THESIS

HOW DOES ROCK-RAMP FISHWAY SURFACE TEXTURE AFFECT THE PASSAGE SUCCESS OF SMALL-BOIDED GREAT PLAINS FISHES?

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Cole Brittain

Department of Fish, Wildlife, and Conservation Biology

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Master's Committee:

Advisor: Christopher A. Myrick

Yoichiro Kanno
Lisa Angeloni

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ABSTRACT

HOW DOES ROCK-RAMP FISHWAY SURFACE TEXTURE AFFECT THE PASSAGE SUCCESS OF SMALL-BOIDED GREAT PLAINS FISHES?

The waterways of the North American Great Plains have experienced extensive fragmentation from instream structures and intermittency caused by excessive dewatering. The modifications to these waterways include numerous barriers that prevent the upstream movement of fish. State and federal resource management agencies have turned to fish passage structures to restore connectivity. However, the passage efficiency of current structures may be limited for native small-bodied fish species by a lack of information on how fish swimming behavior and performance are affected by the key fishway design parameters of slope, length, and texture. Recent research has provided more information on fishway slope and length, and identified texture of the surface between the larger roughness elements as an area needing more investigation. We evaluated the effects of four surface textures (smooth; 1 – 2 mm diameter coarse sand; 6 – 10 mm diameter pea gravel, and; 19 – 31 mm diameter small cobble) on the passage success of three native small-bodied fish species, Arkansas Darter (*Etheostoma cragini*), Flathead Chub (*Platygobio gracilis*), and Stonecat (*Noturus flavus*) using a 6.1-m long experimental rock ramp fishway set at a 6% slope. Our results demonstrated that passage success for the Arkansas Darter increased from 0% on the smooth substrate to 32.2% for the small cobble substrate. A similar pattern was observed for the Stonecats, with an increase in passage success from 31.1% on the smooth substrate to 86.7% on the small cobble substrate. Flathead Chub passage success was independent of substrate treatment and exceeded 90% in all cases. Our study suggests that the use

of more highly textured substrates is a viable option for increasing the passage success of small-bodied fishes that otherwise do not perform well on rock ramp fishways.

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The magnitude of work behind this project would not have been possible without the constant and insightful help of Rachel Jones. Her technical support helped navigate the immense amount of labor involved in running a project of this scope. Collaborating with her expertise on fish passage helped this project to become an informative addition to conservation.

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Introduction

Habitat fragmentation has been one of the largest anthropogenic drivers in the decline of migratory terrestrial and aquatic species. River and stream-dwelling freshwater aquatic species are inherently very sensitive to fragmentation because their movement is constrained due to their linear, lotic habitat, unlike terrestrial habitats (Stein and Chipley 1996; Ricciardi and Rasmussen 1999). Barriers existing within a waterway can restrict or prevent longitudinal movements, particularly in an upstream direction, effectively isolating upstream habitats from colonization and utilization, which can negatively impact native fish community structure, size, distribution, and persistence (Poff et al. 1997; Richter et al. 1997).

The western Great Plains eco-region of the United States includes several drainages that are heavily fragmented by instream structures (Wohl 2011; Perkin et al. 2015), for example, the Platte River Basin. This drainage transitions through a suite of hydrologic zones that are ultimately driven by snowmelt from the Rocky Mountains. Flows are impounded and diverted for agricultural and municipal uses both before and after the waterways decrease in gradient, increase in temperature variability, and enter the Great Plains. The variety of gradients, thermal profiles and habitats created by the transition from the mountains to the Great Plains has produced a diverse native fish community adapted to complete their life histories under these fluctuating conditions (Fausch and Bramblett 2008). Pelagically reproducing species, such as Flathead Chub (*Platygobio gracilis*), use extensive longitudinal spawning movements to allow adequate egg dispersal (Harvey 1987; Wilde and Urbanczyk 2013; Walters et al. 2014) and increase population resilience. These waterways also contain a variety of benthic reproducing species, such as suckers (Catostomidae) and darters (Percidae, subfamily Etheostomatinae) that may have specific habitat requirements such as presence of vegetative cover, specific substrate size distributions, and turbidity to successfully reproduce (Albrecht et al. 2017). Although certain species exhibit greater overlap in distribution and suitable habitat range than others, all species are most successful when they have unrestricted longitudinal opportunities to redistribute within their desired habitat range amongst fluctuating conditions.

Contiguous longitudinal access could be restored through the removal of manmade instream barriers, but this is often not a viable management option. However, the use of fishways (also referred to as fish ladders or fish passage structures) can help restore longitudinal connectivity. Fishways vary greatly in their designs. Pool-weir-orifice, vertical slot and Denil fishways are used in coastal and montane regions for strong swimming and jumping species such as the Salmonidae and Clupeidae. Fish locks can successfully pass smaller-bodied species, but are only feasible on major rivers due to cost and size (Baumgartner and Harris 2007). The nature of Great Plains rivers and streams leads to an emphasis on fishway designs that mimic low-gradient systems containing small to moderate-sized substrate and that are not optimized for the passage of strong swimming and jumping species. Rock ramp type fishways meet these criteria and are being installed with greater frequency throughout the Great Plains due to their ability to pass a wide range of fish species with relatively low construction and maintenance costs (Ficke et al. 2011; Richer et al. 2020).

