figure 3.4. Hydrograph of site 28, during 2018 monitoring period, color coded to depict modelled passage condition. The y-axis is discharge through the site in log-scale and the x-axis represents date and time.

Of the 69,923 hourly predictions associated with a recorded discharge value analyzed using the HEC-RAS model, 46,220 (66.1%) had depth combinations that fell into the “out of range” category of the passage index. Sites 23, 27, and 29 never had a modelled depth combination within range of the index. Sites 25, 28, and 55 all had at least 4,784 points fall within the bounds of the passage index, each had at least 73.5% of points within the index. Sites 10, 25, 28, 55, and 63 accounted for 23,080 out of 23,703 (97.3%) of the discharge data points associated with modelled depth combinations within range of the index. In contrast, the remaining sites (23, 27, 29, 30, and 60) only combined for 623 points that fell within bounds of the passage index.

Discussion

Known Passage Conditions

Analyzing modelled passage efficiency predictions within the range of the passage index is useful for comparing the effectiveness of the investigated fishways but must be done cautiously (see Table 3). Overall, more than half of the predicted depth combinations that were within the range of the passage index predicted the “limits” passage condition; so, there is likely a large range in passage efficiencies across all sites through time. Site 55 never exhibited the “prevents” predicted passage condition, however, 87.7% of within range passage conditions were estimated as “limits” passage. The discharge through this site never dropped below 0.026 cubic meters per second (cms) and the fishway had a 10.7% slope so the upstream depth never dropped below 0.190

meters, this puts the upstream depth into a favorable range according to the passage index. On the other hand, site 10 was never predicted to exhibit the “allows” passage condition and 71.1% of within range depth combinations were predicted to “prevent” passage. Based on within range model results, the Denil at site 55 seems more effective at passing grayling than site 10, whether due to physical or hydrological reasons.

Analyzing the data within range of the passage index can help to compare performance between fishways if they both have sufficient data within range. But one must be cautious about inferring effectiveness based on known passage conditions if a significant amount of passage predictions at a site were “out of range.”

Unknown Passage Conditions

Out of 69,923 hourly discharge data points analyzed to predict passage efficiency across all sites, 46,220 (66.1%) modelled depth combinations were out of range of the passage index. When the upstream depth was outside the range of 0.025-0.407 meters or the downstream depth was outside the range 0.076-0.534 meters the depth combination was “out of range” of the passage index. This typically occurs at very high and very low discharges as high discharges cause larger depths at both ends of the fishways and low discharges cause shallower depths. More information about how higher and lower upstream and downstream depth combinations affect passage would be needed to predict passage efficiency for all discharge data points modelled. The passage index provided a baseline level of knowledge about depth combinations that promote favorable hydraulic conditions for grayling passage but observed depth combinations at the studied fishways fell outside of its range often.

A few trends in the passage index (Table 1) can be speculated: high upstream and downstream depths lead to high passage efficiency, low upstream and downstream depths lead to low passage efficiency, and high downstream depths paired with low upstream depths lead to low passage efficiency. High upstream and downstream depths usually correspond to higher instream discharge; if the passage model returns “out of range” at high discharge, then the passage efficiency is likely high. Conversely, upstream depths lower than the index range, regardless of downstream depth, probably correlate to poor passage efficiency. Low upstream depths usually occur at low discharge scenarios and/or when no planks are inserted in the diversion structure. If planks are inserted (i.e. blocking fish passage through the diversion making the fishway the only way up), low discharge is gauged, and the passage model returns “out of range,” then poor passage efficiency could be assumed. Some of the study sites (sites 23, 27, and 29) never had a modelled passage prediction that fell within the range of the index. This is because the downstream ends of the fishways were set low enough such that, at low flow conditions, they were completely submerged. At submerged ladders the authors suspect that high upstream depths lead to higher passage efficiency and low upstream depths lead to lower passage efficiency based on the qualitative trends observed from the passage index. Speculating trends based on the passage index helps to interpret the fish passage model “out of range” points and provides insight into fishway passage effectiveness.

Biologic Consideration

Fish move between feeding, spawning, and refuge habitat; these movements are time-sensitive and differ between species and location; they relate to river discharge,

photoperiod, water temperature, and/or other environmental factors (Katopodis 2005). Grayling are spring spawning fish, usually moving into spawning areas following ice-off when the water is cool (Bishop 1971; Northcote 1995). Multiple studies conducted in the 1980's found that grayling spawning in the Big Hole river occurred from late April to mid-May in the main stem Big Hole, side channels, and up to 3.2 kilometers up several tributaries (Liknes 1981; Shepard and Oswald 1989). Big Hole grayling spawned when water temperatures reached 10 degrees Celsius and during the receding limb of the initial (low elevation) melt off spike in the hydrograph (Shepard and Oswald 1989). Grayling in the Big Hole drainage move to seek thermal refuge from high instream temperatures by migrating to the cooler tributaries in the later part of July through mid-September (Vatland 2015; 2019 email from Jim Magee, USFWS Biologist). Instream temperatures in the Big Hole River during the low-flow summer months have contributed to fish kills in the past (Lohr et al. 1996). Maximum daily water temperatures above 25 degrees Celsius, the upper incipient lethal temperature (UILT) for grayling, have been observed in several studies (Lohr et al. 1996; Sladek 2013). It is important for the fishways in the Big Hole to provide upstream passage for spawning and thermal refuge purposes, at the associated discharges and times of year, so that grayling life history stages are not delayed or prevented. The fish passage models presented herein provide managers with clues about the level of habitat fragmentation at these key times of year.

For the Big Hole grayling to spawn successfully, upstream passage must be insured at irrigation diversions before and during April 29-May 11 annually. This is the time period when Shepard and Oswald (1989) found the numbers of ripe females peaked,

so fish would be migrating to spawning habitat before and during this time period. In general, irrigators in the Big Hole Valley do not operate their pin-and-plank diversions with planks inserted during this time. Of the 11 sites modelled and investigated during this study, only one had planks in place at the diversion structure during peak time for ripe females. This was site 55, which had planks inserted in the diversion throughout the duration of the study. During the typical grayling spawning period flows are much higher than baseflow conditions. When no planks are inserted and high discharges are flowing through the site, the diversions are typically hydraulically submerged and likely not barriers to moving fish. Shepard and Oswald (1989) observed grayling spawning mostly in the lower 3.2 kilometers of tributaries, so irrigation diversions further up the tributaries are less likely to inhibit migration to spawning habitat. It is important to note that successful migration to spawning grounds is only half the reproduction battle, successful reproduction will not occur if the fry emerge and drift into irrigation ditches and flood-irrigated fields. Investigating the effect of irrigation on downstream passage and ditch entrainment of downstream migrants is beyond the scope of this research. Irrigation diversions in the Big Hole Valley probably do not inhibit large numbers of grayling from migrating to spawning habitat because flows are relatively high during spawning times, the diversions are typically not operated with planks inserted at this time, and grayling tend to spawn in the lower 3.2 kilometers of tributaries.

It is imperative for grayling to have access to thermal refuge during low flow, high instream temperature periods. Passage through the modelled fishways was evaluated between July 15 and September 14, 2017 and 2018. On average, based on data

from 1996-2012, the receding limb of the hydrograph for the Big Hole River in Wisdom, Montana was around 7.08 cubic meters per second (cms) on July 15 and recedes to under 1.13 cms by September 14 (Sladek 2013). Looking into 1996-2012 average temperature at the Wisdom gauging station, the mean daily water temperature slowly rose during July, peaked around the last week of the month, then cooled through the end of September (Sladek 2013).

There were 30,754 hourly discharge data points for which passage condition was predicted between July 15 and September 14, across both years and all sites. Of these, 18,265 (59.4%) were out of range of the passage index, 1,902 (6.2%) were classified as allowing passage, 6,853 (22.3%) were classified as limiting passage, and 3,734 (12.1%) were classified as preventing passage of grayling. Many of these “out of range” points probably correspond to poor passage efficiencies because low instream discharges cause low upstream depths, which negatively affect grayling passage (Blank et al. forthcoming). For example, a ladder with 10% slope will have an upstream depth of 0.127 meters with a discharge through it equal to 0.012 cubic meters per second. Between July 15 and September 14, each year, irrigators are likely to operate their diversion structures with planks inserted to provide head to the headgate that connects the stream to the ditch. Habitat is likely fragmented to some degree during low-flow situations because the fishways are not providing efficient upstream passage for grayling at these times and diversions are likely operated as weirs, making the fishway the only route to navigate the diversion.

At site 28 the 2018 grayling spawning period corresponded with conditions that lead to effective upstream passage at the diversion structure. Figure 3.4 shows the 2018 hydrograph at site 28, located on a side channel of the Big Hole upstream of Wisdom, with the points color coded to represent the output of the passage model. The transparent, pink zone of the graph represents when planks were inserted in the diversion, from June 6 to August 11, 2018. The modelled fishway passage condition is mostly “out of range” with some “limits” passage modelled points from April 27 through June 6, 2018. The “out of range” points were associated with high upstream and downstream depth conditions so passage efficiencies through the ladder were probably high based on results from the 2016 laboratory study (Blank et al. forthcoming) which observed passage efficiencies increased as upstream depth increased. From April 27 to June 6 no planks were inserted in the diversion structure. The diversion was probably not acting as a barrier to grayling moving upstream to spawning habitat because there were no planks inserted and the passage efficiencies through the fishway were likely high during the typical spawning time period.

Combining fish passage models with temperature data gives valuable insight into the passage effectiveness during low flow periods and whether thermal refuge was required for grayling during this time. From July 24 through August 11, 2018 the discharge through site 28 was low (under 0.051 cms) and planks were present in the diversion structure. The fishway was the only way for grayling to navigate the diversion during this time. The passage condition was modelled as “limits” passage during this time, so the model predicted that fish passage was 25-75% efficient. During this time the

maximum, minimum, and average hourly water temperatures recorded downstream of the diversion were 24.84 degrees Celsius, 13.08 degrees Celsius, and 18.77 degrees Celsius respectively. Lohr et al. (1996) found the mean upper incipient lethal temperature (UILT), the temperature at which half of experimental subjects could survive indefinitely, for juvenile grayling from the Big Hole was 25.0 degrees Celsius. At site 28, during this low flow and high temperature time period, when planks were inserted in the diversion, the grayling would not be lethally threatened by water temperatures at the site. However, 2018 happened to be a big water year with relatively cool instream temperatures as no river reaches were shut down to angling due to temperatures or low flows (BHCW 2018 Fall Newsletter). Even though grayling UILT temperatures were not sustained at site 28 during 2018, concerns should be raised about the ability and need for fish to navigate this structure in search of thermal refuge because of the small margin of safety between lethal and observed temperatures during a year with more cool water than usual.

Hydraulic Models

Overall, the hydraulic models proved accurate at predicting water surface elevations at the ends of the fishway. The mean of the absolute errors calculated using all 406 pairs of modelled and observed data between trials, operating conditions, and staff gauges was 0.013 meters. Of these 406 modelled versus observed pairs only 39 (9.6%) had absolute error greater than 0.030 meters and 10 (2.5%) had absolute error greater than 0.076 meters.

The largest errors between observed and modelled water surface elevations at a staff gauge location resulted from error in the specified discharge or from the

representation of the fishway on the inline structure. Eight out of the 10 cases where error was greater than 0.076 meters were associated with a discharge that was determined from the gauging station, as opposed to manual measurement. Error can result from using the gauged discharge values, especially when discharge was estimated by extrapolating the discharge-rating curve. It should be noted that 8 out of 10 of these high-error cases corresponded with error at the SG3 location. Three out of 8 high-error SG3 cases corresponded with scenarios where the upstream end of the ladder was partially or fully obstructed, a practice observed at several study sites. Fishways were represented as completely blocked off or a representative orifice for scenarios where most or all of the upstream cross-sectional area was obstructed. Because 90.4% of the WSEs at staff gauge locations are associated with error less than or equal to 0.030 meters and most cases where error exceeded 0.076 meters are associated with gauged discharge inputs or obstructed fishways, confidence in the accuracy of the models is high.

Error in the model could stem from model input data or the observed data model output is compared to. For example, a poorly read staff gauge could give an erroneous “observed” WSE. Particularly, SG2 readings could be consistently off because their location below the ladder was often associated with chaotic hydraulics, making the gauge difficult to read such that the pressure head was measured accurately. Measured stream discharges input to the HEC-RAS models could be inaccurate. It is recognized that error from manual flow measurement using the USGS Midsection Method is usually around 5% but can easily be more than 8% (Turnipseed and Sauer 2010). Sources of error causing uncertainty in discharge measurement include: limited exposure time for velocity

measurements, flow velocity pulsing, uncertainties in sampling the spatial average velocity corresponding to a sub-section, instrument error in the current meter, streamlines that vary in their orientation to the cross section, spacing and amount of observation verticals, and changes in stage during measurement (Pelletier 1987; Sauer and Meyer 1992; Turnipseed and Sauer 2010). All data used to construct and calibrate the models were subject to error, however general agreement between modelled and observed WSEs gives grounds for confidence in the accuracy of the hydraulic models.

Model Application

The hydrology and physical attributes of a barrier site influence the hydraulics fish experience when navigating the barrier, therefore, assessment of fish passage structures must be conducted on a site-by-site basis. Direct studies of fish passage often involve using mark-recapture, trapping methods, or Passive Integrated Transponder (PIT) technology to monitor fish movement about their habitat or barriers. Evaluating the movements of individual fish is labor, time, and financially intensive. The approach presented in this study attempts to determine whether Denil fishways are effective for providing upstream passage using an indirect approach that considers site hydrology and physical layout. The indirect approach may be preferred because it requires less rigorous data collection, it estimates flow thresholds for effective passage, and can estimate passage efficiency over time based on these flow thresholds at gauged sites. It is important to consider site hydrology and hydraulics as well as target species life histories and capabilities to inform managers about whether fish can complete their movement requirements effectively.

This approach to fish passage evaluation can be employed by practitioners and managers to design Denil fishways at diversions and determine upstream passage effectiveness of existing fishways. Much like FishXing does with evaluating passage through culverts, this strategy employs hydraulic modeling coupled with species-specific biologic response to hydraulic conditions. Once the hydraulic model is trained, the passage windows give inference into how well the fishway works under varying instream flow regimes. Biologists can use information from the model to determine if a fishway is effective at providing passage during times corresponding to key life history movements. The hydraulic models can also be adjusted so that any operating condition of the diversion could be modelled, ideal operating conditions could be determined which allow for broader windows of effective passage. Passage during climate change scenarios can be inferred by predicting hydrologic effects and modeling future instream discharges to predict how they affect passage at existing structures. Developing hydraulic models can aid in the design of Denil fishways by using them to orient the fishway to the diversion and surrounding waterway such that favorable hydraulic conditions are sustained for optimal or maximum timeframes. Hydraulic models can be used to model fish passage through fishways and over barriers because they predict the hydraulic conditions individual fish may experience while attempting to navigate these structures. Coupled with biologic data, hydraulic models are useful tools for fish passage engineers and biologists.

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Disclosure Statement

The authors declare no conflicts of interest associated with this research. The views expressed herein are those of the authors and not necessarily those of Montana State University, the United States Geological Survey, or the United States Fish and Wildlife Service. Any use of product and brand names was not done for endorsement purposes.

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References

- Big Hole Watershed Committee (BHWC). 2012. Big Hole River, Montana watershed restoration plan; part 1: upper and North Fork Big Hole watershed. [edition unknown]. Divide Montana: BHWC. [report number unknown].
- Big Hole Watershed Committee (BHWC). 2018. Fall/winter 2018 snowpack & climate forecast. Big Hole Watershed Committee Newsletter (Fall 2018). Page 7.
- Bishop FG. 1971. Observations on spawning habits and fecundity of the Arctic Grayling. Prog Fish Cult 33(1): 12-19.
- Blank MD. 2008. Advanced studies of fish passage through culverts: 1-D and 3-D hydraulic modeling of velocity, fish energy expenditure, and a new barrier assessment method [dissertation]. Bozeman MT: Montana State University.

Blank M, Kappenman K, Banner K, Ryan E. Forthcoming. Arctic Grayling (*Thymallus arcticus* Pallas) and Denil fishways: a study to determine how water depth affects passage success.

Brink K, Gough P, Royt J, Schollemma PP, Wanningen H. 2018. From Sea to Source 2.0 Protection and restoration of fish migration in rivers worldwide. The Netherlands: World Fish Migration Foundation.

Bryant MD, Frenette BJ, McCurdy SJ. 1999. Colonization of a watershed by anadromous salmonids following the installation of a fish ladder in Margaret Creek, Southeast Alaska. *N Am J Fish Man* 19(4): 1129-1136.

Bunt CM, Katopodis C, McKinley RS. 1999. Attraction and passage efficiency of white suckers and smallmouth bass by two Denil fishways. *N Am J Fish Man* 19(3): 793-803.

Bunt CM, Castro-Santos T, Haro A. 2012. Performance of fish passage structures at upstream barriers to migration. *River Res Applic* 28: 457-478.

Burford DD, McMahon TE, Cahoon JE, Blank M. 2009. Assessment of trout passage through culverts in a large Montana drainage during summer low flow. *N Am J Fish Man* 29(3): 739-752.

Cahill CL. 2015. Status of Arctic Grayling (*Thymallus arcticus*) in Alberta: Update 2015. Alberta, Canada: Alberta Government and Alberta Conservation Association. Report number 57.

Castro-Santos T, Haro A, Walk S. 1996. A passive integrated transponder (PIT) tag system for monitoring fishways. *Fish Res* 28: 253-261.

Cayer E and McCullough A. 2013. Arctic Grayling monitoring report, 2013. [edition unknown]. Dillon MT: Montana Fish, Wildlife, and Parks. [report number unknown].

Chow VT. 1959. Open-Channel Hydraulics. Reprint of 1959 edition. Caldwell NJ: The Blackburn Press.

Clarkin K, Connor A, Furniss MJ, Gubernick B, Love M, Moynan K, WilsonMusser S. 2005. National inventory and assessment procedure- for identifying barriers to aquatic organisms at road-stream crossings. [edition unknown]. San Dimas CA: US Dept of Agriculture Forest Service. [report number unknown].

Davis BA. 2015. Endangered waters: interdependency on Montana's Big Hole River [thesis]. Bozeman MT: Montana State University.

Dockery DR, Ryan E, Kappenman KM, Blank M. Forthcoming 2019. Swimming performance of Arctic grayling (*Thymallus arcticus* Pallas) in an open-channel flume. *J Ecohydraul*.

Duffield JW, Neher CJ, Brown TC. 1992. Recreation benefits of instream flow: application to Montana's Big Hole and Bitterroot Rivers. *Water Resour Res* 28(9): 2169-2181.

Dunham JB, Vinyard GL, Rieman BE. 1997. Habitat fragmentation and extinction risk of lahontan cutthroat trout. *N Am J Fish Man* 17(4): 1126-1133.

FAO/DVWK. 2002. Fish passes- design, dimensions and monitoring. [edition unknown]. Rome, Italy: Food and Agricultural Organization of the United Nations. [report number unknown].

Fausch KD, Rieman BE, Dunham JB, Young MK, Peterson DP. 2009. Invasion versus isolation: trade-offs in managing native salmonids with barriers to upstream movement. *Conserv Biol* 23(4): 859-870.

Flynn K, Kron D, Granger M. 2009. Modeling streamflow and water temperature in the Big Hole River, Montana – 2006. [edition unknown]. Helena MT: Montana Department of Environmental Quality. [report number unknown].

Fulton LA and Bair SH. 1953. Trial of Denil-Type Fish Ladder on Pacific Salmon. [edition unknown]. [publisher unknown]. Report Number 99.

Furniss MJ, Firor S, Love M. 2000. FishXing 2.0 software and learning system for the analysis of fish migration through culverts. Stream notes to aid in securing favorable conditions of water flows (July 2000). [section unknown]: 1-4.

Gosset C, Rives J, Labonne J. 2006. Effect of habitat fragmentation on spawning migration of brown trout (*Salmo trutta* L.). *Ecol Freshwat Fish* 15: 247-254.

Grantham TE. 2013. Use of hydraulic modeling to assess passage flow connectivity for salmon in streams. *River Res Applic* 29: 250-267.

Hardy TB and Addley CR. 2003. Instream flow assessment modeling: combining physical and behavioural-based approaches. *Can Water Resour J* 28(2): 273-282.

Haro A, Odeh M, Castro-Santos T, Noreika J. 1999. Effect of slope and headpond on passage of American shad and Blueback herring through simple Denil and deepened Alaska Steeppass fishways. *N Am J Fish Man* 19(1): 51-58.

Heim KC, Wipfli MS, Whitman MS, Arp CD, Adams J, Falke JA. 2015. Seasonal cues of Arctic Grayling movement in a small Arctic stream: the importance of surface water connectivity. *Environ Biol Fish* 99: 49-65.

Hendrickson S, Walker K, Jacobson S, Bower F. 2008. Assessment of aquatic organism passage at road/stream crossings for the northern region of the USDA Forest Service. [edition unknown]. [publisher unknown]. [report number unknown].

Jackson A, Moser M. 2012. Low-elevation dams are impediments to adult pacific lamprey spawning migration in the Umatilla River, Oregon. *N Am J Fish Man* 32(3): 548-556.

Katopodis C. 1992. Introduction to fishway design. [edition unknown]. [publisher unknown]. [report number unknown].

Katopodis C. 2003. Case studies of instream flow modeling for fish habitat in Canadian prairie rivers. *Can Water Resour J* 28(2): 199-216.

Katopodis C. 2005. Developing a toolkit for fish passage, ecological flow management and fish habitat works. *J Hydraul Res* 43(5): 451-467.

Katopodis C, Rajaratnam N, Wu S, Tovell D. 1997. Denil fishways of varying geometry. *J Hydraul Eng* 123(7): 624-631.

Letcher BH, Nislow KH, Coombs JA, O'Donnell MJ, Dubreuil TL. 2007. Population response to habitat fragmentation in a stream-dwelling brook trout population. *PLoS ONE* 2(11): e1139.

Liknes GA. 1981. The fluvial Arctic Grayling (*Thymallus arcticus*) of the upper Big Hole River drainage, Montana [thesis]. Bozeman MT: Montana State University.

Lohr SC, Byorth PA, Kaya CM, Dwyer WP. 1996. High-temperature tolerances of fluvial Arcti grayling and comparisons with summer river temperatures of the Big Hole River, Montana. *Trans Am Fish Soc* 125(6): 933-939.

Mahlum S, Cote D, Wiersma YF, Kehler D, Clarke K. 2014. Evaluating the barrier assessment technique derived from FishXing software and the upstream movement of brook trout through road culverts. *Trans Am Fish Soc* 143(1): 39-48.

MDNRC Conservation Districts Bureau. 2001. Montana stream permitting: a guide for conservation district supervisors and others. [edition unknown]. Helena MT: MDNRC. [report number unknown].

MFWP and USFWS. 2006. Candidate conservation agreement with assurances (CCAA) for Fluvial Arctic grayling in the Upper Big Hole River. [edition unknown]. Helena MT: MFWP. USFWS Tracking #TE104415-0.

Morita K, Morita SH, Yamamoto S. 2009. Effects of habitat fragmentation by damming on salmonid fishes: lessons from white-spotted charr in Japan. *Ecol Res* 24: 711-722.

National Marine Fisheries Service (NMFS). 2008. Anadromous salmonid passage facility design. [edition unknown]. Portland OR: NMFS, Northwest Region. [report number unknown].

Noonan MJ, Grant JWA, Jackson CD. 2012. A quantitative assessment of fish passage efficiency. *Fish* 13: 450-464.

Northcote TG. 1995. Comparative biology and management of Arctic and European grayling (*Salmonidae*, *Thymallus*). *Rev Fish Biol Fisher* 5: 141-194.

Odeh M. 2003. Discharge rating equation and hydraulic characteristics of standard Denil fishways. *J Hydraul Eng* 129(5): 341-348.

Pelletier PM. 1988. Uncertainties in the single determination of river discharge: a literature review. *Can J Civ Eng* 15: 834-850.

Peterson DP and Ardren WR. 2009. Ancestry, population structure, and conservation genetics of Arctic Grayling (*Thymallus arcticus*) in the Upper Missouri River, USA. *Can J Fish Aquat Sci* 66: 1758-1774.

Rajaratnam N and Katopodis C. 1984. Hydraulics of Denil fishways. *J Hydraul Eng* 110(9): 1219-1233.

Rajaratnam N and Katopodis C. 1997. Hydraulics of resting pools for Denil fishways. *J Hydraul Eng* 123(7): 632-638.

Reinfelds I, Lincoln-Smith M, Haeusler T, Ryan D, Growns I. 2010. Hydraulic assessment of environmental flow regimes to facilitate fish passage through natural riffles: Shoalhaven River below Tallowa Dam, New South Wales, Australia. *River Res Applic* 26: 589-604.

Reiser DW, Huang CM, Beck S, Gagner M, Jeanes E. 2006. Defining flow windows for upstream passage of adult anadromous salmonids at cascades and falls. *Trans Am Fish Soc* 135: 668-679.

Roni P, Beechie TJ, Bilby RE, Leonetti FE, Pollock MM, Pess GR. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. *N Am J Fish Man* 22(1): 1-20.

Ryan ER. 2015. Effects of hydraulic structures on fish passage: an evaluation of 2D vs 3D hydraulic analysis methods [thesis]. Fort Collins CO: Colorado State University.

Sanford P, Cahoon J, Hughes T. 1998. Modeling a concrete block irrigation diversion system. *J Amer Water Resour Assoc* 34(5): 1179-1187.

Sauer VB and Meyer RW. 1992. Determination of error in individual discharge measurements. [edition unknown]. Norcross GA: USGS. Report number 92-144.

Schmetterling DA, Pierce RW, Liermann BW. 2002. Efficacy of three Denil fish ladders for low-flow fish passage in two tributaries to the Blackfoot River, Montana. *N Am J Fish Man* 22(3): 929-933.

Schrank AJ, Rahel FJ. 2004. Movement patterns in inland cutthroat trout (*Oncorhynchus clarki* Utah): management and conservation implications. *Can J of Fish and Aquat Sci* 61(8): 1528-1537.

Sheer MB and Steel EA. 2006. Lost watersheds: barriers, aquatic habitat connectivity, and salmon persistence in the Willamette and Lower Columbia River basins. *Trans Amer Fish Soc* 135(6): 1654-1669.

Shepard BB and Oswald RA. 1989. Timing, location and population characteristics of spawning Montana Arctic Grayling (*Thymallus arcticus montanus* [Milner]) in the Big Hole River drainage, 1988. [edition unknown]. Bozeman MT: Montana Department of Fish, Wildlife, and Parks. [report number unknown].

Sladek H. 2013. Trend analysis of water temperature relative to air temperatures and flow in the Big Hole River, Final Report. [unknown edition]. Dillon MT: US Forest Service. [report number unknown].

Stewart G, Anderson R, Wohl E. 2005. Two-dimensional modeling of habitat suitability as a function of discharge in two Colorado rivers. *River Res Applic* 21: 1061-1074.

Taylor RN. 2000. Final report: Humboldt county culvert inventory and fish passage evaluation. [edition unknown]. McKinleyville CA: Ross Taylor and Associates. [report number unknown].

Towler B, Mulligan K, Haro A. 2015. Derivation and application of the energy dissipation factor in the design of fishways. *Ecol Eng* 83: 208-217.

Turnipseed DP and Sauer VB. 2010. Discharge measurements at gauging stations: USGS techniques and methods book, chap. A8. 3rd edition. Reston VA: USGS. [unknown report number].

US Army Corps of Engineers (USACE). 2016. HEC-RAS river analysis system hydraulic reference manual. Version 5. Davis CA: USACE Institute for Water Resources Hydrologic Engineering Center. [unknown report number].

USFWS. 2017. Fish passage engineering design criteria. [edition unknown]. Hadley MA: USFWS Northeast Region R5. [report number unknown].

USFWS. 2012. National fish passage program: 2011 annual report and outlook. [edition unknown]. Arlington VA: USFWS National Fish Passage Program. [report number unknown].

USFWS. 2013. National fish passage program: 2012 annual report and outlook. [edition unknown]. Arlington VA: USFWS National Fish Passage Program. [report number unknown].

Vatland SJ. 2015. Effects of stream temperature and climate change on fluvial Arctic Grayling and non-native salmonids in the upper Big Hole River, Montana [dissertation]. Bozeman MT: Montana State University.

Warren ML and Pardew MG. 1998. Road crossings as barriers to small-stream fish movement. Trans Amer Fish Soc 127: 637-644.

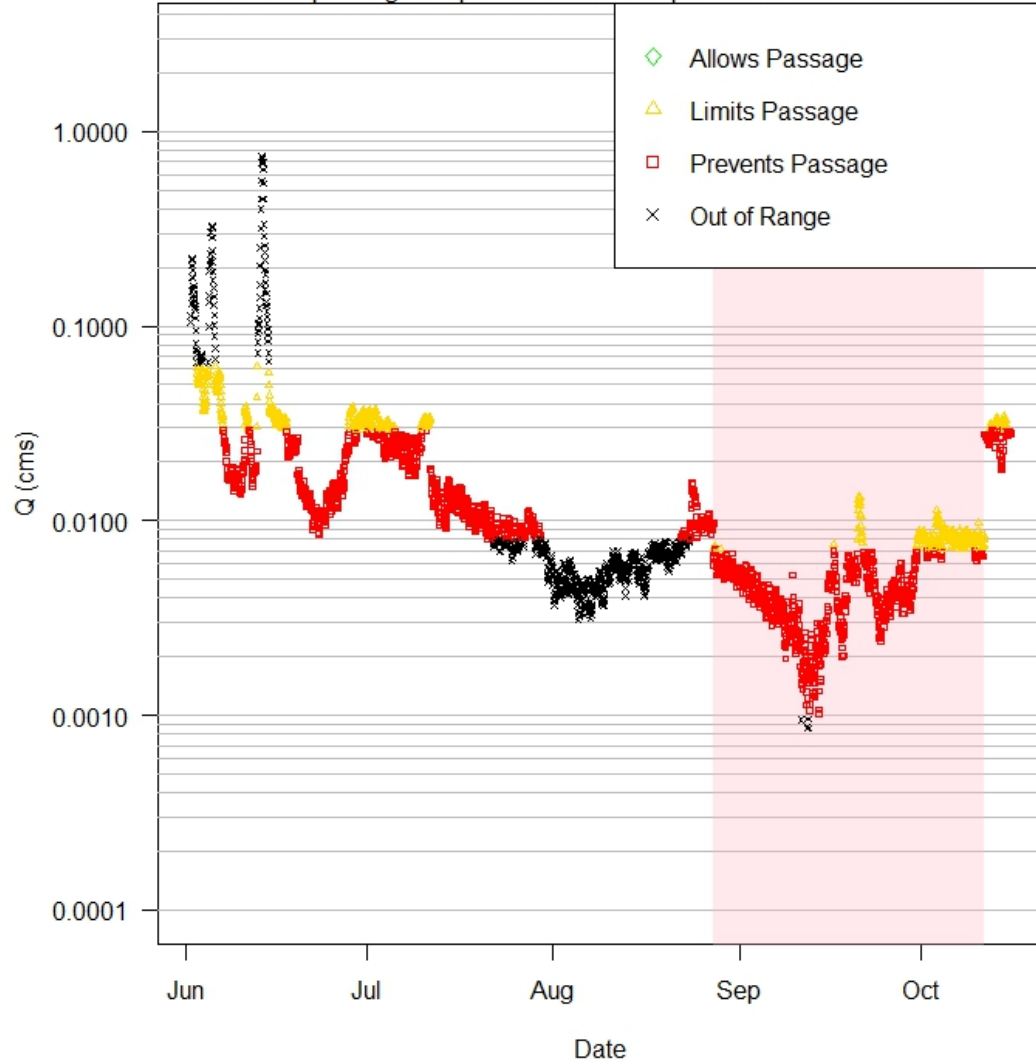
Wright KA, Goodman DH, Som NA, Alvarez J, Martin A, Hardy TB. 2017. Improving hydrodynamic modeling: an analytical framework for assessment of two-dimensional hydrodynamic models. River Res Appl 33: 170-181.

Appendix

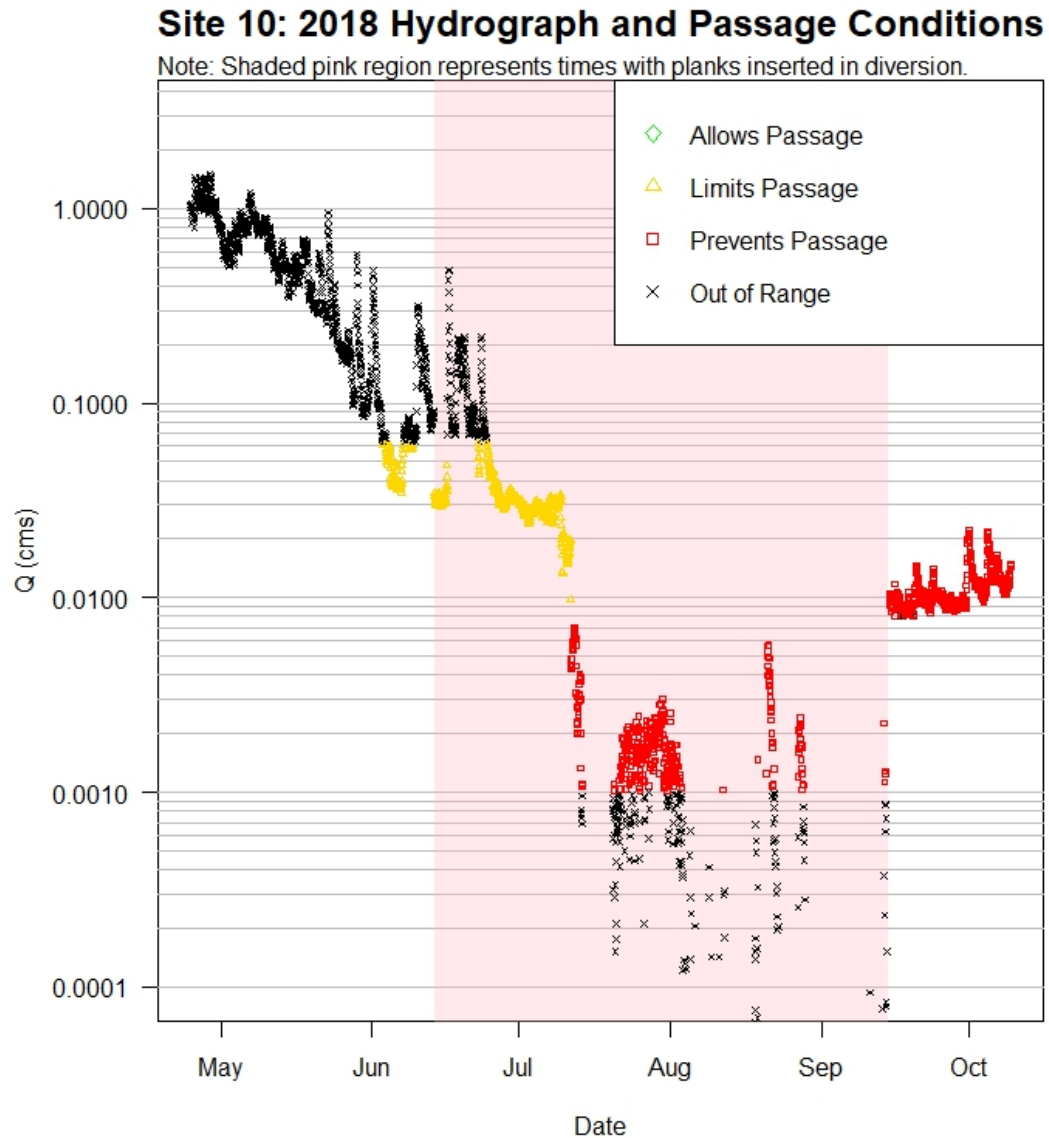
This appendix contains color coded hydrographs like Figure 3.4 for each site and year observed. On the figures, date is on the x-axis and the discharge through the site (in cms, log scale) is on the y-axis. Each point represents a discharge at a given time, points are color and shape coded to represent predicted passage conditions. The pink, shaded regions represent times when planks were inserted into the diversions, it is assumed that the fishway is the only route to navigate the diversion at these times. If no planks were inserted in the diversions, they did not act as barriers to fish movement at high discharges (they were hydraulically submerged) but may have acted as barriers at low discharges. Exact instream discharges when these diversions acted as barriers are unknown.

Site 10: 2017 Hydrograph and Passage Conditions

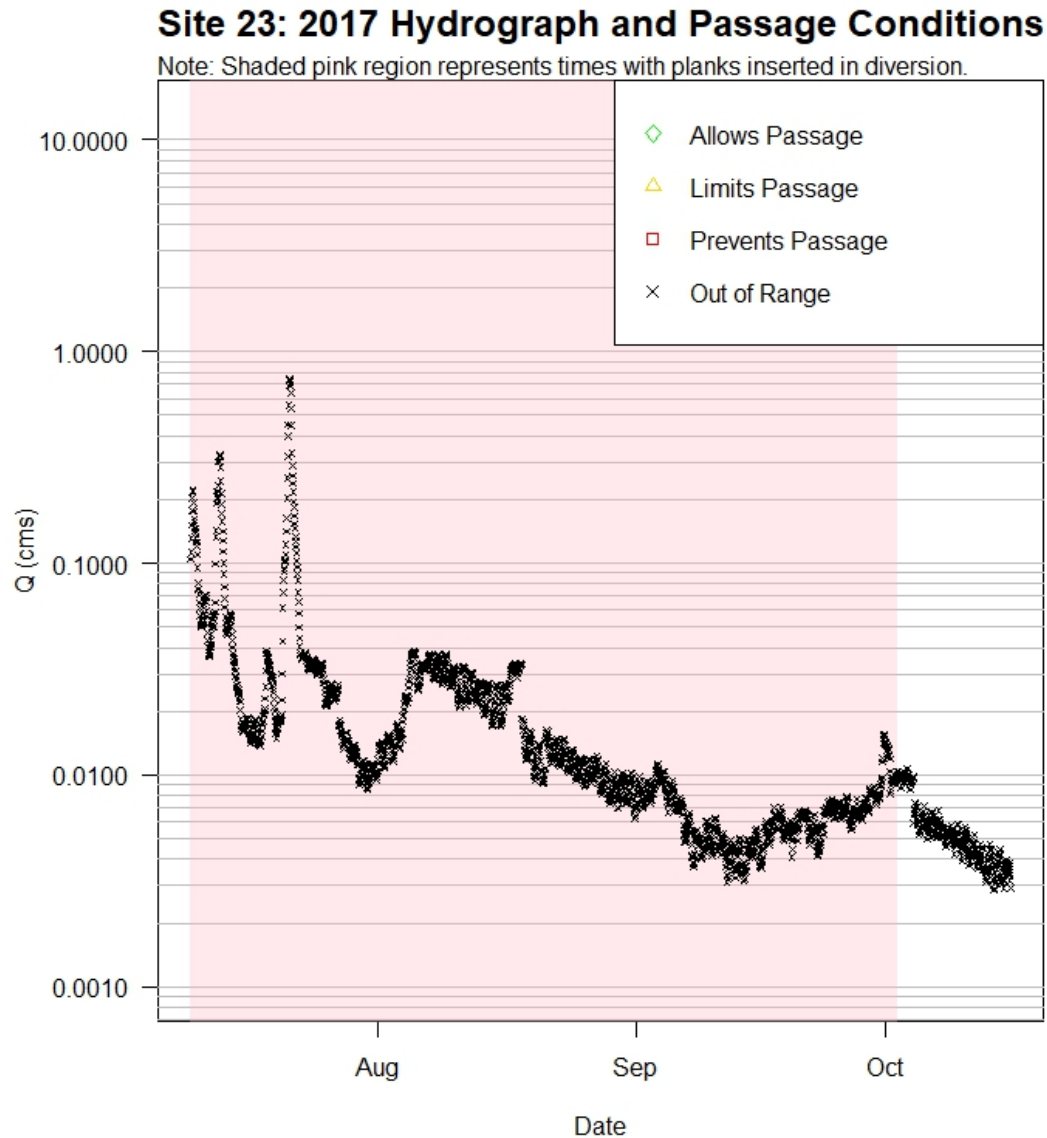
Note: Shaded pink region represents times with planks inserted in diversion.



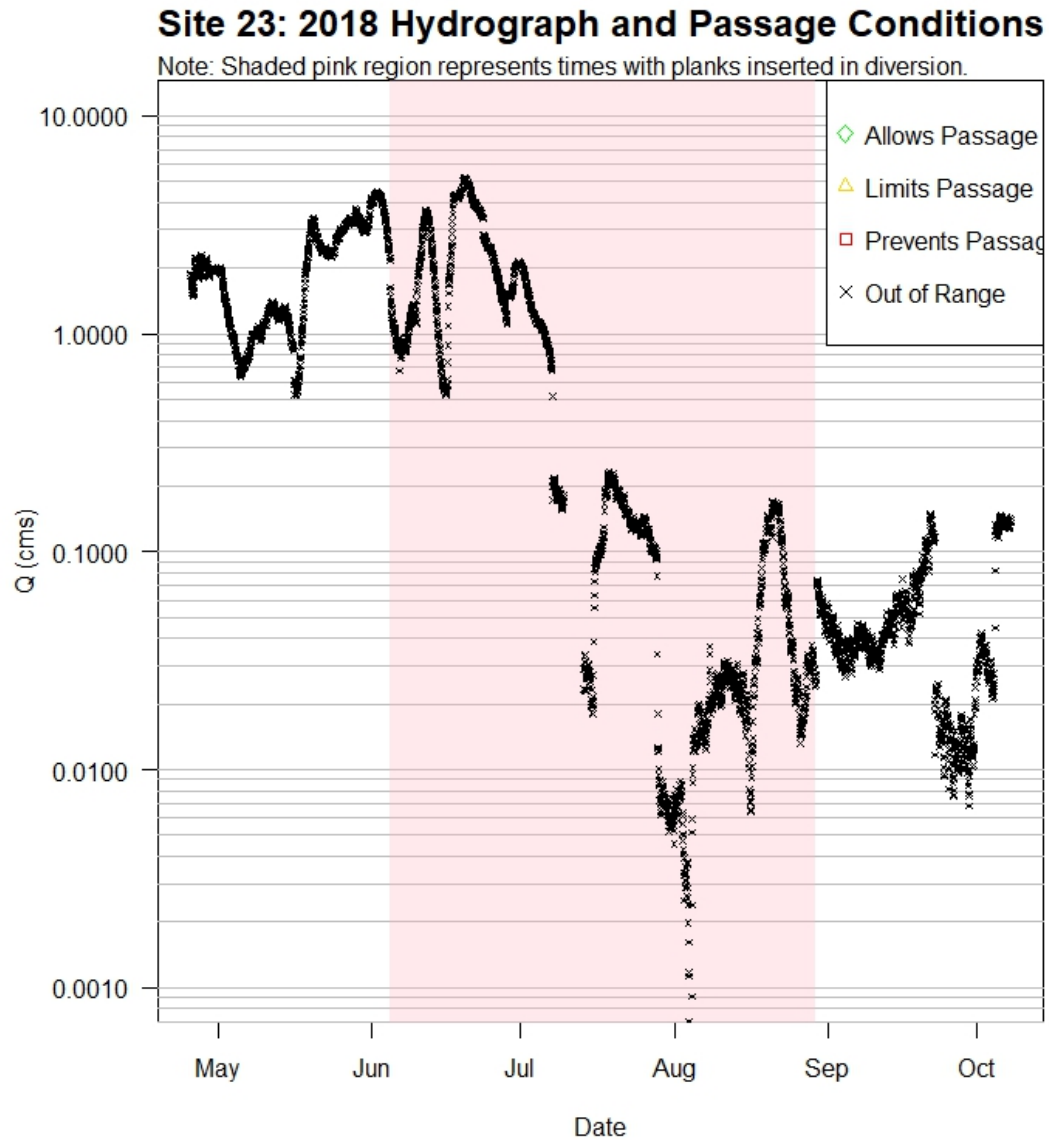
The above graph shows modelled passage windows superimposed on a hydrograph for site 10 during 2017 monitoring. The Denil fishway at site 10 has a length of 1.63 meters and a slope of 18.7%. Discharge was gauged hourly from June 1 to October 15, 2017. The estimated maximum and minimum discharges during this time were 0.742 and 0.001 cms. It is estimated that planks were inserted in the diversion from August 27 to October 11, 2017. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



The above graph shows modelled passage windows superimposed on a hydrograph for site 10 during 2018 monitoring. The Denil fishway at site 10 has a length of 1.63 meters and a slope of 18.7%. Discharge was gauged hourly from April 24 to October 9, 2018. The estimated maximum and minimum discharges during this time were 1.492 and 0.000 cms. It is estimated that planks were inserted in the diversion from June 13 to September 14, 2018. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



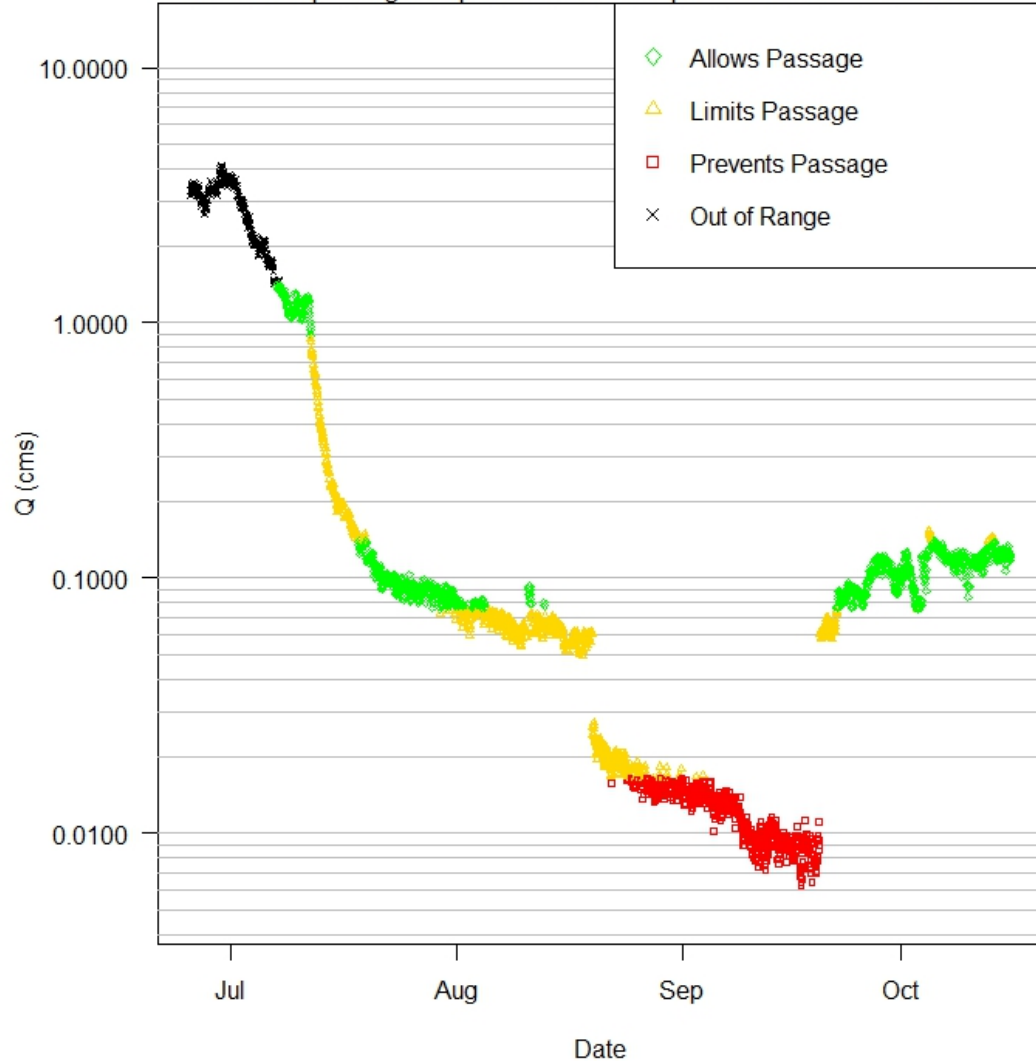
The above graph shows modelled passage windows superimposed on a hydrograph for site 23 during 2017 monitoring. The Denil fishway at site 23 has a length of 3.66 meters and a slope of 15.7%. The downstream invert of this fishway was set such that it was always “submerged” (i.e. downstream end of fishway completely under water). Discharge was gauged hourly from July 9 to October 15, 2017. The estimated maximum and minimum discharges during this time were 0.423 and 0.000 cms. It is estimated that planks were inserted in the diversion from the beginning of monitoring to October 2, 2017. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



The above graph shows modelled passage windows superimposed on a hydrograph for site 23 during 2018 monitoring. The Denil fishway at site 23 has a length of 3.66 meters and a slope of 15.7%. The downstream invert of this fishway was set such that it was always “submerged” (i.e. downstream end of fishway completely under water). Discharge was gauged hourly from April 25 to October 7, 2018. The estimated maximum and minimum discharges during this time were 5.188 and 0.000 cms. It is estimated that planks were inserted in the diversion from June 4 to August 29, 2018. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.

Site 25: 2017 Hydrograph and Passage Conditions

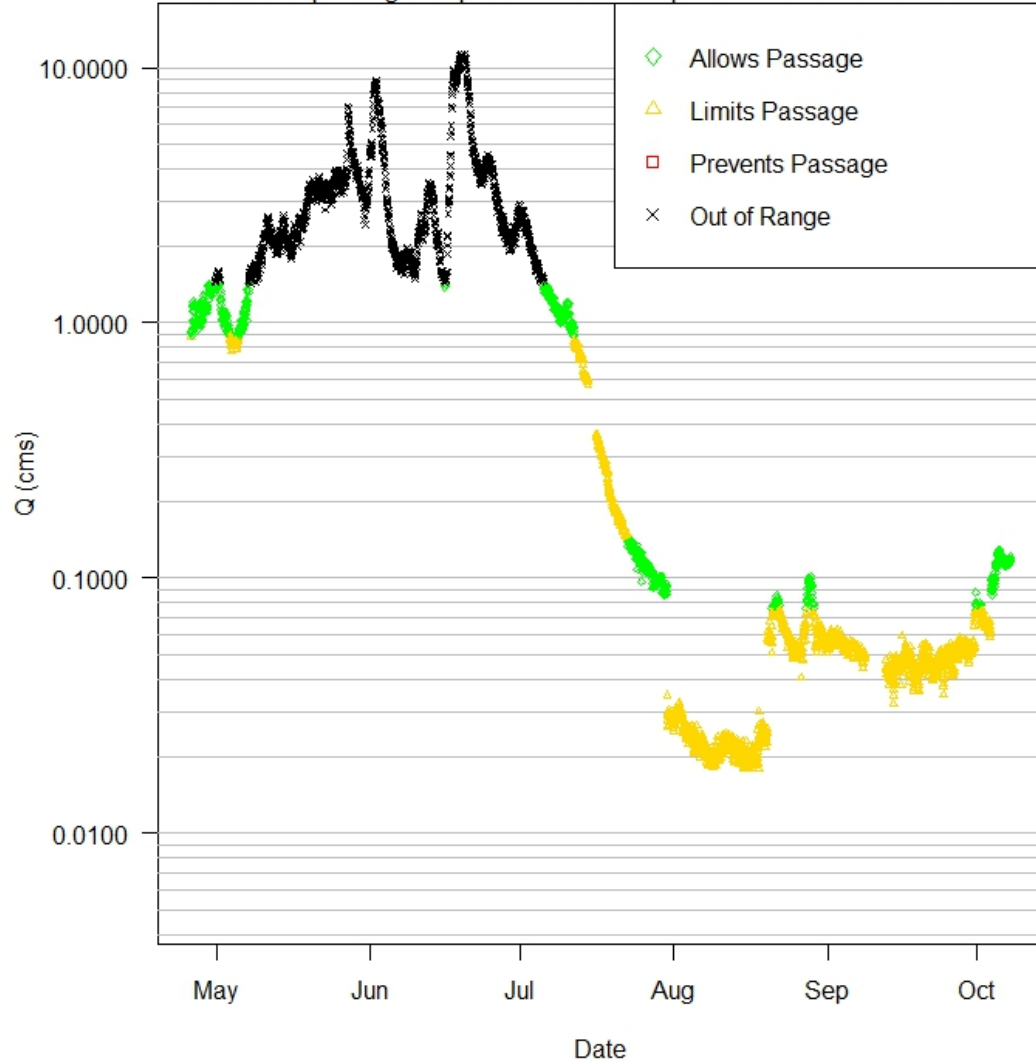
Note: Shaded pink region represents times with planks inserted in diversion.



The above graph shows modelled passage windows superimposed on a hydrograph for site 25 during 2017 monitoring. The Denil fishway has a length of 2.77 meters and a slope of 5.0%. Discharge was gauged hourly from June 25 to October 15, 2017. The estimated maximum and minimum discharges during this time were 4.146 and 0.006 cms. Planks were never inserted in the diversion during monitoring. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.

Site 25: 2018 Hydrograph and Passage Conditions

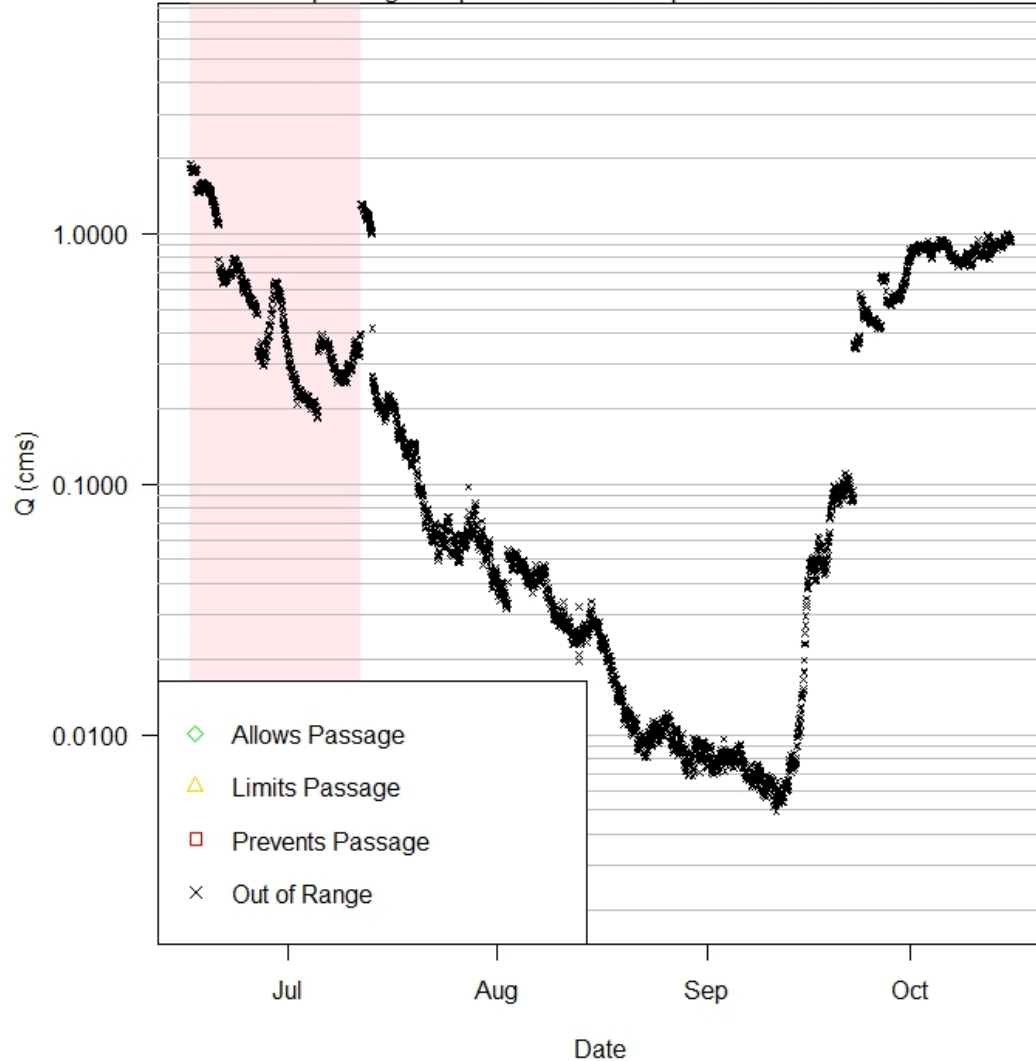
Note: Shaded pink region represents times with planks inserted in diversion.



The above graph shows modelled passage windows superimposed on a hydrograph for site 25 during 2018 monitoring. The Denil fishway has a length of 2.77 meters and a slope of 5.0%. Discharge was gauged hourly from April 25 to October 7, 2018. The estimated maximum and minimum discharges during this time were 11.297 and 0.018 cms. Planks were never inserted in the diversion during monitoring. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.

Site 27: 2017 Hydrograph and Passage Conditions

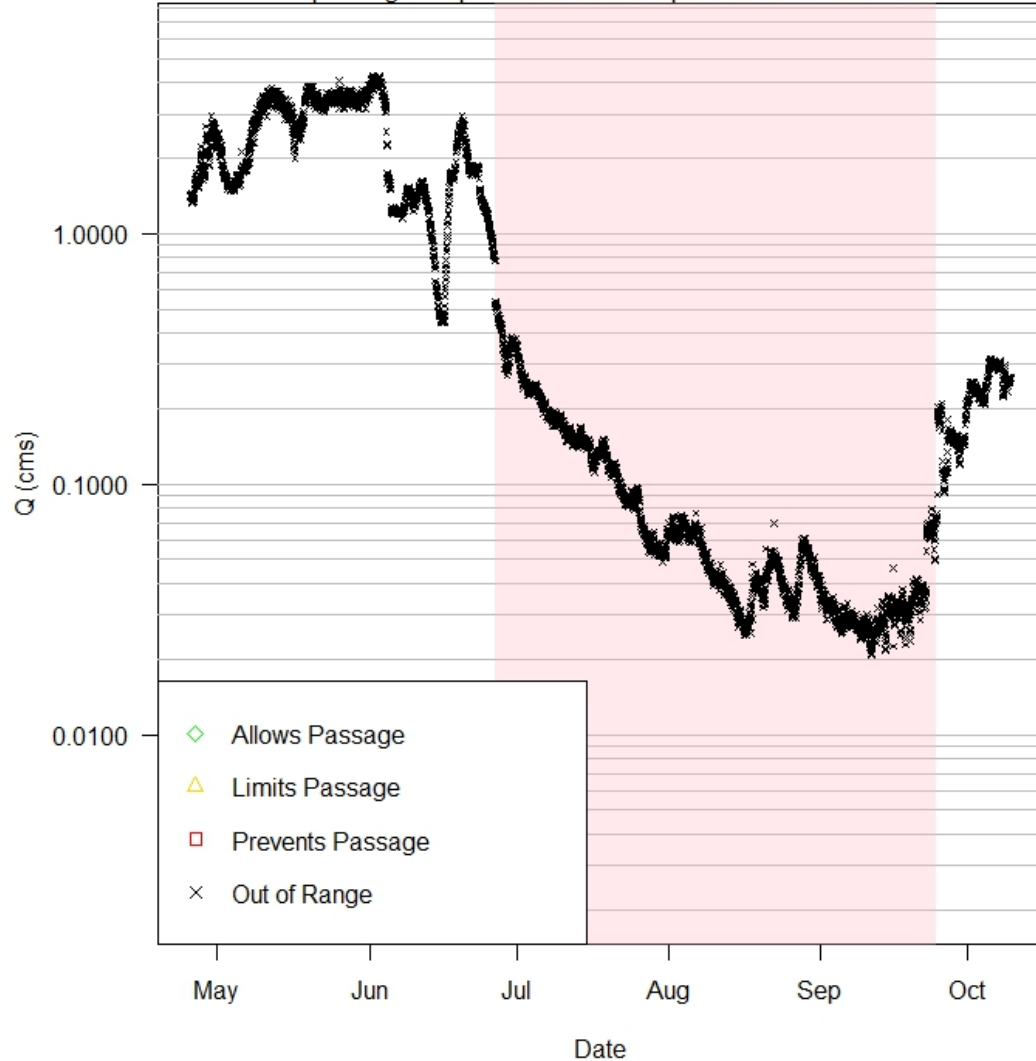
Note: Shaded pink region represents times with planks inserted in diversion.



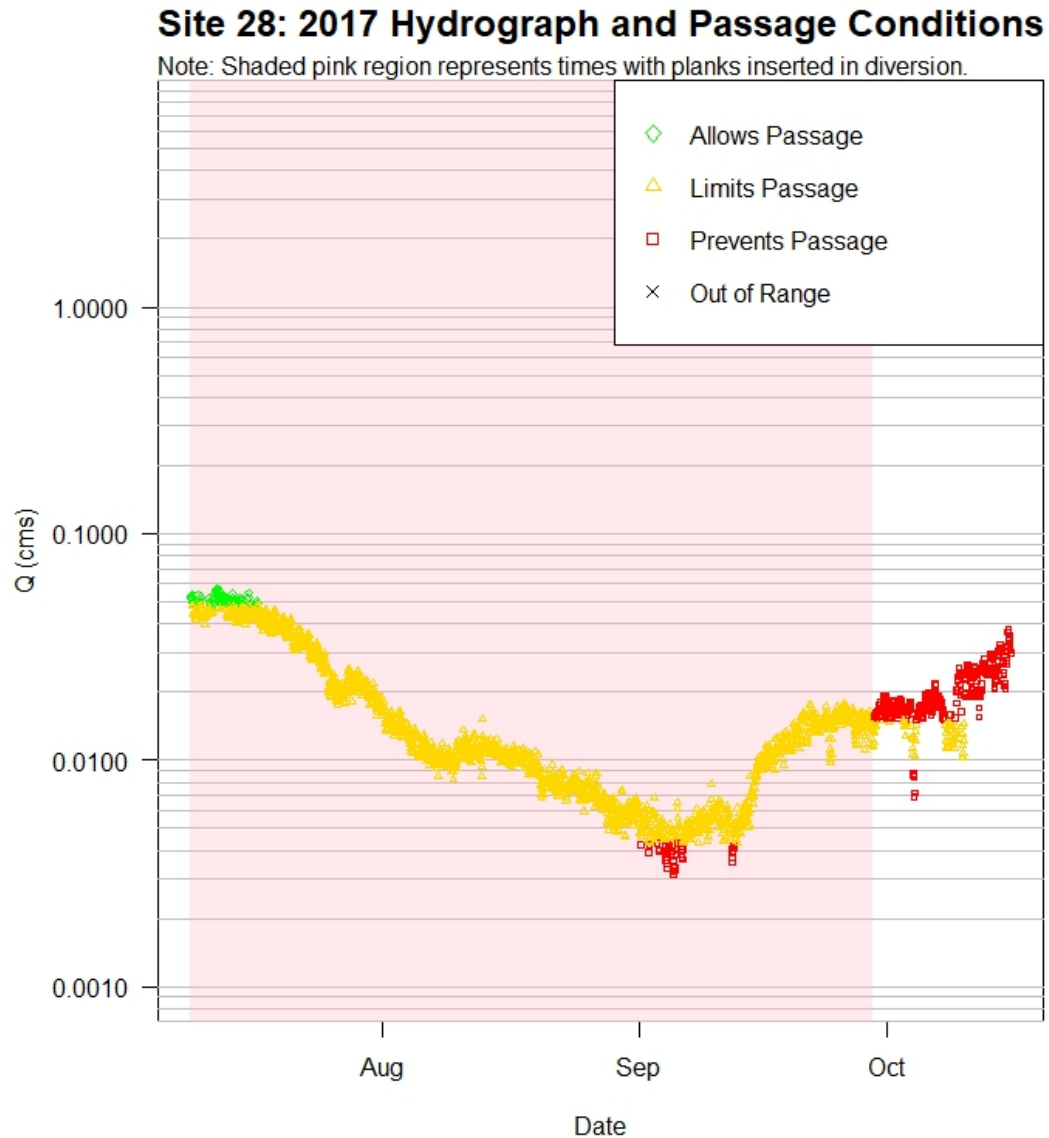
The above graph shows modelled passage windows superimposed on a hydrograph for site 27 during 2017 monitoring. The Denil fishway at site 27 has a length of 3.66 meters and a slope of 19.9%. The downstream invert of this fishway was set such that it was always “submerged” (i.e. downstream end of fishway completely under water). Discharge was gauged hourly from June 16 to October 15, 2017. The estimated maximum and minimum discharges during this time were 1.895 and 0.005 cms. It is estimated that planks were inserted in the diversion from the beginning of monitoring to July 11, 2017. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.

Site 27: 2018 Hydrograph and Passage Conditions

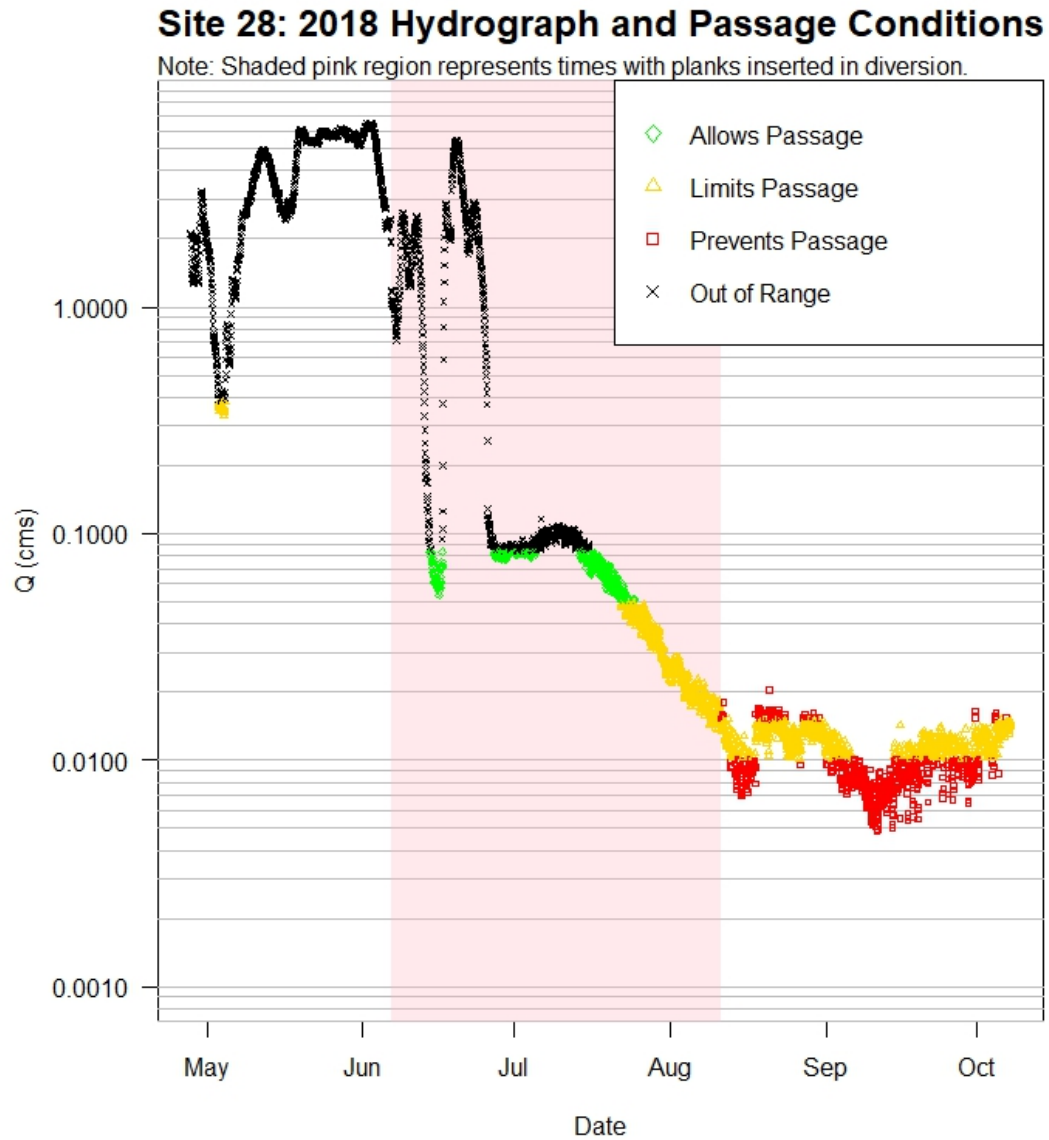
Note: Shaded pink region represents times with planks inserted in diversion.



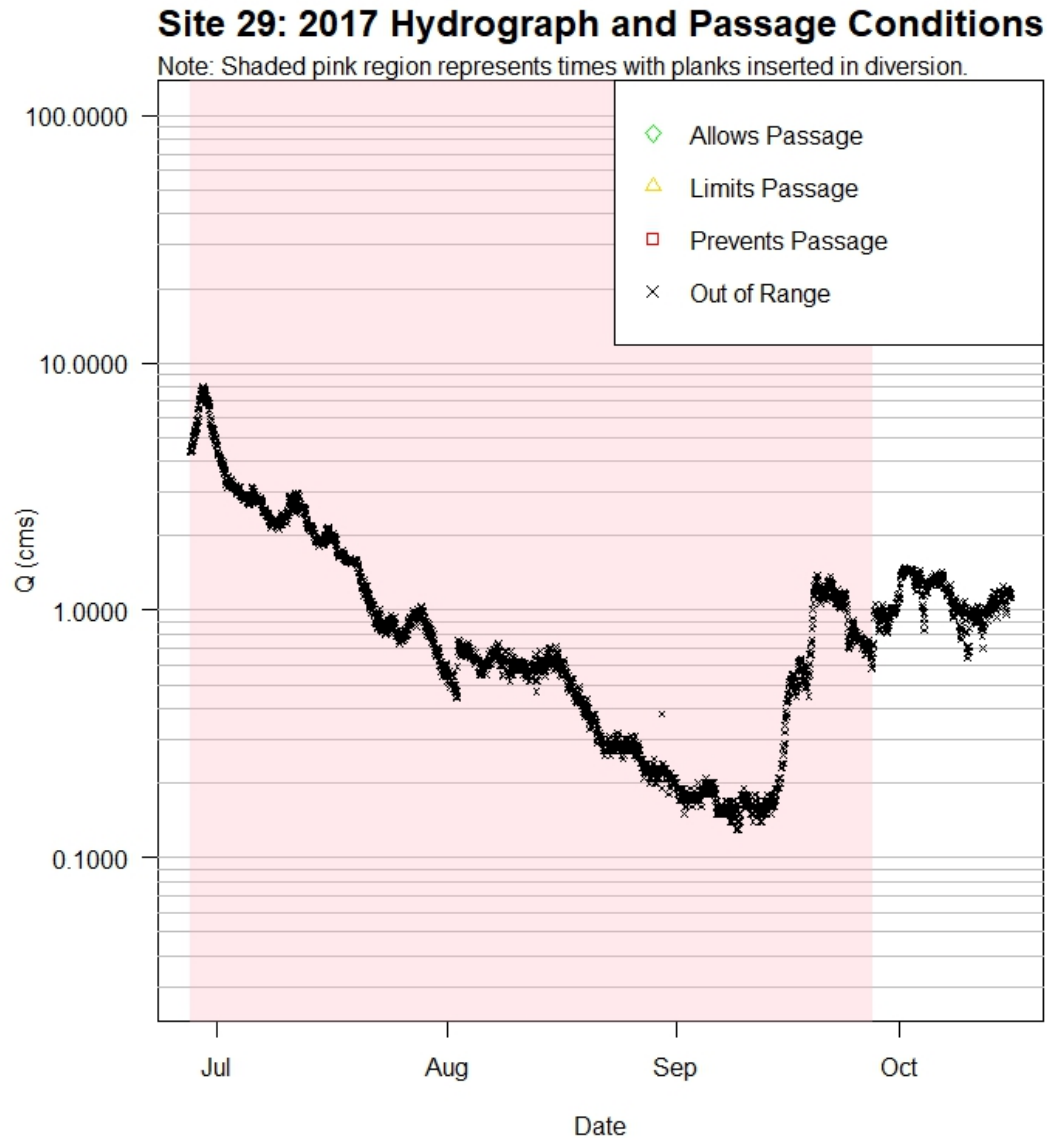
The above graph shows modelled passage windows superimposed on a hydrograph for site 27 during 2018 monitoring. The Denil fishway at site 27 has a length of 3.66 meters and a slope of 19.9%. The downstream invert of this fishway was set such that it was always “submerged” (i.e. downstream end of fishway completely under water). Discharge was gauged hourly from April 25 to October 9, 2018. The estimated maximum and minimum discharges during this time were 4.242 and 0.021 cms. It is estimated that planks were inserted in the diversion from June 26 to September 24, 2018. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



The above graph shows modelled passage windows superimposed on a hydrograph for site 28 during 2017 monitoring. The Denil fishway has a length of 3.66 meters and a slope of 6.1%. Discharge was gauged hourly from July 8 to October 15, 2017. The estimated maximum and minimum discharges during this time were 0.058 and 0.003 cms. It was estimated that planks were inserted in the diversion from the beginning of monitoring to September 29, 2017. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



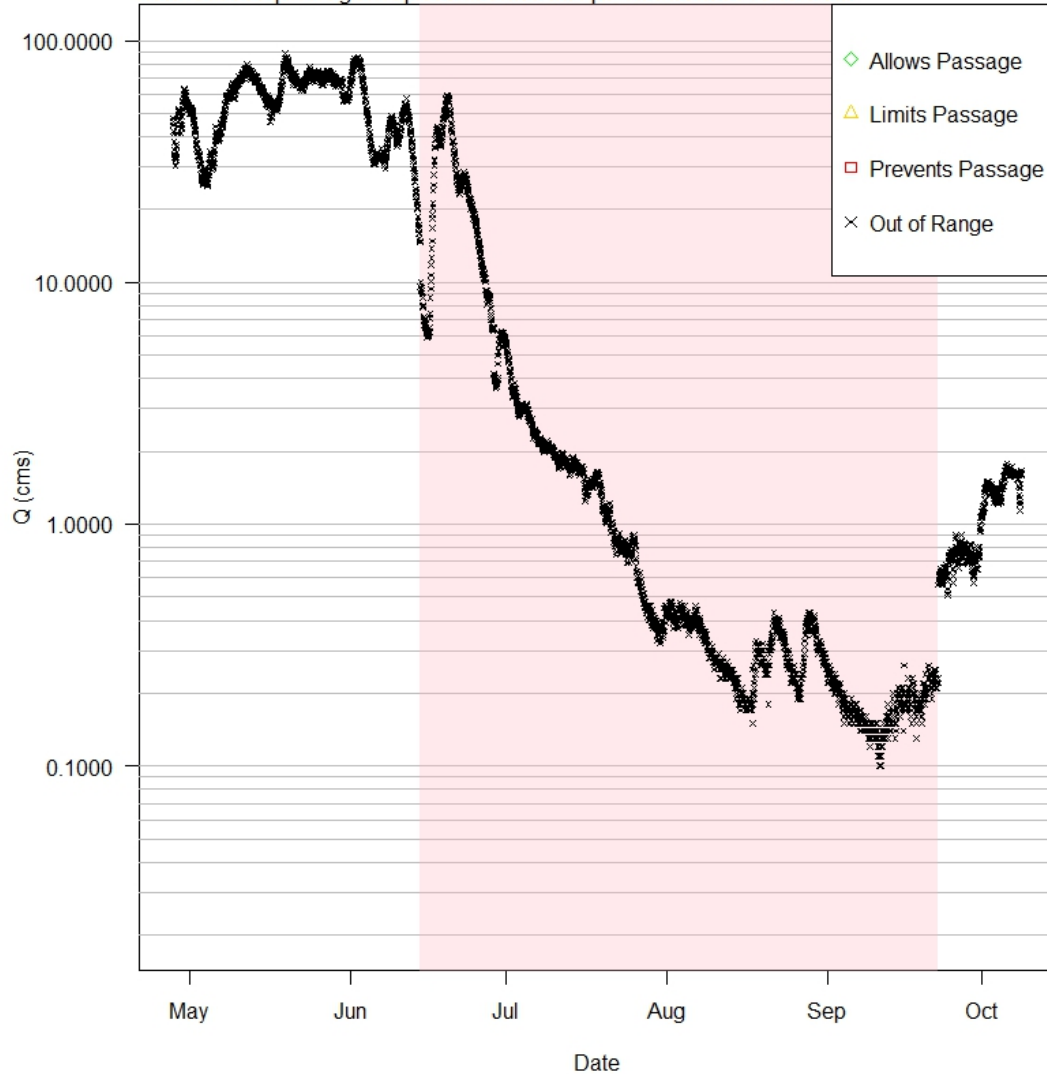
The above graph shows modelled passage windows superimposed on a hydrograph for site 28 during 2018 monitoring. The Denil fishway has a length of 3.66 meters and a slope of 6.1%. Discharge was gauged hourly from April 27 to October 7, 2018. The estimated maximum and minimum discharges during this time were 6.507 and 0.005 cms. It was estimated that planks were inserted in the diversion from June 6 to August 11, 2018. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



The above graph shows modelled passage windows superimposed on a hydrograph for site 29 during 2017 monitoring. The Denil fishway has a length of 6.10 meters and a slope of 11.6%. The downstream invert of this fishway was set such that it was always “submerged” (i.e. downstream end of fishway completely under water). Discharge was gauged hourly from June 27 to October 15, 2017. The estimated maximum and minimum discharges during this time were 7.990 and 0.130 cms. It was estimated that planks were inserted in the diversion from the beginning of monitoring to September 27, 2017. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.

Site 29: 2018 Hydrograph and Passage Conditions

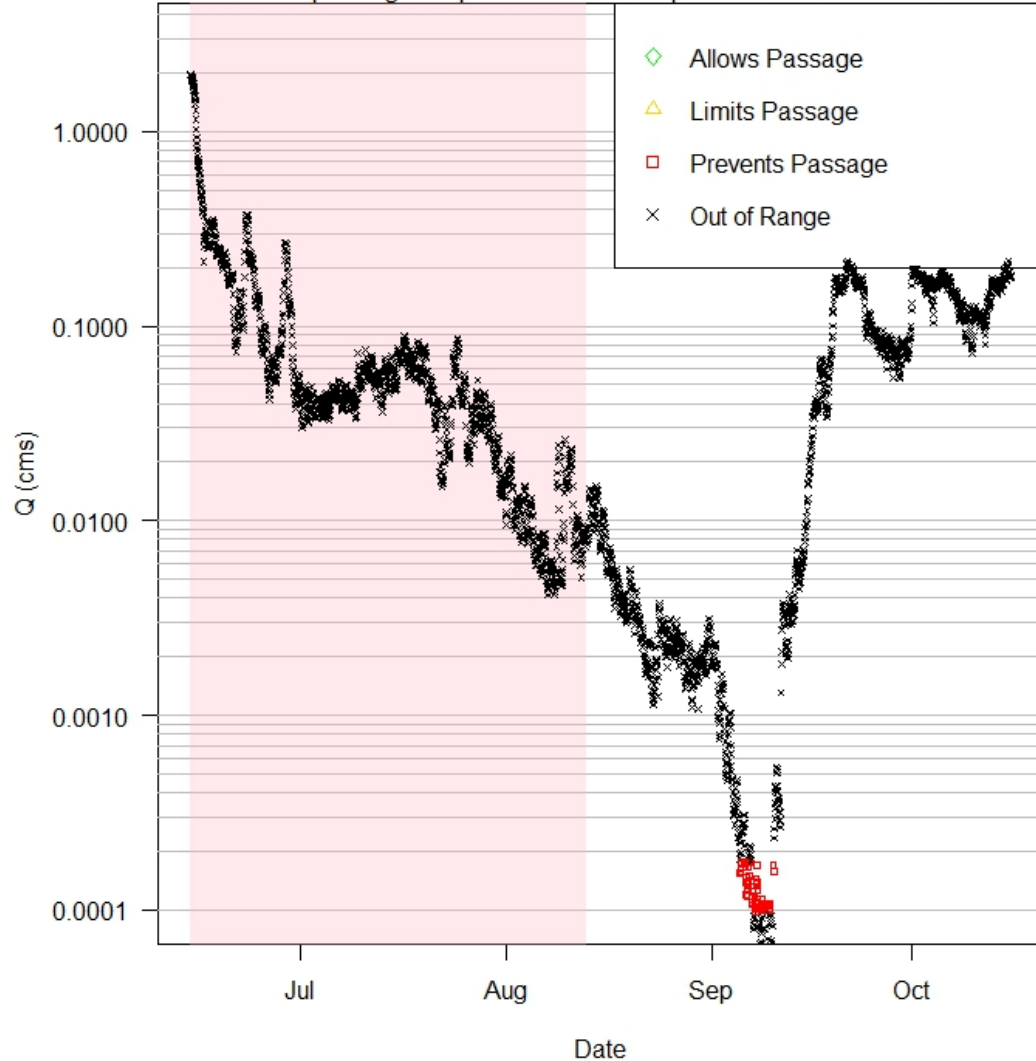
Note: Shaded pink region represents times with planks inserted in diversion.



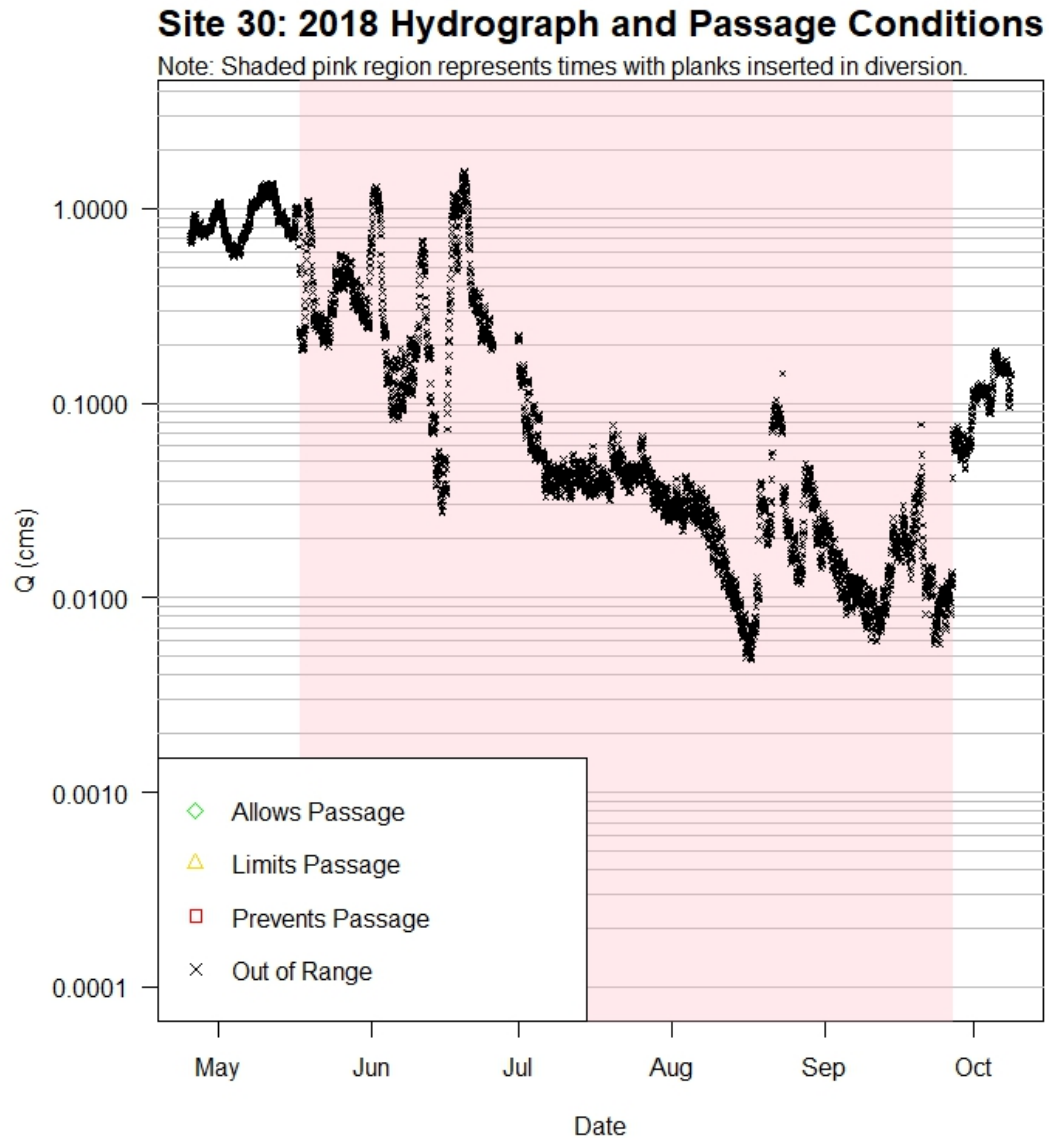
The above graph shows modelled passage windows superimposed on a hydrograph for site 29 during 2018 monitoring. The Denil fishway has a length of 6.10 meters and a slope of 11.6%. The downstream invert of this fishway was set such that it was always “submerged” (i.e. downstream end of fishway completely under water). Discharge was gauged hourly from April 27 to October 8, 2018. The estimated maximum and minimum discharges during this time were 88.674 and 0.100 cms. It was estimated that planks were inserted in the diversion from June 14 to September 22, 2018. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.

Site 30: 2017 Hydrograph and Passage Conditions

Note: Shaded pink region represents times with planks inserted in diversion.



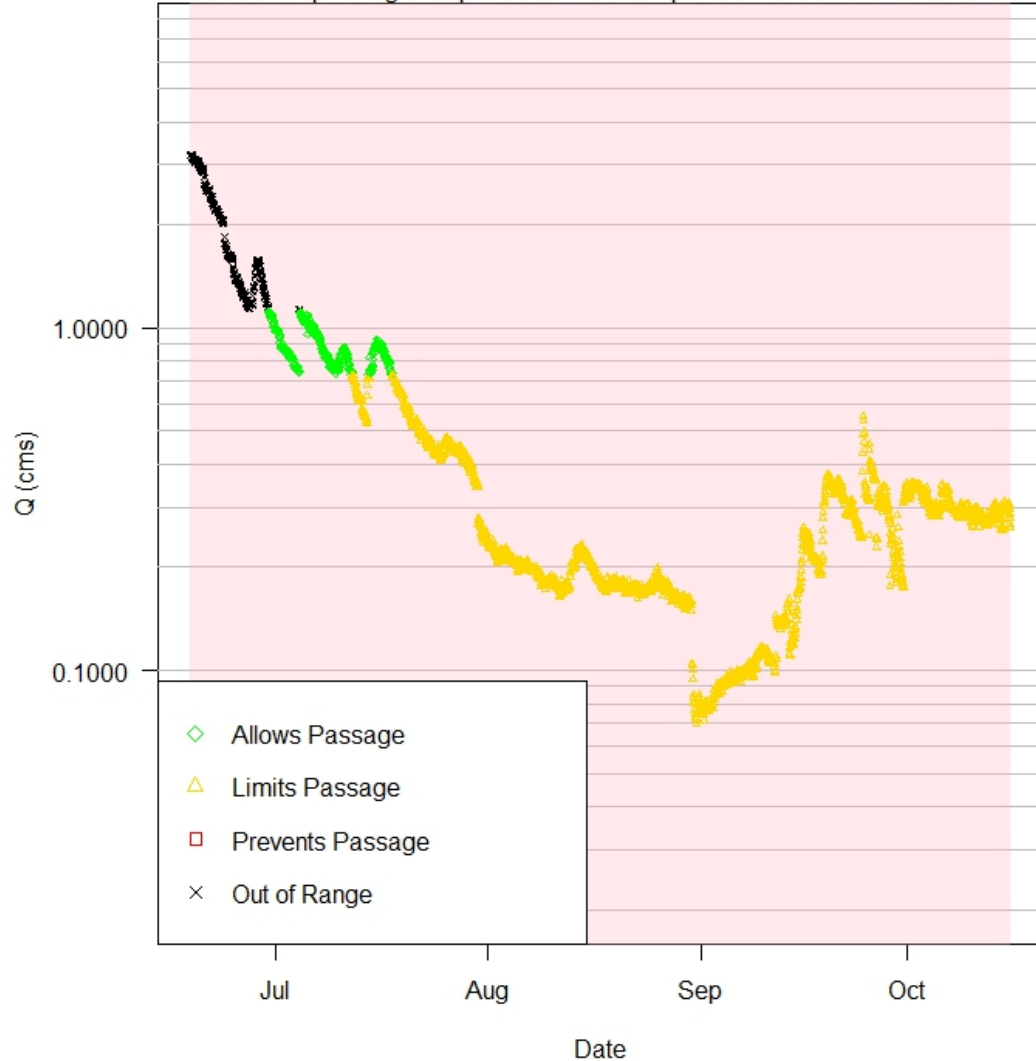
The above graph shows modelled passage windows superimposed on a hydrograph for site 30 during 2017 monitoring. The Denil fishway at site 30 has a length of 3.66 meters and a slope of 13.4%. The downstream invert of this fishway was set such that it was “submerged” (i.e. downstream end of fishway completely under water) most of the time. Discharge was gauged hourly from June 14 to October 15, 2017. The estimated maximum and minimum discharges during this time were 1.958 and 0.000 cms. It is estimated that planks were inserted in the diversion from the beginning of monitoring to August 13, 2017. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



The above graph shows modelled passage windows superimposed on a hydrograph for site 30 during 2018 monitoring. The Denil fishway at site 30 has a length of 3.66 meters and a slope of 13.4%. The downstream invert of this fishway was set such that it was “submerged” (i.e. downstream end of fishway completely under water) most of the time. Discharge was gauged hourly from April 25 to October 8, 2018. The estimated maximum and minimum discharges during this time were 1.538 and 0.005 cms. It is estimated that planks were inserted in the diversion from May 17 to September 26, 2018. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.

Site 55: 2017 Hydrograph and Passage Conditions

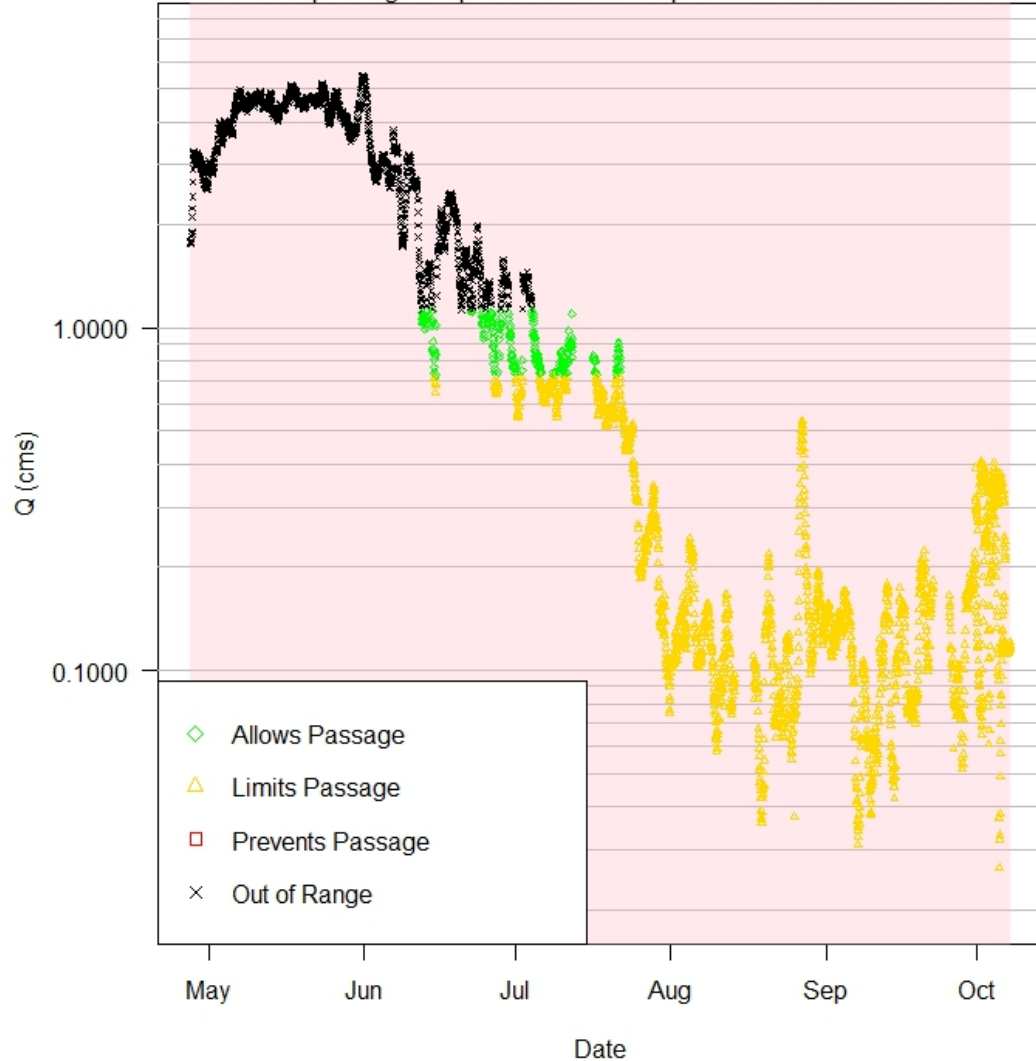
Note: Shaded pink region represents times with planks inserted in diversion.



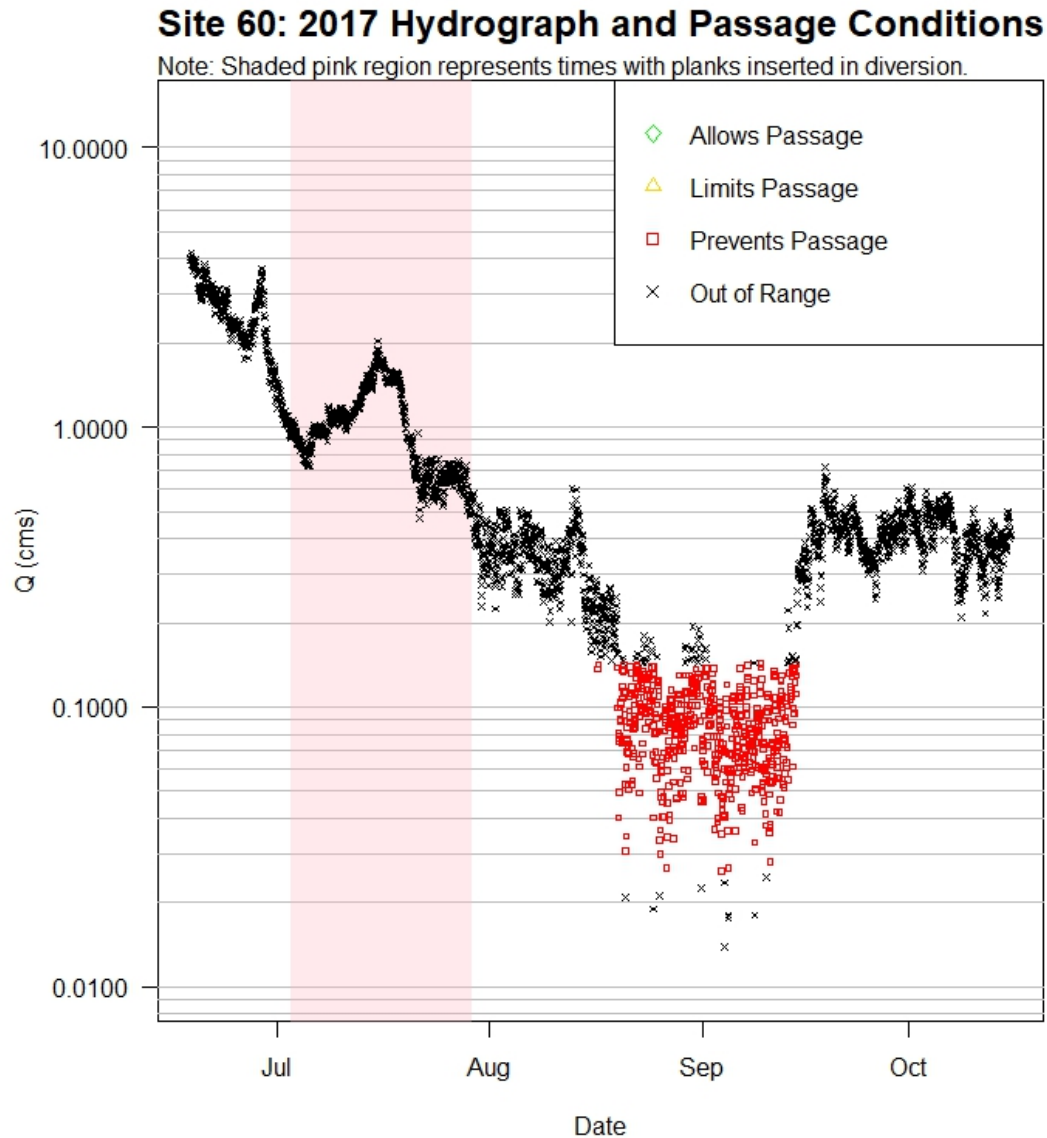
The above graph shows modelled passage windows superimposed on a hydrograph for site 55 during 2017 monitoring. The Denil fishway has a length of 3.66 meters and a slope of 10.7%. Discharge was gauged hourly from July 18 to October 15, 2017. The estimated maximum and minimum discharges during this time were 3.222 and 0.070 cms. Planks were inserted for the duration of monitoring. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.

Site 55: 2018 Hydrograph and Passage Conditions

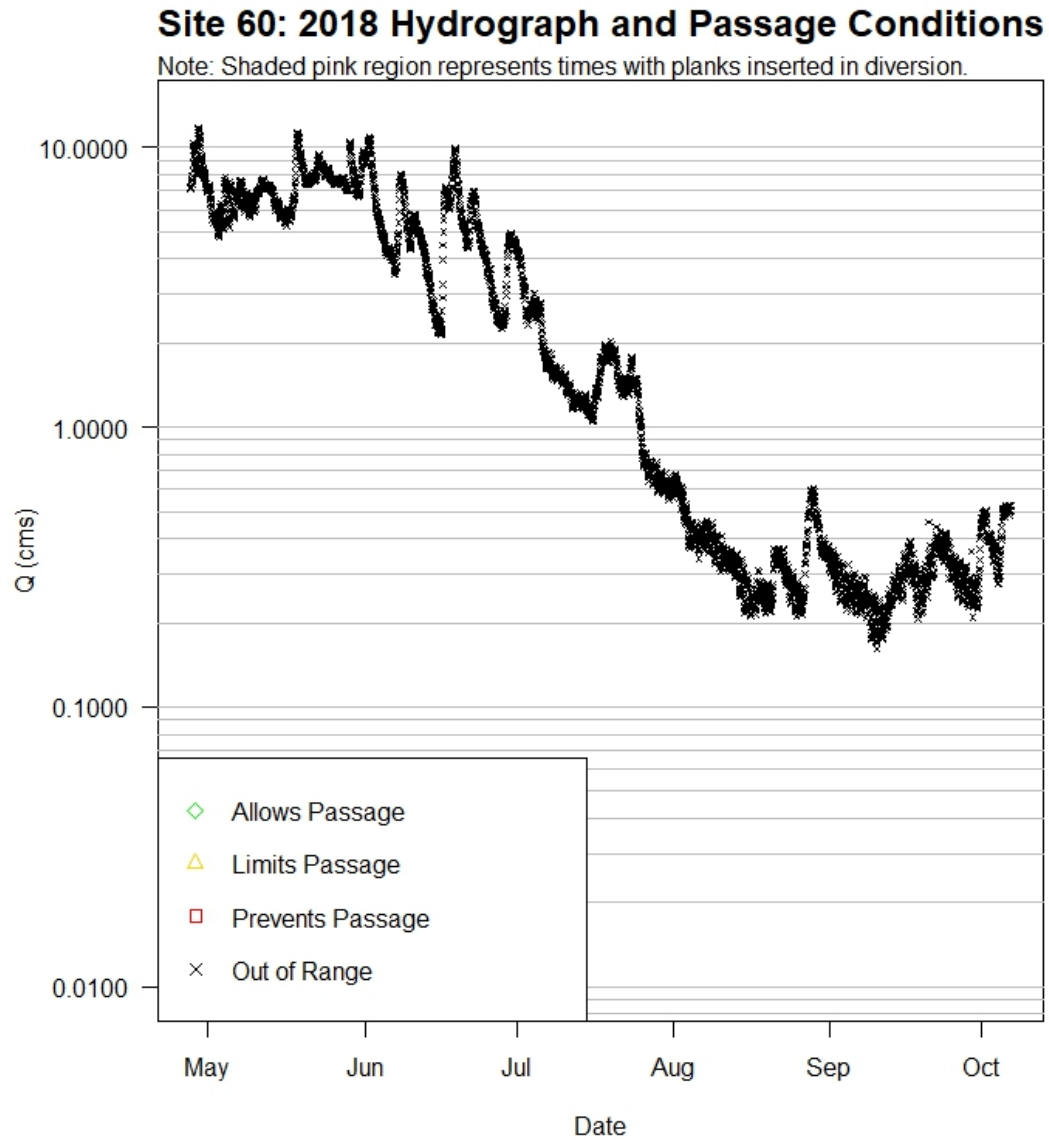
Note: Shaded pink region represents times with planks inserted in diversion.



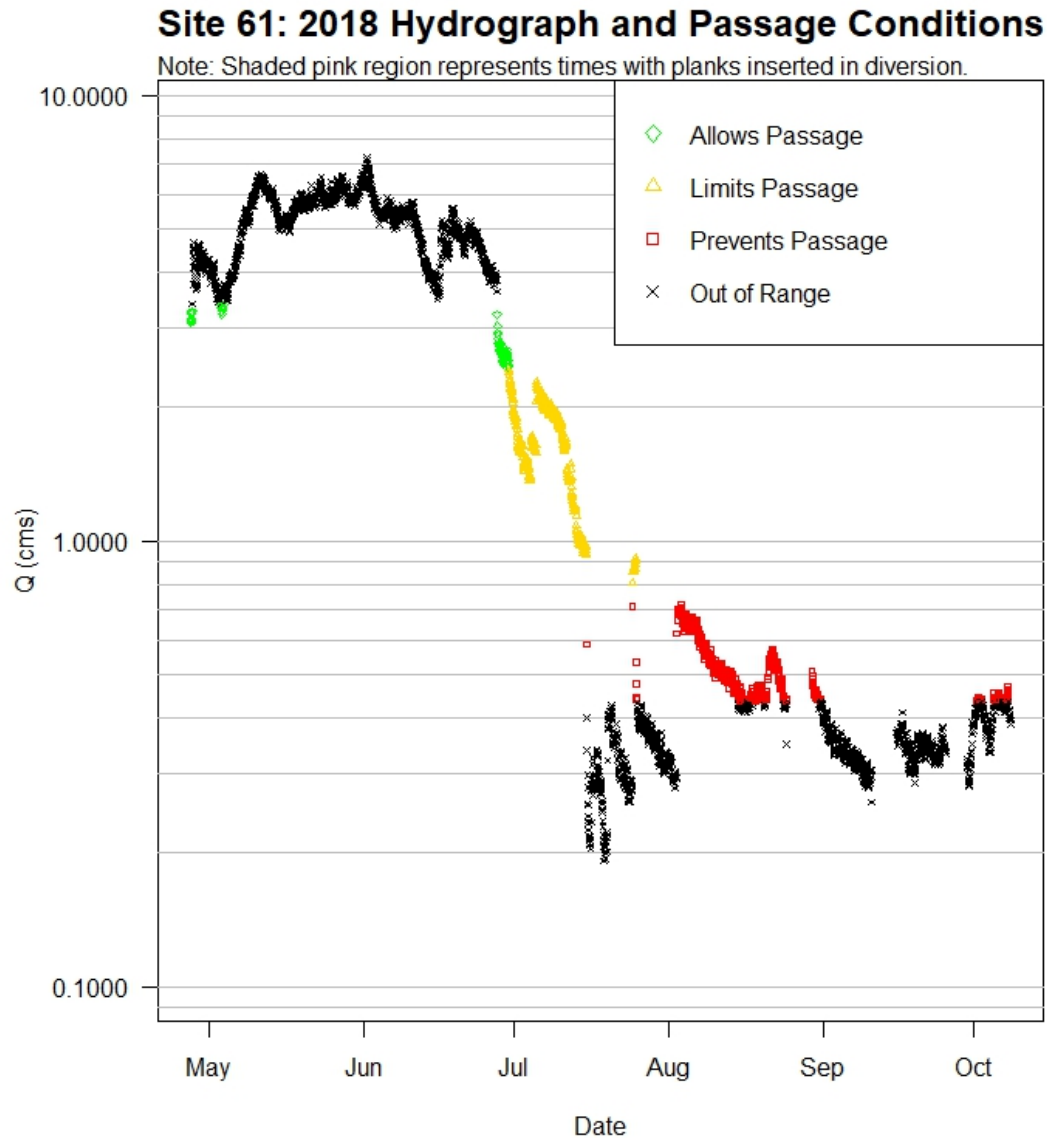
The above graph shows modelled passage windows superimposed on a hydrograph for site 55 during 2018 monitoring. The Denil fishway has a length of 3.66 meters and a slope of 10.7%. Discharge was gauged hourly from April 27 to October 7, 2018. The estimated maximum and minimum discharges during this time were 5.477 and 0.027 cms. Planks were inserted for the duration of monitoring. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



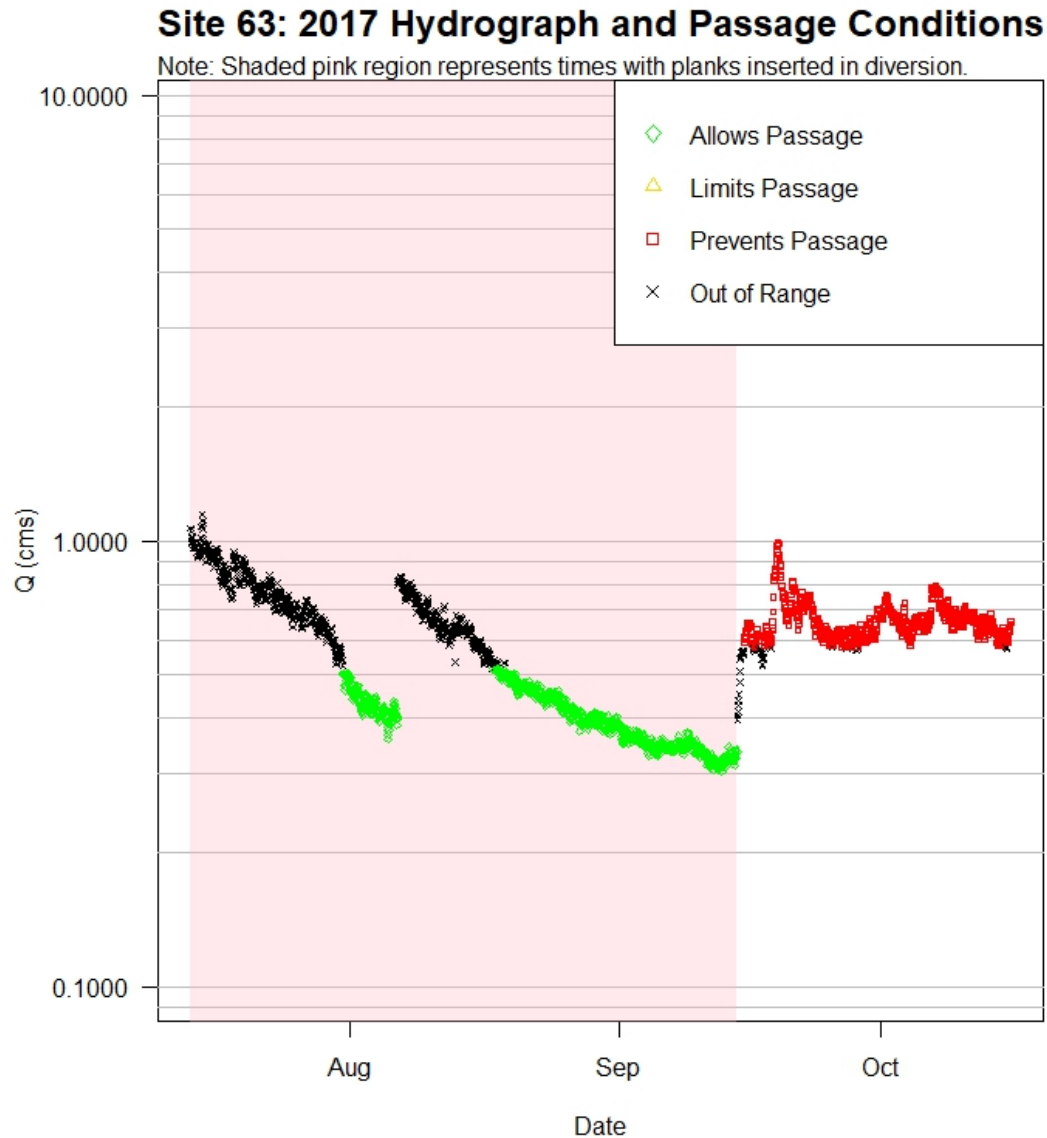
The above graph shows modelled passage windows superimposed on a hydrograph for site 60 during 2017 monitoring. The Denil fishway at site 60 has a length of 3.66 meters and a slope of 12.2%. The downstream invert of this fishway was set such that it was “submerged” (i.e. downstream end of fishway completely under water) most of the time. Discharge was gauged hourly from June 18 to October 15, 2017. The estimated maximum and minimum discharges during this time were 4.171 and 0.014 cms. It is estimated that planks were inserted in the diversion from July 3 to July 29, 2017. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



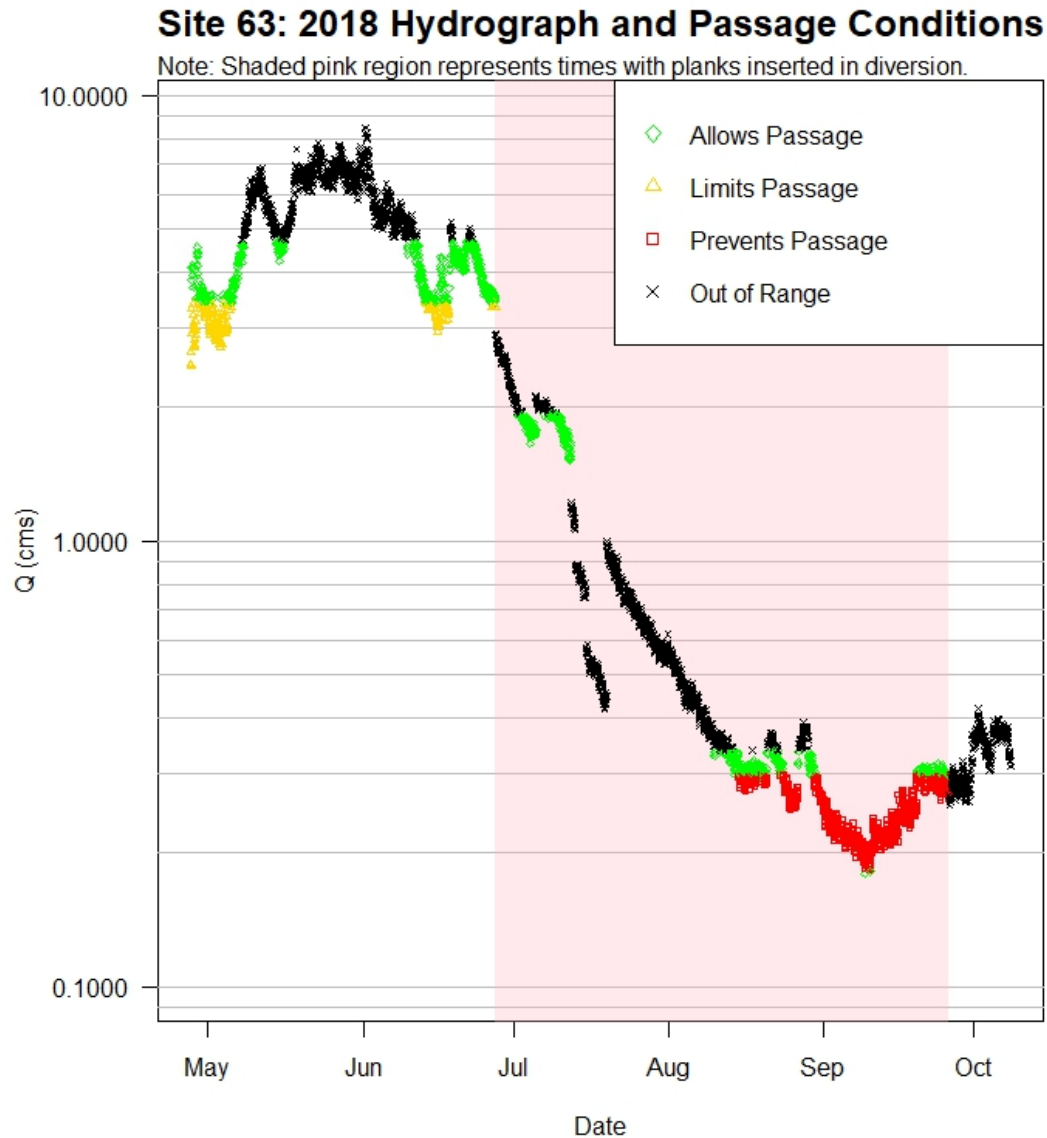
The above graph shows modelled passage windows superimposed on a hydrograph for site 60 during 2018 monitoring. The Denil fishway at site 60 has a length of 3.66 meters and a slope of 12.2%. The downstream invert of this fishway was set such that it was “submerged” (i.e. downstream end of fishway completely under water) most of the time. Discharge was gauged hourly from April 27 to October 6, 2018. The estimated maximum and minimum discharges during this time were 11.866 and 0.162 cms. Planks were never observed inserted in the diversion during 2018. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



The above graph shows modelled passage windows superimposed on a hydrograph for site 61 during 2018 monitoring (passage at this site was only modelled during 2018). The Denil fishway has a length of 3.66 meters and a slope of 15.6%. Discharge was gauged hourly from April 27 to October 8, 2018. The estimated maximum and minimum discharges during this time were 7.240 and 0.019 cms. Planks were never inserted in the diversion during monitoring. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



The above graph shows modelled passage windows superimposed on a hydrograph for site 63 during 2017 monitoring. The Denil fishway has a length of 3.66 meters and a slope of 13.3%. Discharge was gauged hourly from July 13 to October 15, 2017. The estimated maximum and minimum discharges during this time were 1.146 and 0.304 cms. It is estimated that planks were inserted in the diversion from the beginning of monitoring to September 14, 2017. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.



The above graph shows modelled passage windows superimposed on a hydrograph for site 63 during 2018 monitoring. The Denil fishway has a length of 3.66 meters and a slope of 13.3%. Discharge was gauged hourly from April 27 to October 8, 2018. The estimated maximum and minimum discharges during this time were 8.458 and 0.180 cms. It is estimated that planks were inserted in the diversion from June 27 to September 26, 2018. Two different operating conditions were observed during this time, one from June 27 to July 12, 2018 and the other from July 12 to September 26, 2018. For more information see Table 3.3, which presents the proportion of time passage conditions were observed at sites, and Figure 3.1, which shows a map of the study area.

HYDRAULIC DESIGN OF A DENIL FISHWAY AT PIN-AND-PLANK

IRRIGATION DIVERSIONS: A TECHNICAL REPORT

Contribution of Authors and Co-Authors

Manuscript in Chapter 4

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Contributions: Collected data, helped form conceptual basis of manuscript, developed design process, wrote manuscript.

Co-Author: Matt Blank Ph.D.

Contributions: Helped form conceptual basis of manuscript, contributed sound advice about design process development, provided hydraulic modeling insight, and reviewed and revised manuscript.

Co-Author: Kathryn Plymesser Ph.D.

Contributions: Reviewed and revised manuscript.

Co-Author: Kevin Kappenman

Contributions: Reviewed and revised manuscript.

Co-Author: Joel Cahoon Ph.D.

Contributions: Contributed sound advice about design process development, provided hydraulic modeling insight, reviewed and revised manuscript.

Manuscript Information

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Summary

The purpose of this technical report is to provide practitioners with design criteria and a procedure to aid in the hydraulic design of Denil fishways at pin-and-plank irrigation diversions. Denil fishways should operate effectively for upstream fish passage at a range of instream flows. The relationship between hydrology, the characteristics of the diversion structure, the surrounding topography/bathymetry, and the fishway invert elevations relative to the upstream and downstream water surfaces influence the hydraulic conditions within and around the fishway. The hydraulic conditions within Denil fishways are primarily controlled by upstream and downstream depth relative to the fishway, and slope.

The early phases of this design process involve declaring design criteria and collecting pertinent data for the design process. Fishway hydraulic conditions that facilitate passage are promoted by constraining physical, hydrologic, and hydraulic design parameters such as:

- fishway slope
- upstream and downstream depth
- depth ratio (DR)
- low design flow (LDF)
- fishway invert elevations
- fishway length

The design criteria presented herein were derived from a lab study investigating Arctic Grayling (*Thymallus arcticus*) passage efficiency through Denil fishways and a

field study of fishway effectiveness in the Big Hole River basin, Southwest Montana (Blank et al. forthcoming; Platt forthcoming 2019). The required, site-specific data include:

- hydrologic information about low flows
- topographic and bathymetric survey
- stage-discharge relationships to calibrate the hydraulic model
- physical dimensions of the diversion structure
- knowledge of hydraulic conditions favorable to upstream passage for the species of interest

Once design criteria are set and the required data collected, the next step is to construct a Hydraulic Engineering Center River Analysis System (HEC-RAS) hydraulic model of the site. The initial HEC-RAS model should be constructed to reflect as-built conditions and calibrated using stage-discharge relationships observed during data collection. Once calibrated, the model will be modified and used to determine how changing design parameters alters hydraulic conditions within and about the fishway.

Optimal elevations of the upstream and downstream ends of the fishway will be determined with the goal of maintaining sufficient depth for passage during low flow conditions. First, the downstream invert elevation of the fishway is determined using the as-built HEC-RAS model. This downstream invert elevation is paired with the lowest possible upstream invert resulting in the minimum-slope design. Then the hydraulic model is used to determine if the upstream depth, at the LDF and minimum fishway slope, meets design criteria. If the LDF at minimum-slope results in too low an upstream

depth, then sub-optimal passage conditions must be accepted at flows as low as the LDF or alternative fish passage options should be explored. If the low design flow and minimum-slope result in an upstream depth higher than the minimum criteria, then the optimum upstream invert elevation must be determined in subsequent steps. The HEC-RAS model is used in an iterative manner to model hydraulic conditions at various upstream invert elevations until all design criteria are met. Once all design criteria are met, a final design check is performed, and the hydraulic design is completed.

These steps are summarized in Figure 4.1, a conceptual flow chart detailing the design process.

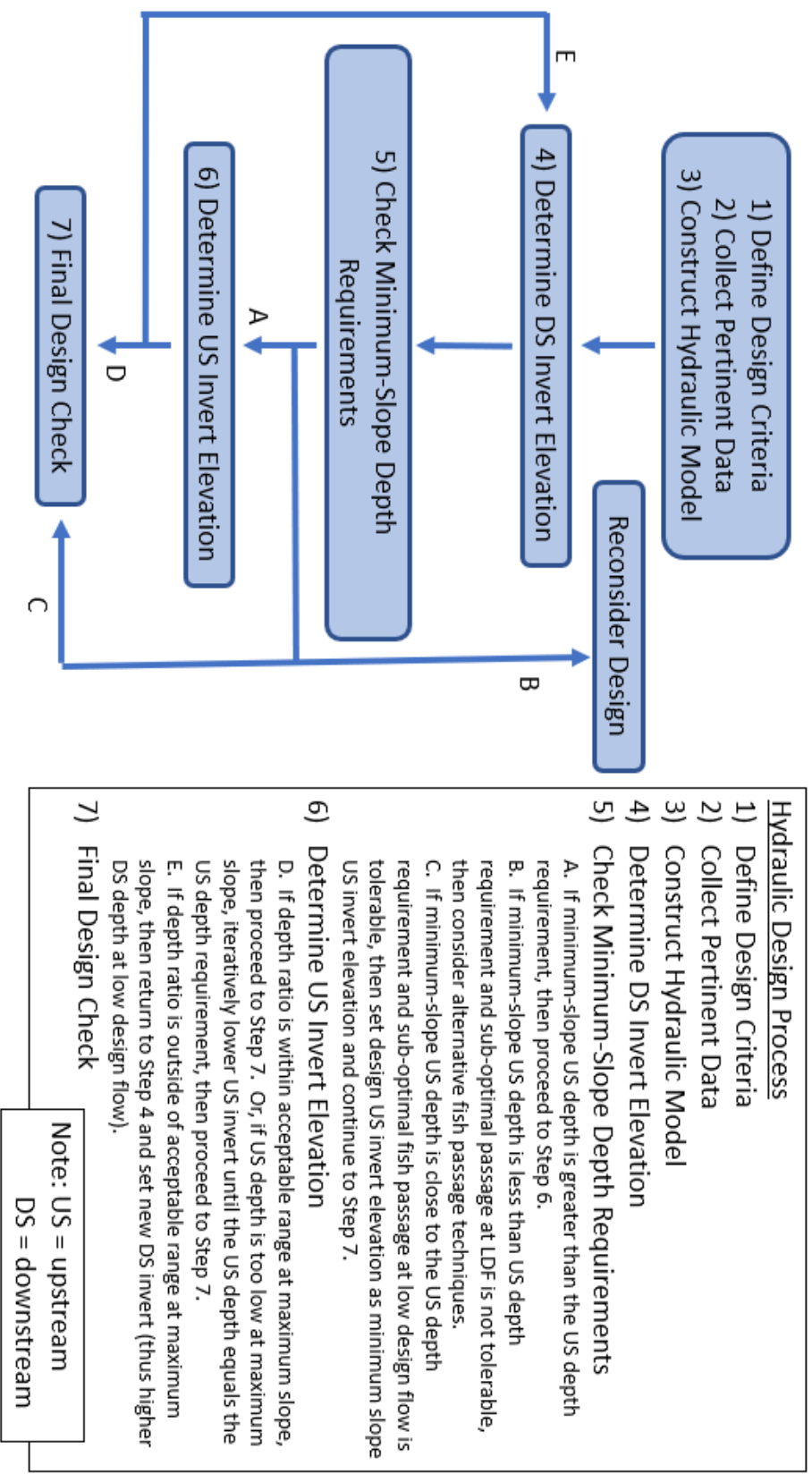


Figure 4.1: Flow chart summarizing design process.

Design Scenario

This design process will aid in the hydraulic design of Denil fishways at pin-and-plank diversion structures. The objective of this design is to provide effective upstream fish passage at a range of instream flows by ensuring passage at low flows. At low flows, it is important to provide fish passage while ensuring irrigators maintain sufficient head at their ditch headgate structures. If passage is ensured at low flows, fishways will likely provide high passage efficiencies at higher flows (Blank et al. forthcoming). This design process and associated design criteria are most applicable to promote upstream passage in small streams (i.e. baseflow between 0-15 cfs) for salmonids. Denil fishways can be retrofitted onto existing diversion structures or incorporated into the design of new ones. The hydraulic modeling aspect of this design process can be applied in any situation where modeling a Denil fishway is desired, but the design criteria are specific to provide effective passage for salmonid fishes in small streams.

Pin-and-plank diversion structures are a type of adjustable weir that allow the operator to control the dimensions of the weir by inserting or removing planks to temporarily raise the water surface at the point of diversion (Axness and Clarkin 2013). These structures are often preferred over permanent weirs because the structure can be operated without planks to reduce sediment build up in the headwater area, promote fish passage, and prevent damage due to debris or ice flow (MDNRC 2001). See Montana Stream Permitting: a Guide for Conservation District Supervisors and Others (2001), Section 4.2, for more information about these structures.

Two examples outlining this design process are found in Appendix 1. The example pin-and-plank diversions are located on Steel Creek, near Wisdom, Montana, and a Big Hole River channel upstream of Jackson, Montana. Data was collected at these sites as part of a field evaluation of Denil fishways in the area during the spring-fall 2017-2018 (Platt forthcoming 2019).

Step 1: Define Design Criteria

Before beginning data collection or the hydraulic design process, it is important to define design criteria. The design process presented herein is constrained by depth requirements relative to the fishway, slope of the fishway, the upstream invert of the ditch headgate structure, and length of available fishways. See Table 4.1 for a summary of the design criteria used. Note the design criteria associated with depths at both ends and the depth ratio are derived from a 2016 laboratory study involving Arctic Grayling and are applicable to salmonid fishes with similar swimming abilities (e.g. trout, whitefish, and grayling) (Blank et al. forthcoming). The LDF and minimum V-notch elevation are based on site-specific hydrologic and physical data.

Table 4.1: Summary of design criteria for Denil fishways at pin-and-plank irrigation diversions.

Design Parameter	Criteria	Comments
Upstream (US) Depth	Minimum is 1ft	Measured from US invert
Downstream (DS) Depth	Minimum is 1ft	Measured from DS invert
Depth Ratio (DR)	Between 1.0-1.5	DR = US Depth/DS Depth
Slope	Maximum of 16.7%	
V-notch Elevation	Cannot be lower than headgate invert	V-notch is located on upstream most baffle
Length	12ft	Based on previous studies
Low Design Flow (LDF)	Site dependent	~ Baseflow Discharge

The LDF is the lowest discharge for which the ladder is designed to meet the depth requirements that are associated with favorable hydraulic conditions for fish passage. It corresponds to baseflow discharge and is determined through hydrological analysis. The LDF is crucial for determining the invert elevations of the upstream and downstream ends of the fishway. Since upstream passage through Denil fishways is positively correlated with discharge through the fishway (Blank et al. forthcoming) providing passage at low flows will likely provide passage at higher flows as well.

The United States Fish and Wildlife Service (USFWS) (2017) suggests limiting the slope of Denil fishways designed to pass salmonids to 1:6 (16.7%). High fishway slopes up to 25% have been shown to negatively affect passage of American Shad through Denil fishways (Haro et al. 1999). Schmetterling et al. (2002) conducted a field study and observed similar passage efficiency for Westslope Cutthroat Trout, Bull Trout, and Brown Trout of various sizes through Denil fishways with slopes ranging from 9.6%-16.4%.

The minimum depth required at the upstream and downstream ends of the Denil at the LDF is 1.0 ft. The upstream depth is measured from the upstream invert and the downstream depth is measured from downstream invert. The depth requirements presented herein were derived from a laboratory study which investigated the effects of hydraulic variables on passage efficiency of Arctic Grayling through Denil fishways (Blank et al. forthcoming). Greater discharge through the fishway (and therefore depth at the upstream end) correlated with better passage, but high upstream depths paired with low downstream depths led to poor passage (Blank et al. forthcoming). In order to sustain favorable hydraulic conditions within the fishway for grayling and similarly capable Salmonids the minimum allowable upstream and downstream depths are 1.0 ft.

The depth ratio (DR) is the ratio of upstream depth divided by downstream depth, the acceptable DR range for this design is from 1.0 to 1.5. A logistic regression model was applied to grayling passage efficiency data and it was found that when DR = 1.0 the passage efficiency for 6 ft and 12 ft fishways, respectively, was 95% and 75% (Blank et al. forthcoming). Both passage efficiencies were about 100% at DR = 1.5 (Blank et al. forthcoming). However, at a DR = 2.33 (upstream depth = 1.17 ft, downstream depth = 0.50 ft) zero out of twenty fish passed the fishway over two trials, which may indicate that a too high a DR inhibits passage. In order to buffer the design against errors in hydraulic analysis or the observed trends in the lab study, the maximum value of depth ratio tolerated for this design process is 1.5 and the minimum is 1.0.

The length of the Denil fishway for this design is 12 ft, see Figure 4.2 for physical dimensions of Denil fishways pertinent to this design. During the 2017-2018 field study

in the Big Hole drainage, 11 out of 15 measured fishways were 12 ft long (Platt forthcoming 2019) and a 12 ft fishway was used in the 2016 lab study (Blank et al. forthcoming). Shorter ladders may also be used with this design procedure. For head differences between the upstream and downstream sides of the diversion greater than 2 ft it may be impossible to conform to all design criteria with a 12 ft ladder (12 ft ladder with a 2 ft drop would have a 16.7% slope). Longer ladders can be used to span higher head structures while maintaining an appropriate slope. Denil fishways with length up to 23-26 ft are common (Katopodis et al. 1997), resting pools can be incorporated into designs for longer ladders used to span high head barriers (Rajaratnam and Katopodis 1997). While Denil fishways of various sizes are commonly used, a 12 ft ladder is used for this design because the head difference at the diversions are small and this size has been previously studied.

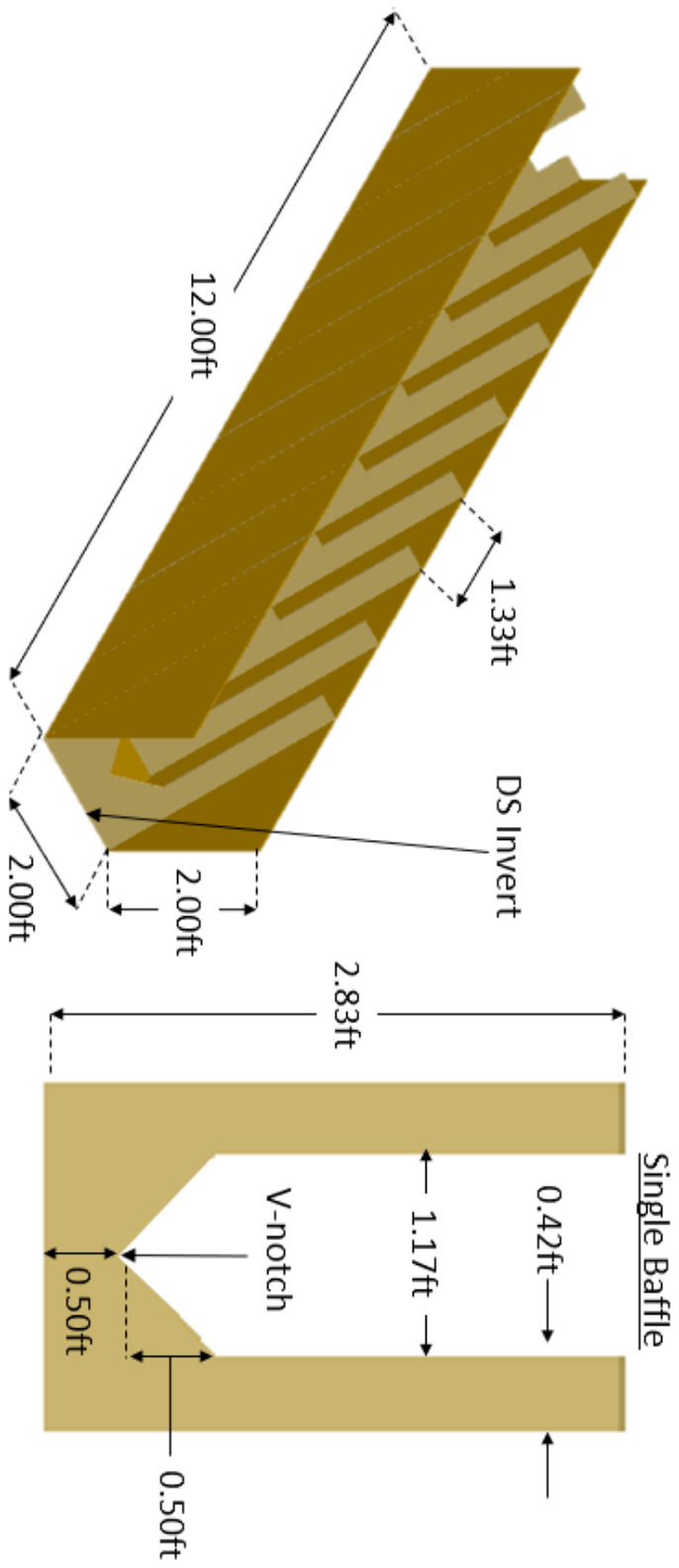


Figure 4.2: Schematics showing dimensions of “typical” Denil fishway used in example designs.

The elevation of the V-notch on the upstream-most baffle of the Denil must not be lower than the elevation of the upstream invert (i.e. hydraulic control) of the headgate structure which controls flow into the ditch. This is necessary because if the V-notch is below the headgate invert, the ditch would go dry before the stream as stream stage dropped. In the Big Hole Valley, some Denil fishways were installed such that the V-notch is lower than the ditch headgate invert; during field investigations (Platt forthcoming 2019), ladders with this characteristic were boarded up at the upstream end when low instream flows caused the stage to drop below the headgate invert. Setting the fishway V-notch level with, or above, the headgate invert ensures that there will be head at the headgate if the instream discharge is greater than zero upstream of the diversion. Additionally, if the ditch headgate structure is a sluice gate, or other flow controlling device, the flow partitioning between the ditch and stream can be controlled over a range of stages.

The stated design criteria were used for the examples in Appendix 1, but depending on site hydrologic and physical characteristics they may not be appropriate. For example, in streams with higher baseflow discharge, the discharge through the fishway may not be enough to promote fish attraction to the downstream end. In high-baseflow situations, the diversion weir must be arranged such that water can spill-over through gaps in the weir; this is done so that the upstream end of the fishway is not overtopped with water. For diversions with a large difference in head (i.e. >2 ft) a ladder length of 12 ft will not span the head difference and maintain an appropriate slope. If site constraints such as these exist, other design methods or passage structures may be more

appropriate. Design criteria presented herein are based on the best information available to the authors.

Step 2: Collect Pertinent Data

Data concerning baseflow hydrology, site topography/bathymetry, substrate roughness, observations of localized hydraulics (i.e. levees and ineffective flow areas), stage-discharge relationships at surveyed cross sections, and data concerning the hydraulics of Denil fishways will be needed to conduct this design process. Most of this data can be collected in one site visit with survey equipment. The LDF can be determined through hydrologic methods or analysis of local stream gauges. Roughness and hydraulic observations should be photographed for future reference.

Site-specific hydrologic data is used to determine the LDF (i.e. discharge observed downstream of the diversion structure under baseflow conditions). To determine the LDF, create a flow duration curve (FDC), if the site is gauged and several years of data are available or use regional hydrologic regression equations for ungauged locations. If creating an FDC, the LDF can correspond to a flow with 90-95% exceedance probability. For the examples in Appendix 1, the USGS Streamstats database was used to collect hydrologic information of the sites (USGS 2017). Streamstats uses regional hydrologic regression equations to determine flow rates associated with various recurrence intervals. This design process focusses on maintaining effective fish passage at the LDF.

The hydraulic model requires topographic and bathymetric data to represent the physical geometry of the stream. HEC-RAS models require topographic/bathymetric data to be configured into cross sections (Figure 4.3), with a point at each breakline, perpendicular to bulk flow velocities. Reach lengths between cross sections must be measured over the thalweg and each bank. The cross section representing the downstream boundary condition (DSBC) should be placed far enough downstream for flow development purposes. The DSBC could be set as a uniform flow boundary with an estimate of stream slope or a discharge-rating curve if available. The average stream slope can be estimated by surveying several of the lowest elevation points at each riffle crest and linearly regressing a slope from them. This slope will be used to estimate friction slope as discussed in Step 3. Additional cross sections should be surveyed, with appropriate spacing, between the DSBC and diversion structure. A cross section at a distance downstream of the diversion equal to the design length of the fishway should be surveyed so that the WSE at the downstream end of the fishway can be extracted from model results. The diversion structure and ditch headgate structure should be surveyed as if they were cross sections, including the upstream invert of the headgate structure. Another cross section should be established within 2 ft upstream of the diversion structure to infer the WSE at the upstream end of the fishway from the model. If possible, place this cross section between the point of diversion at the ditch headgate and the diversion structure. Specify a flow change at this cross section, where discharge upstream of this cross section includes the irrigated discharge, and discharge downstream of this cross section does not include irrigated water. Place a minimum of 2-3 additional

cross sections upstream of the diversion structure. For the examples in Appendix 1 a benchmark with arbitrary elevation of 5000 ft was used, all other elevations are relative to this point.

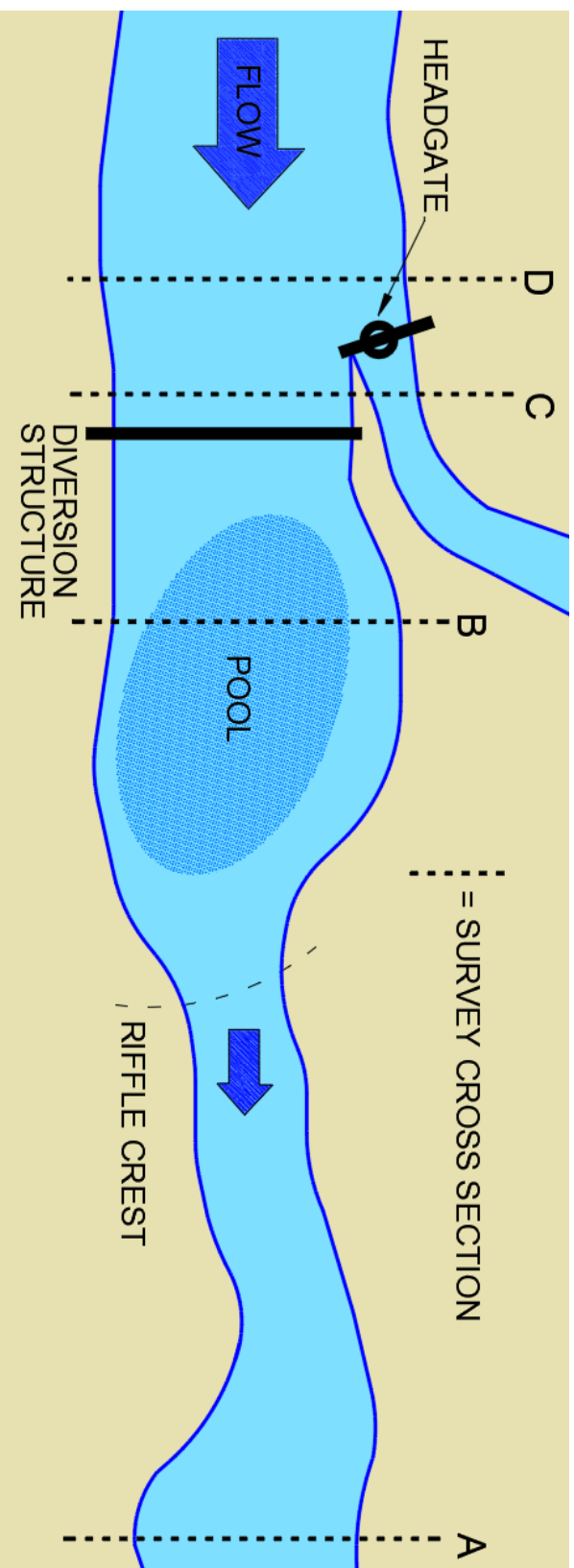


Figure 4.3. Site schematic showing typical relations of the stream, ditch, diversion structure, headgate, and select cross sections. Cross section “A” represents the DSBC, cross section “B” represents the cross section placed at the future location of the downstream end of the Denil, cross section “C” represents the cross section adjacent to the upstream end of the Denil, and cross section “D” represents the cross section upstream of the point of diversion.

In addition to topographic data, the HEC-RAS models require information concerning roughness, ineffective flow areas, levees, and stage-discharge data. HEC-RAS requires input of Manning's n roughness coefficients, determine these by visual inspection referencing Chow's (1959) *Open Channel Hydraulics* or other sources. Note locations within cross sections of qualitative hydraulic features like "ineffective flow areas" and features that act as levees as these may aid in the calibration of the model. Photographs can be helpful for recording these features, however the importance of these features may change with stream stage. After construction of the model, it is important to calibrate it using at least one stage-discharge data pair, this data can be obtained by measuring discharge (Turnipseed and Sauer 2010) in the stream and ditch the day of the topographic survey and surveying water surface elevation points on each bank of each cross section. For additional information about data needs for one-dimensional HEC-RAS models see the HEC-RAS Hydraulic Reference Manual (USACE 2016).

Another important data requirement for the hydraulic model are rating curves for Denil fishways, which relate discharge to upstream depth. These rating curves are important to build into the model in order to represent the fishway within HEC-RAS. The governing hydraulics of Denil fishways have been extensively studied. Five rating curve equations derived from laboratory studies were averaged to obtain the Denil rating curves used in the example HEC-RAS models (Katopodis 1992; Katopodis et al. 1997; Rajaratnam and Katopodis 1997; FAO/DVWK 2002; Odeh 2003). See Appendix 2 for rating curve equations. The rating curve equations are functions of the physical

dimensions of the fishways (e.g. baffle shape/dimensions, baffle spacing, chute dimensions, and slope) (Katopodis et. al. 1997).

Step 3: Construct Hydraulic Model

Once pertinent data is collected, the HEC-RAS hydraulic model should be constructed. It is assumed that readers have a working knowledge of HEC-RAS modeling and understand best practices associated with model development and calibration. The model will be one-dimensional and run as subcritical, steady flow for all required analyses. Two-dimensional modeling could be utilized, with the same information extracted from it as the one-dimensional model, but that is outside the scope of this document. Subcritical flow regimes should be modelled because streams rarely exhibit significant supercritical flow, if significant longitudinal stretches of supercritical flow are observed then this assumption should be reconsidered. For additional resources to aid in building these models see the HEC-RAS User Manual and Hydraulic Reference Guide (USACE 2016).

The HEC-RAS model geometry should initially be constructed to reflect existing conditions at the site so the model can be calibrated using the measured stage-discharge data pair(s). Aspects of the model that can be adjusted during calibration include Manning's n (within published ranges for substrates observed), ineffective flow areas, levees, and the weir coefficient associated with the diversion. The model should be calibrated until satisfactory agreement between surveyed water surface elevations and model-predicted water surface elevations at each cross section is reached. When the

model is modified iteratively during design, all calibration parameters will remain constant.

For models with only subcritical flow, a downstream boundary condition (DSBC) which specifies stage at the downstream most cross section given discharge is required. The DSBC of the model could be specified as uniform flow with an estimate of average friction slope, which can be estimated by using the channel slope described in Step 2. HEC-RAS will then use Manning's Equation for Uniform Flow to determine depth at the DSBC given discharge (USACE 2016). Since flow at this location is likely not uniform, provide ample space and cross sections between the DSBC and the study area so an accurate flow profile develops by the cross section downstream of the diversion. The DSBC could also be represented as a rating curve, this was done for the examples in Appendix 1 because the data was available from the Big Hole field study (Platt forthcoming 2019). Only the DSBC is required for subcritical flow modeling, if the model is run as a mix of subcritical and supercritical flow an upstream boundary condition (USBC) with specified stage-discharge relationship will also be required.

The diversion structure acts as the hydraulic control for the pool upstream, creating a backwater profile when operated as a weir. The diversion structure should be represented in the model as an "Inline Structure." The surveyed cross section of the diversion should be entered in the "Weir/Embankment Editor" and represented as a broad crested weir. During the design process, the diversion structure should be modelled as if it was backing up water, the examples in Appendix 1 model the diversion with 2 ft of planks inserted. Calibrate the stage-discharge relationship upstream of the inline

structure by adjusting the “weir coefficient.” This “weir coefficient” is used to calculate the stage-discharge relationship of the weir using the Standard Weir Equation and should range between 2.6-3.1 for broad crested weirs (USACE 2016).

The Denil fishway should be represented in the model as a gate on the inline structure. The cross-sectional area occupied by the gate should be blocked off by the inline structure weir/embankment, the gate will allow water to flow through it based on rating curves or other hydraulic governing equations (i.e. standard weir equation, submerged or free flowing sluice gate equations, etc.) (USACE 2016). The gate should have a width and height representing the geometry of the fishway used. The cross-sectional dimensions of Denils in the Appendix 1 examples were 2 ft by 2 ft, so the gate was represented with a width of 2 ft and a height of 2.5 ft (to account for some freeboard). Assign station and invert values (which control the location of the gate on the cross section) such that they reflect where the ladder would be on the diversion. Denil fishways should be placed on the far, opposite end of the diversion structure from the ditch headgate. Set the Denil “Gate Type” as “User Defined Curves” because this allows the user to specify the rating curve which governs the flow through the gate. The Denil rating curves in Appendix 2 should be averaged and used as the rating curve for the gate representing the Denil.

The HEC-RAS models will be modified during the design process as iterations are performed to determine the invert elevation of the fishway. By setting the downstream invert elevation and changing the upstream invert elevation, the slope of the fishway will change. This will change the associated discharge-rating curve and the

relationship between the elevation of the upstream invert and V-notch of the upstream-most baffle. See Appendix 3 for the equation relating the V-notch and upstream invert elevations of the fishway depending on physical dimensions and slope. For each modelled ladder slope a new rating curve must be calculated, and the gate invert and weir/embankment profile will need to be adjusted.

Step 4: Determine the Downstream Invert Elevation

The first step in utilizing the hydraulic model for the design process is to determine the downstream invert elevation of the fishway. This is determined from existing site conditions because, typically, fishway installation does not affect the WSE at the downstream end of the fishway. Run the HEC-RAS model with discharge equal to the LDF to determine the WSE at the cross section just downstream of the fishway. Then set the downstream invert 1 ft below the water surface (Figure 4.4). Once this WSE and invert elevation are obtained from the model it will be set for the remainder of the design process unless it is determined in Step 6 that the downstream depth should be increased.

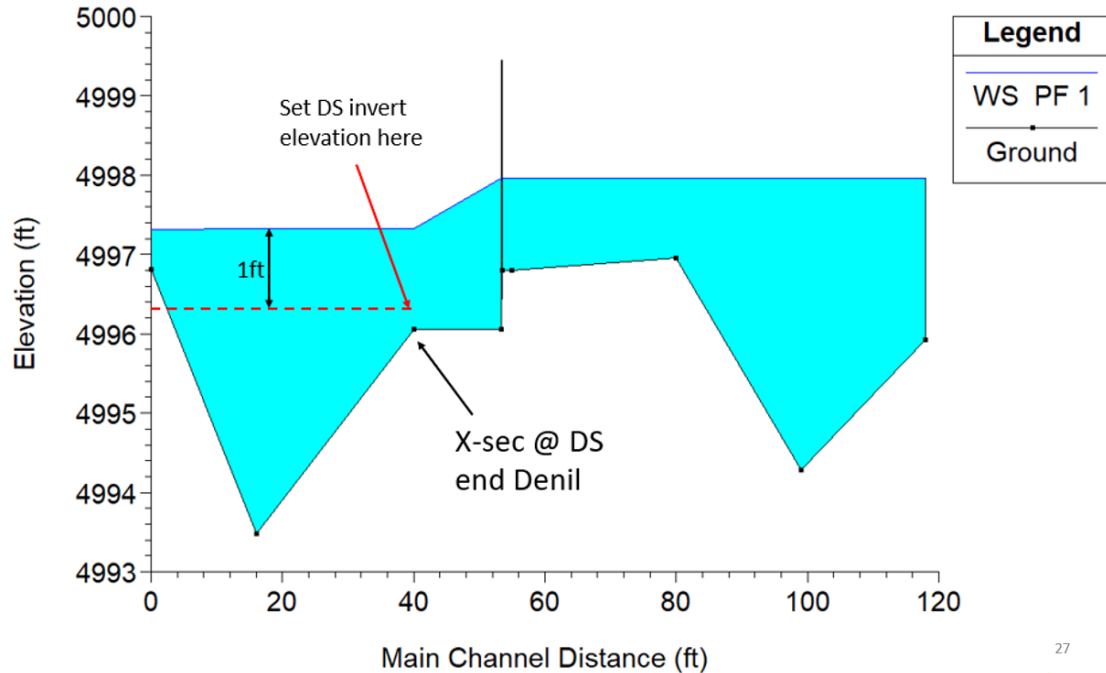


Figure 4.4. Side-view schematic of HEC-RAS model at Steel Creek site with discharge equal to the LDF. The schematic shows how to use model results (WSE at cross section just downstream of the diversion) to determine the downstream invert elevation.

Step 5: Check Minimum-Slope Depth Requirements

The minimum allowable slope for the fishway corresponds to the combination of the highest downstream invert elevation and lowest upstream invert elevation. The highest downstream invert elevation was determined during Step 4 and the lowest upstream invert elevation corresponds to the scenario where the upstream-most V-notch and ditch headgate invert are level. The rating curve for Denil fishways is dependent only on slope for ladders with otherwise identical dimensions, the minimum-slope would have the largest upstream depth possible, given discharge. The LDF modelled with the minimum-slope geometry will result in the highest possible upstream depth the fishway could experience at discharge equal to the LDF. The upstream depth modelled at LDF

and minimum-slope is compared to the requirement for upstream depth to determine the feasibility of using a Denil with specified length to provide favorable passage conditions.

The results of the minimum-slope model iteration will have one of two outcomes with different paths forward:

- 1) If the modelled upstream depth is less than the depth requirement specified in the design criteria, at LDF and minimum-slope, then it is impossible to meet this depth requirement. The LDF may not supply enough flow to provide adequate upstream depth so a decision is presented.
 - a. If sub-optimal passage is unacceptable, then reconsider using Denil fishways to provide passage at low flows because the flow available is not enough to provide acceptable passage efficiency using this fishway type.
 - b. If the modelled depth is close enough to the depth requirement, and sub-optimal passage can be tolerated at discharges as low as the LDF, then this minimum-slope situation should be the final hydraulic design. In this case, skip Step 6 (Determine Upstream Invert Elevation) and proceed directly to Step 7 (Final Design Check).
- 2) If the modelled upstream depth is greater than the depth requirement specified in the design criteria, then the LDF is enough flow to fill the upstream end of the fishway the required amount. In this case proceed to Step 6 (Determine Upstream Invert Elevation).

Step 6: Determine Upstream Invert Elevation

Once it has been determined that the LDF provides enough discharge to fulfil the upstream depth requirement at minimum-slope, the upstream invert elevation will be determined by utilizing the hydraulic model in an iterative fashion. For each iteration the model geometry will be modified, the model will be run at a discharge equal to the LDF, and the results will be compared to design criteria. For the first iteration, set the ladder slope equal to the maximum allowable slope (1:6 or 16.7%). Check the upstream depth and depth ratio, compare them to the design criteria provided. A decision will be made from the following options depending on the results of this model iteration:

- 1) If, at the LDF and maximum ladder slope, the upstream depth is greater than the design requirement and the DR is within acceptable range, then the upstream invert corresponding to the maximum-slope geometry will be the final design upstream invert elevation. In this case there is too much discharge at the LDF to optimize the upstream invert elevation (i.e. exactly meeting the upstream depth design requirement) but not so much discharge as to make the DR greater than the acceptable maximum.
- 2) If the DR is greater than the acceptable maximum when the LDF is modelled with the maximum ladder slope, then the downstream depth must be increased to decrease the depth ratio. To do this, return to Step 4 and increase the downstream depth by lowering the downstream invert elevation of the fishway. This decreases the upstream invert elevation corresponding to the maximum-slope but also

decreases the depth ratio given the same upstream depth. Proceed through Step 5 again after completing Step 4 because the change in the downstream invert elevation will increase the minimum-slope and may influence design decision making. In some cases, the length of the fishway may prevent the possibility of an acceptable DR due to slope constraints. If this occurs, a longer fishway should be selected for the design or the operating condition of the weir could be modified to allow more water to spill over, as opposed to flowing through the fishway. This option may involve trial and error in setting an appropriate downstream depth (and invert elevation), the goal is to settle on a downstream invert elevation that corresponds to a DR near the middle of the acceptable range.

- 3) If the upstream depth, modelled at the LDF and maximum ladder slope, is less than the required depth set in the design criteria, then the upstream invert elevation can be optimized such that the upstream depth requirement is met exactly. If this occurs, the upstream invert should be iteratively lowered in the model geometry, thus increasing the upstream depth for the same discharge. Iteratively lower the fishway until the upstream depth is equal to the design criteria depth.

After the design upstream invert elevation has been determined through following one of the three above options, proceed to Step 7 to check and finalize the design.

Step 7: Final Design Check

Once the upstream and downstream invert elevations are determined for which all relevant design criteria are within acceptable bounds, the hydraulic design process is over. It is important to check that the design criteria parameters are within acceptable bounds (see Table 1).

Fishway Operation and Maintenance

To ensure effective upstream fish passage through Denil fishways the fishways must be maintained periodically. Debris tends to build up at the upstream end of these fishways, especially if all or most of the instream flow is directed through them. Woody debris can get stuck in the baffles as it flows into the fishway and beavers have been observed to make dams at the upstream end. Debris must be removed from the fishway to prevent blockage. Operators should also remove substrate from the fishway if it fills up the space between baffles. Smaller fish species are known to use this inter-baffle space as refugia from high velocities (Schmetterling et al. 2002) and substrate clogging the bottom may change the hydraulics within the fishway in undesirable ways. Denil fishways are effective at facilitating upstream navigation of fish over low-head barriers but require some maintenance.

Maintaining discharge and upstream depth requirements at the fishway is essential for effective operation. The pin-and-plank diversion structure can be operated such that the hydraulic criteria established herein occur over a broad range of instream flows. For example, if upstream depth is too low, but water is spilling over the diversion weir,

consider adding more planks to back up more water and partition more flow into the fishway to increase the upstream depth; this will also increase head at the headgate. Another example of operating the diversion to increase fishway effectiveness is to remove planks from the diversion (i.e. decreasing the weir height and causing water to spill over) if the DR becomes unsuitable due to high upstream depth. Allowing water to spill over the weir decreases the upstream depth and DR, however this lowers head at the headgate. Using flow-controlling headgate devices (i.e. sluice gates) allows irrigators to compensate for small gains or losses in head and maintain irrigation flow targets. Proper ditch headgate settings are especially important for situations where the ditch headgate invert is lower than the fishway V-notch. More instream flow than desired may be diverted into the ditch if a flow controlling device at the ditch headgate isn't used to restrict flow into the ditch and supply head for the fishway.

Definitions and Abbreviations

cfs: abbreviation for “cubic feet per second.”

DR: acronym for “depth ratio.” Upstream depth divided by downstream depth.

DS: downstream.

DSBC: downstream boundary condition.

FDC: acronym for “flow duration curve.” A graphical representation of the likelihood a stream discharge will be exceeded in a given day.

ft: short for feet, the English unit of length measurement.

HEC-RAS: acronym for “Hydraulic Engineering Center River Analysis System.” HEC-

RAS is an open-source hydraulic modeling software developed by the United States Army Corps of Engineers.

Invert: the base interior level of the fishway. The upstream and downstream ends of the fishway have inverts associated with them.

LDF: acronym for “low design flow.” This is a design parameter that represents baseflow or the lowest instream discharge for which passage is ensured through the design process.

V-notch: refers to the lowest point on the baffle situated furthest upstream in the Denil fishway. Each baffle has a V-notch, but the elevation of the one on the upstream-most baffle is used as a design parameter.

US: upstream.

USBC: upstream boundary condition.

USFWS: acronym for “United States Fish and Wildlife Service.”

USGS: acronym for the “United States Geological Survey.”

WSE: acronym for “water surface elevation.”

Disclaimer

This design procedure is intended to be used by persons who have appropriate experience and expertise in fish passage and hydraulic design. It was compiled by the authors and other subject experts based on observations and data collected during a field

assessment of Denil fishways in the Big Hole Valley, Montana, laboratory fish passage data, and expertise gained through experience.

The authors accept no responsibility for any inaccuracies or information perceived as misleading in this document. The content of this document was created by the authors and does not necessarily reflect the views of Montana State University. Users are strongly recommended to consider the relevance of this design process to the project of interest and independently confirm all information within it.

References

Axness DS and Clarkin K. 2013. Planning and layout of small-stream diversions. [edition unknown]. San Dimas, CA: USDA Forest Service National Technology & Development Program. [report number unknown].

Blank M, Kappenman K, Banner K, Ryan E. Forthcoming. Arctic Grayling (*Thymallus arcticus* Pallas) and Denil fishways: a study to determine how water depth affects passage success.

Chow VT. 1959. Open-Channel Hydraulics. Reprint of 1959 edition. Caldwell NJ: The Blackburn Press.

FAO/DVWK. 2002. Fish passes- design, dimensions and monitoring. [edition unknown]. Rome, Italy: Food and Agricultural Organization of the United Nations. [report number unknown].

Haro A, Odeh M, Castro-Santos T, Noreika J. 1999. Effect of slope and headpond on passage of American shad and Blueback herring through simple Denil and deepened Alaska Steeppass fishways. *N Am J Fish Man* 19(1): 51-58.

Katopodis C. 1992. Introduction to fishway design. [edition unknown]. [publisher unknown]. [report number unknown].

Katopodis C, Rajaratnam N, Wu S, Tovell D. 1997. Denil fishways of varying geometry. *J Hydraul Eng* 123(7): 624-631.

MDNRC Conservation Districts Bureau. 2001. Montana stream permitting: a guide for conservation district supervisors and others. [edition unknown]. Helena MT: MDNRC. [report number unknown].

Odeh M. 2003. Discharge rating equation and hydraulic characteristics of standard Denil fishways. *J Hydraul Eng* 129(5): 341-348.

Platt NC. Forthcoming 2019. Designing and assessing Denil fishways using hydraulic modeling-based approaches [thesis]. Bozeman MT: Montana State University.

Rajaratnam N and Katopodis C. 1997. Hydraulics of resting pools for Denil fishways. *J Hydraul Eng* 123(7): 632-638.

Schmetterling DA, Pierce RW, Liermann BW. 2002. Efficacy of three Denil fish ladders for low-flow fish passage in two tributaries to the Blackfoot River, Montana. *N Am J Fish Man* 22(3): 929-933.

Turnipseed DP and Sauer VB. 2010. Discharge measurements at gauging stations: USGS techniques and methods book, chap. A8. 3rd edition. Reston VA: USGS. [unknown report number].

US Army Corps of Engineers (USACE). 2016. HEC-RAS river analysis system hydraulic reference manual. Version 5.0. Davis CA: USACE Institute for Water Resources Hydrologic Engineering Center. [unknown report number].

US Army Corps of Engineers (USACE). 2016. HEC-RAS river analysis system user's manual. Version 5.0. Davis CA: USACE Institute for Water Resources Hydrologic Engineering Center. [unknown report number].

United States Fish and Wildlife Service (USFWS). 2017. Fish passage engineering design criteria. [edition unknown]. Hadley MA: USFWS Northeast Region R5. [report number unknown].

United States Geological Survey (USGS) StreamStats [internet]. 2017. Version 4. Reston VA: USGS; [updated 2017, cited February 11, 2019].

AppendicesAppendix 1: Example Designs

Some abbreviations:

- US= upstream
- DS= downstream
- MAX= maximum
- MIN= minimum
- WSE= water surface elevation
- LDF= low design flow
- DR= depth ratio
- ELEV= elevation

Hydraulic Design Process Example: Steel Creek Diversion

In this example the existing Denil fishway will be re-designed.



(above) Steel Creek diversion, operated open (no planks inserted), during baseflow conditions. The existing Denil fishway is shown on the river left side of the diversion.

Step 1: Define Design Criteria

General design criteria explained in text (see Step 1). LDF determined by using the USGS Streamstats website to obtain the “July-October 14-day, 5-year low flow.” MIN V-notch elevation is equal to the elevation of the headgate invert.

Site Specific Design Criteria

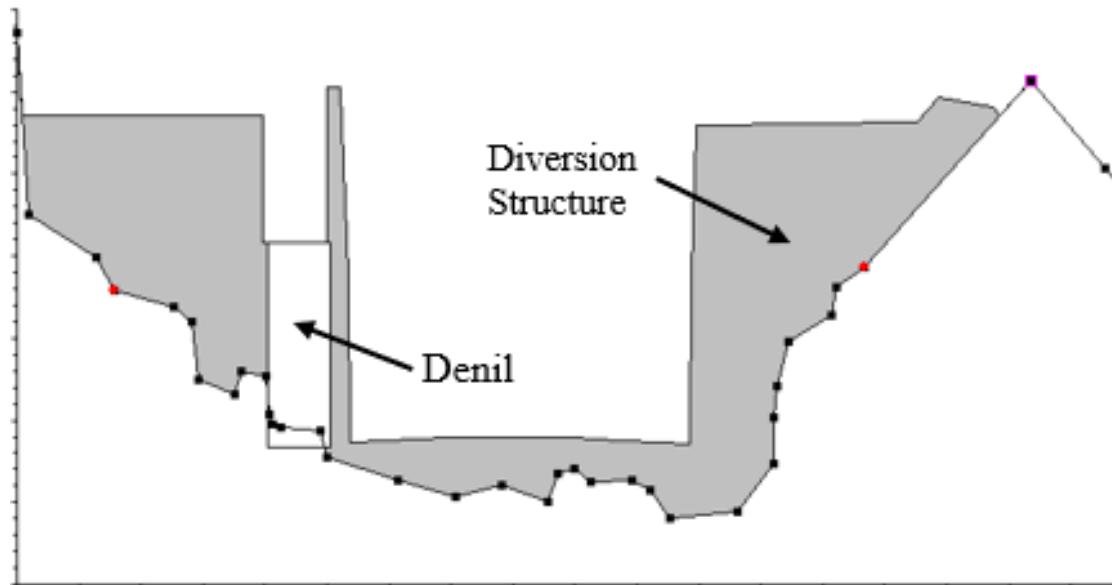
Low Design Flow (LDF) (cfs)=	0.83
MIN V-Notch Elevation (ft) =	4997.25

Step 2: Collect Pertinent Data

Data for this example was collected during Summer 2017. See “Step 2: Collect Pertinent Data” within text for more information regarding data collection.

Step 3: Construct Hydraulic Model

The HEC-RAS model is initially constructed to reflect existing conditions at the site so that it can be calibrated using stage-discharge data collected during site visit.



(above) HEC-RAS inline structure representing existing conditions at the Steel Creek diversion, with no planks inserted (i.e. operated open). Note the shaded gray region represents the diversion structure “weir/embankment” and the white rectangle “user defined gate” towards the left side of the diversion represents the fishway.

Step 4: Determine Downstream Invert Elevation

Run the HEC-RAS model using discharge equal to the LDF and the geometry representing as-built conditions. Then, set the DS Invert to be 1ft lower than the WSE at the DS end of the fishway, per design criteria.

DS WSE (ft) =	4997.32
DS Invert ELEV (ft) =	4996.32

Step 5: Check Minimum-Slope Depth Requirements

The MIN slope corresponds to the highest possible DS invert (i.e. DS Invert ELEV (ft) from Step 4) with the lowest possible US invert (i.e. V-notch has same elevation as US invert of ditch headgate structure). Run the HEC-RAS model with discharge equal to the LDF and check if US depth requirement is met.

Two possible outcomes:

1. If minimum-slope US depth > US depth requirement, then proceed to Step 6.
2. If minimum-slope US depth < US depth requirement, accept sub-optimal passage at LDF or choose alternative fish passage technique.

See below for results and interpretation.

ELEV Ditch Headgate US Invert (ft)=	4997.25
MIN ELEV of Fishway US Invert (ft) =	4996.96
Ladder Length (ft) =	12
MIN Slope (ft/ft) =	0.052
US WSE at MIN Slope (ft) =	4997.95
US Depth (Over invert) (ft) =	0.99
Depth Ratio (DR) (ft/ft) =	0.99

Recall this offset is a function of ladder slope and geometry. See Appendix 3.

$$\text{US Depth} = 0.99\text{ft} < 1.00\text{ft (Min US Depth)}$$

Interpreting the results: accept sub-optimal passage at LDF and proceed to Step 7. In this case, the largest US depth that can be afforded at the LDF is 0.99ft, which is close enough to the design requirement of 1.00ft.

Step 6: Determine Ideal Upstream Invert Elevation

Skip this step. Results from Step 5 indicate that an upstream depth that meets the requirement is not possible. And steepening slope will only decrease the US depth.

Step 7: Final Design Check

State the final design elevations and slope. Check that all design criteria are met.

Final Design Elevations & Slope	
US Invert ELEV (ft) =	4996.96
DS Invert ELEV (ft) =	4996.32
Slope (ft/ft)=	0.052

Depths at LDF	
US Depth (ft)=	0.99
DS Depth (ft)=	1
DR (ft/ft) =	0.99

Hydraulic Design Process Example: Big Hole River Diversion

In this example the existing Denil fishway will be re-designed.



(above) Big Hole River diversion being operated as a weir to increase head at the point of diversion. The discharge through the site at the time the photo was taken was measured at 30.09cfs, significantly higher than baseflow.

Step 1: Define Design Criteria

General design criteria explained in text (see Step 1). LDF determined by using the USGS Streamstats website to obtain the “July-October 14-day, 5-year low flow.” MIN V-notch elevation is equal to the elevation of the headgate invert.

Site Specific Design Criteria:

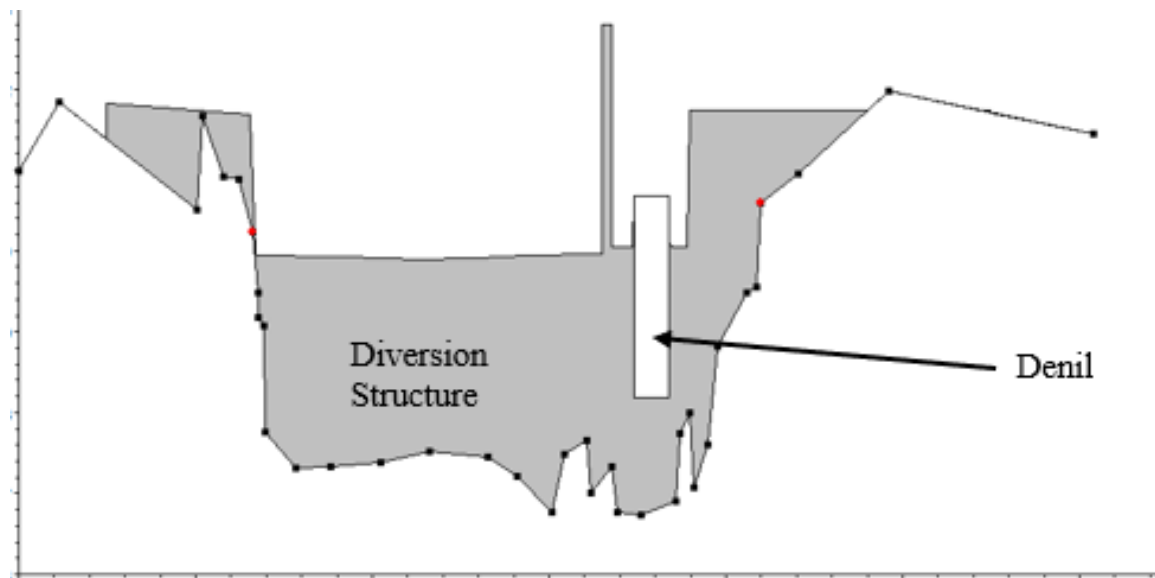
Low Design Flow (LDF) (cfs)=	8.81
MIN V-Notch Elevation (ft) =	4997.76

Step 2: Collect Pertinent Data

Data for this example was collected during Summer 2017. See “Step 2: Collect Pertinent Data” within text for more information regarding data collection.

Step 3: Construct Hydraulic Model

The HEC-RAS model is initially constructed to represent existing conditions at the site so that it can be calibrated using stage-discharge data collected during site visit.



(above) HEC-RAS inline structure representing finalized design conditions at the Big Hole River diversion, with 2ft of planks inserted into the diversion. Note the shaded gray region represents the diversion structure "weir/embankment" and the white rectangle "user defined gate" towards the right side of the diversion represents the fishway.

Step 4: Determine Downstream Invert Elevation (1st iteration)

Run the HEC-RAS model using discharge equal to the LDF and the geometry representing as-built conditions. Then, set the DS Invert to be 1ft lower than the WSE at the DS end of the fishway, per design criteria.

DS WSE (ft) =	4997.18
DS Invert ELEV (ft) =	4996.18

Step 5: Check Minimum-Slope Depth Requirements

The minimum-slope corresponds to the highest possible DS invert (i.e. DS Invert ELEV (ft) from Step 4) with the lowest possible US invert (i.e. same elevation as US invert of ditch headgate structure). Model minimum-slope scenario with LDF and check if US depth requirement is met.

Two possible outcomes:

1. If minimum-slope US depth > US depth requirement, then proceed to Step 6.
2. If minimum-slope US depth < US depth requirement, accept sub-optimal passage at LDF or choose alternative fish passage technique.

See below for results and interpretation:

ELEV Ditch Headgate US Invert (ft)=	4997.76
MIN ELEV of Fishway US Invert (ft) =	4997.51
Ladder Length (ft) =	12
MIN Slope (ft/ft)=	0.111
US WSE at MIN Slope (ft) =	4999.81
US Depth (Over invert) (ft) =	2.30
Depth Ratio (DR) (ft/ft) =	2.3

$$\text{US Depth} = 2.30\text{ft} > 1.00\text{ft (Minimum US Depth)}$$

Interpreting the results: since the modelled upstream depth at LDF and minimum-slope configuration is greater than the required depth per design criteria proceed to Step 6 to determine the fishway upstream invert elevation.

Step 6: Determine Ideal Upstream Invert Elevation

Run the HEC-RAS model with discharge equal to the LDF through a geometry representing the maximum allowable fishway slope. The initial maximum slope corresponds to the DS invert from Step 4 and an US invert calculated using the DS invert and maximum slope (16.7%).

This model iteration will result in one of three scenarios:

1. US depth > required US depth, DR within range
2. US depth > required US depth, DR greater than maximum allowable
3. US depth < required US depth

See below for results and interpretation.

1st MAX Slope Iteration Results

MAX Slope (ft/ft) =	0.167
DS Invert ELEV (ft) =	4996.18
DS Depth (ft) =	1.00
US Invert ELEV (ft) =	4998.18
V-notch ELEV (ft) =	4998.37
US WSE (ft) =	5000.04
US Depth (ft) =	1.86
DR (ft/ft) =	1.86

$$DR = 1.86 > 1.5 \text{ (Maximum DR)}$$

Interpreting the results: the US depth is greater than the minimum allowable, but the DR is greater than the maximum allowable DR. Return to Step 4 and decrease the DS Invert ELEV to increase the DS Depth.

Step 4: Determine Downstream Invert Elevation (2nd iteration)

Increase the DS Depth by lowering the DS Invert Elev. The DS WSE from the first Step 4 iteration will remain constant, the model does not have to be run again.

Assume a new DS Depth = 1.60ft.

DS WSE (ft) =	4997.18
DS Invert ELEV (ft) =	4995.58

Step 5: Check Minimum-Slope Depth Requirements (2nd iteration)

Check the minimum-slope US Depth requirement again, results for this step change for this iteration because the DS Invert ELEV was lowered and minimum-slope increased.

See below for results and interpretation.

ELEV Ditch Headgate US Invert (ft)=	4997.76
MIN ELEV of Fishway US Invert (ft) =	4997.57
Ladder Length (ft) =	12
MIN Slope (ft/ft)=	0.166
US WSE at MIN Slope (ft) =	4999.63
US Depth (Over V-notch) (ft) =	2.06
Depth Ratio (DR) (ft/ft) =	1.29

US Depth = 2.06ft > 1.00ft (Minimum US Depth)

Interpreting the results: since the modelled US depth at LDF and minimum-slope (2nd iteration) configuration is greater than the required depth per design criteria proceed to Step 6 to determine the fishway upstream invert elevation.

Step 6: Determine Ideal Upstream Invert Elevation (2nd iteration)

Run the HEC-RAS model with discharge equal to the LDF and model geometry corresponding to the new maximum slope scenario (with new DS Invert ELEV from 2nd iteration of Step 4) and interpret the results.

2nd MAX Slope Iteration Results

MAX Slope (ft/ft) =	0.167
DS Invert ELEV (ft) =	4995.58
DS Depth (ft) =	1.60
US Invert ELEV (ft) =	4997.58
V-notch ELEV (ft) =	4997.78
US WSE (ft) =	4999.64
US Depth (ft) =	2.06
DR (ft/ft) =	1.29

US Depth (ft) = 2.06 > 1.00 (Minimum US Depth (ft))

DR = 1.29 which is within the bounds of DR specified in design criteria.

Interpreting the results: since the maximum slope corresponding with the DS Depth = 1.60ft results in an US Depth greater than the minimum required and the DR is within the acceptable range this model iteration concludes the hydraulic design. Proceed to Step 7.

Step 7: Final Design Check

State the final design elevations and slope. Check that all design criteria are met.

Final Design Elevations & Slope

US Invert ELEV (ft) =	4997.58
DS Invert ELEV (ft) =	4995.58
Slope (ft/ft)=	0.167

Depths at LDF

US Depth (ft)=	2.06
DS Depth (ft)=	1.60
DR (ft/ft) =	1.29

Appendix 2: Denil Discharge Rating Curve Equations

h^* = upstream depth (from V-notch) (m)

I = fishway slope (m/m)

h_a = fishway height (m)

b = fishway width (m)

b_a = slot width (m)

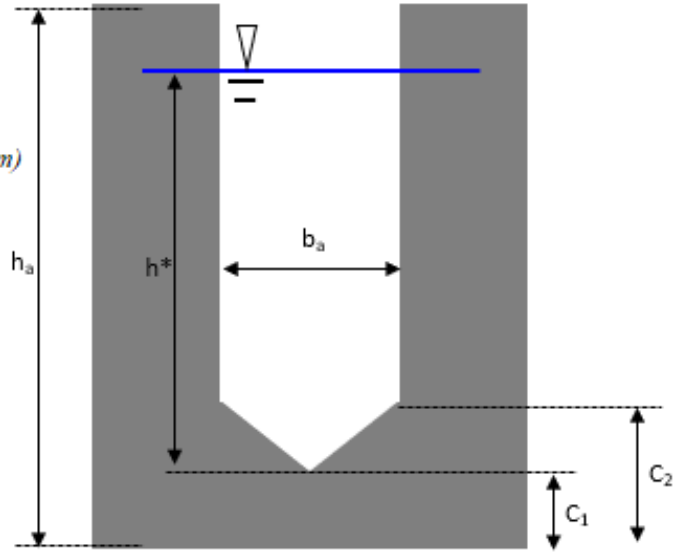
C_1 = fishway floor to slot notch (m)

C_2 = fishway floor to full slot (m)

a = spacing between baffles (m)

g = gravity constant (m)

C_f = friction coefficient



The following 5 discharge rating curve equations were averaged to calculate the discharge rating curves used for gates representing Denil fishways in HEC-RAS. To average the rating curves, compute the Denil rating curve using each equation at the same stage intervals. Then average the discharge for each stage and perform non-linear regression using power function on the average discharge (y-axis) versus stage (x-axis). The below equations and all variables are in metric, rating curves were converted from cubic meters per second to cubic feet per second for use in the models.

Rajaratnam & Katapodis (1997)

$$Q = b_a \bar{d} \left[\frac{2 g I b_a \bar{d}}{b_a + 2 \bar{d}} \right]^{\frac{1}{2}} \frac{1}{\sqrt{C_f}}$$

$$\bar{d} = h^* - \frac{C_2 - C_1}{2}$$

Katapodis et al. (1997)

$$Q = \sqrt{g I b_a^5} \left[1.15 \left(\frac{h^*}{b_a} \right)^{1.85} \right]$$

Odeh (2003)

$$Q = C_d (h^*)^{1.75} b_a^{0.75} \sqrt{g I}$$

$$C_d = 1.34 - 1.84 I$$

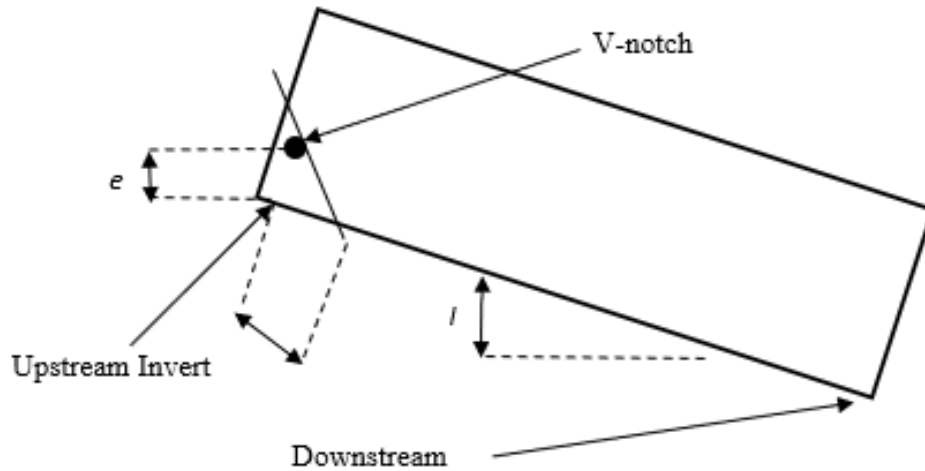
Katapodis (1992)

$$Q = \sqrt{g I b_a^5} \left[0.97 \left(\frac{h^*}{b_a} \right)^2 \right]$$

FAO/DVWK (2002)

$$Q = 1.35 b_a^{2.5} \sqrt{g I} \left[\frac{h^*}{b_a} \right]^{1.584}$$

Appendix 3: Fishway V-notch and Upstream Invert Relationship



(above) Schematic of side view of Denil fishway showing relationship between the V-notch and upstream invert elevations.

e = elevation difference between V-notch and upstream invert (ft)

f = distance from upstream invert to base of top baffle (ft)

I = fishway slope (rad)

Equation relating elevation differences between V-notch and upstream invert:

$$e = \frac{1}{2} * \sin\left(\frac{\pi}{4} + I\right) - (f * \sin(I))$$

CONCLUSION

The chapters of this thesis presented methods which utilize 1D hydraulic modeling for assessing the effectiveness of Denil fishways and designing them to operate efficiently over the maximum range of instream flows. The 1D hydraulic modeling techniques utilized in development of passage windows yielded accurate predictions of water surface elevation about the fishways. However, the passage index limited the scope of the results because of the range of depth combinations for which passage efficiency could be inferred. That is, combinations of upstream and downstream depths observed in field settings did not match well those of Blank et al. (forthcoming). The effectiveness of Denil fishways at connecting habitat for grayling during important time periods was inferred by analyzing fish passage efficiencies over time. The 1D modeling techniques used to predict passage windows were applied to the design of Denil fishways. It is important to install Denil fishways onto low-head weirs such that both ends of the fishways maintain sufficient depth at low flows and slope criteria are met. The hydraulic design procedure will help engineers and fishery managers with the design and installation of Denil fishways that are effective at passing target fish species across the appropriate range of instream flows.

Hydraulic modeling has proven an effective tool for the fish passage community, the applications of hydraulic modeling presented herein may be built upon to aid in the evaluation or design of fishways. To improve the modeling framework presented in Chapter 3, more information regarding grayling response to hydraulic conditions within fishways would be helpful so that the passage index could cover a wider range of depth

combinations and provide inference into fish passage over a wider range of conditions. Data regarding how different fish species react to hydraulic conditions within fishways would be important for projects concerning target species with physical capabilities different than those of Arctic grayling. Passage windows can be predicted for other types of fishways like Alaska Steeppass or Pool/Weir fishways. For Denil, Alaska Steeppass, and Pool/Weir fishways the hydraulic conditions within the fishway are a function of the physical shape of the fishway (often set), the slope of the fishway, and the head at each end of the fishway. In places like the Big Hole Valley, where competing interests for water allocation exist, hydraulic models can be used to predict instream flow requirements for maintaining habitat connectivity. Hydraulic models can be applied to determine the flow through a fishway, or stream channel, required to maintain favorable hydraulic conditions for habitat connectivity. Approaching problems concerning freshwater ecological issues using hydraulic modeling techniques requires an interdisciplinary team, consisting of people who understand hydraulic models and the ecosystem on a fundamental level.

It is the author's hope that this interdisciplinary and collaborative work inspires others to work with people of different areas of study. A complex social and bureaucratic framework must be navigated to holistically improve and conserve the ecological health of our rivers and streams because of the importance waterways have to local economies and communities. Problems facing rivers require holistic solutions implemented by diverse groups of people who take ownership in their freshwater ecosystems.

REFERENCES CITED

Axness DS and Clarkin K. 2013. Planning and layout of small-stream diversions. [edition unknown]. San Dimas, CA: USDA Forest Service National Technology & Development Program. [report number unknown].

Big Hole Watershed Committee (BHC). 2012. Big Hole River, Montana watershed restoration plan; part 1: upper and North Fork Big Hole watershed. [edition unknown]. Divide Montana: BHC. [report number unknown].

Big Hole Watershed Committee (BHC). 2018. Fall/winter 2018 snowpack & climate forecast. Big Hole Watershed Committee Newsletter (Fall 2018). Page 7.

Bishop FG. 1971. Observations on spawning habits and fecundity of the Arctic Grayling. *Prog Fish Cult* 33(1): 12-19.

Blank MD. 2008. Advanced studies of fish passage through culverts: 1-D and 3-D hydraulic modeling of velocity, fish energy expenditure, and a new barrier assessment method [dissertation]. Bozeman MT: Montana State University.

Blank M, Kappenman K, Banner K, Ryan E. Forthcoming. Arctic Grayling (*Thymallus arcticus* Pallas) and Denil fishways: a study to determine how water depth affects passage success.

Brink K, Gough P, Royt J, Schollemma PP, Wanningen H. 2018. From Sea to Source 2.0 Protection and restoration of fish migration in rivers worldwide. The Netherlands: World Fish Migration Foundation.

Bryant MD, Frenette BJ, McCurdy SJ. 1999. Colonization of a watershed by anadromous salmonids following the installation of a fish ladder in Margaret Creek, Southeast Alaska. *N Am J Fish Man* 19(4): 1129-1136.

Bunt CM, Katopodis C, McKinley RS. 1999. Attraction and passage efficiency of white suckers and smallmouth bass by two Denil fishways. *N Am J Fish Man* 19(3): 793-803.

Bunt CM, Castro-Santos T, Haro A. 2012. Performance of fish passage structures at upstream barriers to migration. *River Res Applic* 28: 457-478.

Burford DD, McMahon TE, Cahoon JE, Blank M. 2009. Assessment of trout passage through culverts in a large Montana drainage during summer low flow. *N Am J Fish Man* 29(3): 739-752.

Cahill CL. 2015. Status of Arctic Grayling (*Thymallus arcticus*) in Alberta: Update 2015. Alberta, Canada: Alberta Government and Alberta Conservation Association. Report number 57.

- Castro-Santos T, Haro A, Walk S. 1996. A passive integrated transponder (PIT) tag system for monitoring fishways. *Fish Res* 28: 253-261.
- Cayer E and McCullough A. 2013. Arctic Grayling monitoring report, 2013. [edition unknown]. Dillon MT: Montana Fish, Wildlife, and Parks. [report number unknown].
- Chou WC and Chuang MD. 2011. Habitat evaluation using suitability index and habitat type diversity: a case study involving shallow forest stream in central Taiwan. *Environ Monit Assess* 172:689-704.
- Chow VT. 1959. Open-Channel Hydraulics. Reprint of 1959 edition. Caldwell NJ: The Blackburn Press.
- Clarkin K, Connor A, Furniss MJ, Gubernick B, Love M, Moynan K, WilsonMusser S. 2005. National inventory and assessment procedure- for identifying barriers to aquatic organisms at road-stream crossings. [edition unknown]. San Dimas CA: US Dept of Agriculture Forest Service. [report number unknown].
- Coulthard TJ and Van De Wiel MJ. 2012. Modeling river history and evolution. *Philos Trans Royal Soc* 370: 2123-2142.
- Davis BA. 2015. Endangered waters: interdependency on Montana's Big Hole River [thesis]. Bozeman MT: Montana State University.
- Deal EC, Parr DA, BC Young. 2017. A comparison study of one- and two-dimensional hydraulic models for river environments. Final Report. Lawrence KA: University of Kansas. Report number KS-17-02.
- Dockery DR, Ryan E, Kappenman KM, Blank M. Forthcoming 2019. Swimming performance of Arctic grayling (*Thymallus arcticus* Pallas) in an open-channel flume. *J Ecohydraul*.
- Duffield JW, Neher CJ, Brown TC. 1992. Recreation benefits of instream flow: application to Montana's Big Hole and Bitterroot Rivers. *Water Resour Res* 28(9): 2169-2181.
- Dunham JB, Vinyard GL, Rieman BE. 1997. Habitat fragmentation and extinction risk of lahontan cutthroat trout. *N Am J Fish Man* 17(4): 1126-1133.
- FAO/DVWK. 2002. Fish passes- design, dimensions and monitoring. [edition unknown]. Rome, Italy: Food and Agricultural Organization of the United Nations. [report number unknown].

- Fausch KD, Rieman BE, Dunham JB, Young MK, Peterson DP. 2009. Invasion versus isolation: trade-offs in managing native salmonids with barriers to upstream movement. *Conserv Biol* 23(4): 859-870.
- FishXing User Manual [internet]. 2006. Version 3.0 Beta. San Dimas CA: USFS National Technology and Development Program. [unknown date updated, cited 2/14/19]. Available at http://www.fsl.orst.edu/geowater/FX3/help/FX3_Help.html
- Flynn K, Kron D, Granger M. 2009. Modeling streamflow and water temperature in the Big Hole River, Montana – 2006. [edition unknown]. Helena MT: Montana Department of Environmental Quality. [report number unknown].
- Fulton LA and Bair SH. 1953. Trial of Denil-Type Fish Ladder on Pacific Salmon. [edition unknown]. [publisher unknown]. Report Number 99.
- Furniss MJ, Firor S, Love M. 2000. FishXing 2.0 software and learning system for the analysis of fish migration through culverts. Stream notes to aid in securing favorable conditions of water flows (July 2000). [section unknown]: 1-4.
- Goodwin RA, Nestler JM, Anderson JJ, Weber LJ, Loucks DP. 2006. Forecasting 3-D fish movement behavior using a Eulerian-Lagrangian-agent method (ELAM). *Ecol Model* 192: 197-223.
- Gosset C, Rives J, Labonne J. 2006. Effect of habitat fragmentation on spawning migration of brown trout (*Salmo trutta* L.). *Ecol Freshwat Fish* 15: 247-254.
- Grantham TE. 2013. Use of hydraulic modeling to assess passage flow connectivity for salmon in streams. *River Res Applic* 29: 250-267.
- Hardy TB and Addley CR. 2003. Instream flow assessment modeling: combining physical and behavioural-based approaches. *Can Water Resour J* 28(2): 273-282.
- Haro A, Odeh M, Castro-Santos T, Noreika J. 1999. Effect of slope and headpond on passage of American shad and Blueback herring through simple Denil and deepened Alaska Steeppass fishways. *N Am J Fish Man* 19(1): 51-58.
- Heim KC, Wipfli MS, Whitman MS, Arp CD, Adams J, Falke JA. 2015. Seasonal cues of Arctic Grayling movement in a small Arctic stream: the importance of surface water connectivity. *Environ Biol Fish* 99: 49-65.
- Hendrickson S, Walker K, Jacobson S, Bower F. 2008. Assessment of aquatic organism passage at road/stream crossings for the northern region of the USDA Forest Service. [edition unknown]. [publisher unknown]. [report number unknown].

Jackson A, Moser M. 2012. Low-elevation dams are impediments to adult pacific lamprey spawning migration in the Umatilla River, Oregon. *N Am J Fish Man* 32(3): 548-556.

Katopodis C. 1992. Introduction to fishway design. [edition unknown]. [publisher unknown]. [report number unknown].

Katopodis C. 2003. Case studies of instream flow modeling for fish habitat in Canadian prairie rivers. *Can Water Resour J* 28(2): 199-216.

Katopodis C. 2005. Developing a toolkit for fish passage, ecological flow management and fish habitat works. *J Hydraul Res* 43(5): 451-467.

Katopodis C, Rajaratnam N, Wu S, Tovell D. 1997. Denil fishways of varying geometry. *J Hydraul Eng* 123(7): 624-631.

Khan LA. 2006. A three-dimensional Computational Fluid Dynamics (CFD) model analysis of a free surface hydrodynamics and fish passage energetics in a Vertical-Slot fishway. *N Am J Fish Man* 26:255-267.

Kilgore RT, Bergendahl BS, Hotchkiss RH. 2010. Culvert design for aquatic organism passage hydraulic engineering circular 26. First Edition. Lakewood CO: Central Federal Lands Highway Division of the Federal Highways Administration. Report number FHWA-HIF-11-008-HEC-26.

Lee JH, Kil JT, Jeong S. 2010. Evaluation of physical habitat quality enhancement designs in urban streams using 2D hydrodynamic model. *Ecol Eng* 36:1251-1259.

Letcher BH, Nislow KH, Coombs JA, O'Donnell MJ, Dubreuil TL. 2007. Population response to habitat fragmentation in a stream-dwelling brook trout population. *PLoS ONE* 2(11): e1139.

Liknes GA. 1981. The fluvial Arctic Grayling (*Thymallus arcticus*) of the upper Big Hole River drainage, Montana [thesis]. Bozeman MT: Montana State University.

Lohr SC, Byorth PA, Kaya CM, Dwyer WP. 1996. High-temperature tolerances of fluvial Arcti grayling and comparisons with summer river temperatures of the Big Hole River, Montana. *Trans Am Fish Soc* 125(6): 933-939.

Mahlum S, Cote D, Wiersma YF, Kehler D, Clarke K. 2014. Evaluating the barrier assessment technique derived from FishXing software and the upstream movement of brook trout through road culverts. *Trans Am Fish Soc* 143(1): 39-48.

MDNRC Conservation Districts Bureau. 2001. Montana stream permitting: a guide for conservation district supervisors and others. [edition unknown]. Helena MT: MDNRC. [report number unknown].

MFWP and USFWS. 2006. Candidate conservation agreement with assurances (CCAA) for Fluvial Arctic grayling in the Upper Big Hole River. [edition unknown]. Helena MT: MFWP. USFWS Tracking #TE104415-0.

Montana Ecological Services Office (MESO). 2014. Federal register: Wednesday August 20, 2014, proposed rules. Vol 79 No 161. Washington DC: US Department of Interior USFWS. Report number 19353.

Morita K, Morita SH, Yamamoto S. 2009. Effects of habitat fragmentation by damming on salmonid fishes: lessons from white-spotted charr in Japan. *Ecol Res* 24: 711-722.

National Marine Fisheries Service (NMFS). 2008. Anadromous salmonid passage facility design. [edition unknown]. Portland OR: NMFS, Northwest Region. [report number unknown].

Noonan MJ, Grant JWA, Jackson CD. 2012. A quantitative assessment of fish passage efficiency. *Fish* 13: 450-464.

Northcote TG. 1995. Comparative biology and management of Arctic and European grayling (*Salmonidae*, *Thymallus*). *Rev Fish Biol Fisher* 5: 141-194.

Odeh M. 2003. Discharge rating equation and hydraulic characteristics of standard Denil fishways. *J Hydraul Eng* 129(5): 341-348.

Pelletier PM. 1988. Uncertainties in the single determination of river discharge: a literature review. *Can J Civ Eng* 15: 834-850.

Peterson DP and Ardren WR. 2009. Ancestry, population structure, and conservation genetics of Arctic Grayling (*Thymallus arcticus*) in the Upper Missouri River, USA. *Can J Fish Aquat Sci* 66: 1758-1774.

Plymesser K. 2014. Modeling fish passage and energy expenditure for American shad in a Steeppass fishway using computational fluid dynamics model [dissertation]. Bozeman MT: Montana State University.

Rajaratnam N and Katopodis C. 1984. Hydraulics of Denil fishways. *J Hydraul Eng* 110(9): 1219-1233.

Rajaratnam N and Katopodis C. 1997. Hydraulics of resting pools for Denil fishways. *J Hydraul Eng* 123(7): 632-638.

- Reinfelds I, Lincoln-Smith M, Haeusler T, Ryan D, Growns I. 2010. Hydraulic assessment of environmental flow regimes to facilitate fish passage through natural riffles: Shoalhaven River below Tallowa Dam, New South Wales, Australia. *River Res Applic* 26: 589-604.
- Reiser DW, Huang CM, Beck S, Gagner M, Jeanes E. 2006. Defining flow windows for upstream passage of adult anadromous salmonids at cascades and falls. *Trans Am Fish Soc* 135: 668-679.
- Roni P, Beechie TJ, Bilby RE, Leonetti FE, Pollock MM, Pess GR. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. *N Am J Fish Man* 22(1): 1-20.
- Ryan ER. 2015. Effects of hydraulic structures on fish passage: an evaluation of 2D vs 3D hydraulic analysis methods [thesis]. Fort Collins CO: Colorado State University.
- Sanford P, Cahoon J, Hughes T. 1998. Modeling a concrete block irrigation diversion system. *J Amer Water Resour Assoc* 34(5): 1179-1187.
- Sauer VB and Meyer RW. 1992. Determination of error in individual discharge measurements. [edition unknown]. Norcross GA: USGS. Report number 92-144.
- Schmetterling DA, Pierce RW, Liermann BW. 2002. Efficacy of three Denil fish ladders for low-flow fish passage in two tributaries to the Blackfoot River, Montana. *N Am J Fish Man* 22(3): 929-933.
- Schrank AJ, Rahel FJ. 2004. Movement patterns in inland cutthroat trout (*Oncorhynchus clarki* Utah): management and conservation implications. *Can J of Fish and Aquat Sci* 61(8): 1528-1537.
- Sheer MB and Steel EA. 2006. Lost watersheds: barriers, aquatic habitat connectivity, and salmon persistence in the Willamette and Lower Columbia River basins. *Trans Amer Fish Soc* 135(6): 1654-1669.
- Shepard BB and Oswald RA. 1989. Timing, location and population characteristics of spawning Montana Arctic Grayling (*Thymallus arcticus montanus* [Milner]) in the Big Hole River drainage, 1988. [edition unknown]. Bozeman MT: Montana Department of Fish, Wildlife, and Parks. [report number unknown].
- Sladek H. 2013. Trend analysis of water temperature relative to air temperatures and flow in the Big Hole River, Final Report. [unknown edition]. Dillon MT: US Forest Service. [report number unknown].

Stewart G, Anderson R, Wohl E. 2005. Two-dimensional modeling of habitat suitability as a function of discharge in two Colorado rivers. *River Res Applic* 21: 1061-1074.

Taylor RN. 2000. Final report: Humboldt county culvert inventory and fish passage evaluation. [edition unknown]. McKinleyville CA: Ross Taylor and Associates. [report number unknown].

Towler B, Mulligan K, Haro A. 2015. Derivation and application of the energy dissipation factor in the design of fishways. *Ecol Eng* 83: 208-217.

Turnipseed DP and Sauer VB. 2010. Discharge measurements at gauging stations: USGS techniques and methods book, chap. A8. 3rd edition. Reston VA: USGS. [unknown report number].

United States Court of Appeals for the Ninth Circuit (USCANC). 2018. Center for Biological Diversity v. Zinke. [edition unknown]. Seattle WA: USCANC. No 16-35866.

United States Geological Survey (USGS) StreamStats [internet]. 2017. Version 4. Reston VA: USGS; [updated 2017, cited February 11, 2019].

US Army Corps of Engineers (USACE). 2016. HEC-RAS river analysis system hydraulic reference manual. Version 5. Davis CA: USACE Institute for Water Resources Hydrologic Engineering Center. [unknown report number].

US Army Corps of Engineers (USACE). 2016. HEC-RAS river analysis system user's manual. Version 5.0. Davis CA: USACE Institute for Water Resources Hydrologic Engineering Center. [unknown report number].

USFWS. 2017. Fish passage engineering design criteria. [edition unknown]. Hadley MA: USFWS Northeast Region R5. [report number unknown].

USFWS. 2012. National fish passage program: 2011 annual report and outlook. [edition unknown]. Arlington VA: USFWS National Fish Passage Program. [report number unknown].

USFWS. 2013. National fish passage program: 2012 annual report and outlook. [edition unknown]. Arlington VA: USFWS National Fish Passage Program. [report number unknown].

USGS: Science for a Changing World [internet]. July 9, 2012. Fort Collins CO: USGS. [released/updated last July 9, 2012, cited January 28, 2019].

<https://www.usgs.gov/software/physical-habitat-simulation-phabsim-software-windows>.

Vatland SJ. 2015. Effects of stream temperature and climate change on fluvial Arctic Grayling and non-native salmonids in the upper Big Hole River, Montana [dissertation]. Bozeman MT: Montana State University.

Warren ML and Pardew MG. 1998. Road crossings as barriers to small-stream fish movement. *Trans Amer Fish Soc* 127: 637-644.

Wright KA, Goodman DH, Som NA, Alvarez J, Martin A, Hardy TB. 2017. Improving hydrodynamic modeling: an analytical framework for assessment of two-dimensional hydrodynamic models. *River Res Appl* 33: 170-181.