Rock ramp fishway design characteristics are continually being improved in order maximize the passage rates of the target species. Previous research on rock ramp fishways has demonstrated that even small-bodied native species that are not strong swimmers (e.g., Arkansas Darters, *Etheostoma cragini*) can successfully navigate the rock ramp fishway under very specific conditions (Swarr 2018). This has driven a number of recent studies investigating the passage success of different combinations of rock ramp slope, flows, and physical length. Our study focused on evaluating how passage success rates might be influenced by using different types of substrate.

The addition of roughness elements to rock ramp structures aids small-bodied fish passage due to the hydrological conditions generated (Ficke 2015; Stuart and Marsden 2021). Roughness elements are typically represented by large cobbles or concrete “teeth” that protrude vertically out of the fishway. Similar to a boulder in a stream, roughness elements effectively reduce velocity within a fishway by dissipating the force of the flow sometimes resulting in small scour holes for resting areas. They are also able to provide velocity refuges by creating a downstream wake, and are therefore common rock ramp fishway design features.

One area of fishway design not studied as extensively are the spaces between the roughness elements. The use of more highly textured surfaces between the roughness elements may serve to reduce fishway velocities (Baker and Boubée 2006) possibly increasing passage success for fish with poor swimming abilities. Certain benthic species may take advantage of rough surface textures by gripping the textured bottom, possibly increasing their ability to move upstream against high velocity flows (Bulkley et al. 1982). The goal of this study was to determine how the use of different textured surfaces between the larger roughness elements influenced the passage rates of small bodied Great Plains fishes. We hypothesized that increasing the size of the material (i.e., the texture) would increase passage success of the smaller, less-capable swimming species.

Materials and Methods

We evaluated the passage success of three species of fish, Flathead Chub (*Platygobio gracilis*), Stonecats (*Noturus flavus*), and Arkansas Darters (*Etheostoma cragini*), in a full-scale experimental rock ramp fishway. These fishes are designated as threatened or species of conservation concern by the state of Colorado (Table 1), and represent a gradient of swimming abilities within the small-bodied native fish community of the Great Plains ecoregion. Flathead Chub are a strong swimming species due to their fusiform body shape, falcate dorsal fin, and deeply forked caudal fin. Stonecats (*Noturus flavus*) have moderate swimming abilities as a result of their anguilliform body shape and swimming style. Arkansas Darters (*Etheostoma cragini*) have relatively poor swimming abilities caused by the absence of slow twitch axial musculature. These species swimming abilities are based on previous work described by Ficke et al. (2011), Ficke et al. (2012), and Ficke (2015). These species were also used in a prior study on the effects of rock ramp slope on passage success by Swarr (2018) that formed some of the basis for our study.

Wild fish were used when possible to generate representative criteria for target populations. Stonecats were collected from Horse Creek, northwest of Cheyenne, WY using a Smith-Root Inc. LR-24 Electrofisher. Flathead Chub were collected in Fountain Creek, south of the town of Fountain Creek, Colorado. Arkansas Darters were provided by the Colorado Parks and Wildlife Native Aquatic Species Research Facility (NASRF) located in Alamosa, CO. All fish were transported to the Colorado State University (CSU) Foothills Fisheries Laboratory (FFL) where they were held for experimentation. Fish were held in 300-l circular tanks and fed a mixture of frozen bloodworms and 1.5-mm and 3-mm Bio-Oregon pellets. Holding tanks received continuous flows of 20° ± 1°C water to mimic thermal conditions during a typical spring-time migration season. Spray bars created 0.05 m/s – 0.1 m/s currents within each holding tank in order to provide fish with a heterogenous current field and to provide rheotactic cues. Directional flow was reversed weekly to prevent disproportionate muscular development. Each tank included PVC pipe sections and plastic aquarium plants as cover.

After acclimating to laboratory settings over 30 days, each fish was PIT tagged for identification and tracking. Flathead chubs and Stonecats were tagged in the posterior portion of the peritoneal cavities (Hooley-Underwood et al. 2019) with 12 x 2.15-mm full-duplex (FDX) Biomark PIT tags using a Biomark implanter. Arkansas Darters were tagged with 8 x 1.4-mm FDX Biomark PIT tag using the incision method described by Swarr (2018). Fish recovered from tagging for at least 30 days prior to use in experiments.

Fish passage experiments were conducted in a 9.1-m long fiberglass flume constructed by Swarr (2018) with flows provided by a 15-hp Vertiflo pump. The 6.1-m long fishway was constructed within the flume with 1.5-m long resting pools located at each end of the fishway. The fishway was composed of 6-mm thick PVC forming a trapezoidal cross-section (base width of 0.6 m, and angled sides set at 30°). Uniform polyethylene roughness elements (95-mm diameter, 55-mm high) were placed in a chevron pattern on the floor of the fishway approximately one diameter apart (Figure 1). A PVC ramp provided the transition from the downstream resting pool to the fishway entrance, creating uniform entrance conditions and reducing turbulence within the downstream pool. Concrete blocks were placed within the downstream pool to provide additional velocity refuges. A baffle installed under the water inflow in the upstream pool reduced turbulence as water entered the fishway from the head tank.

We selected four surface texture treatments that could be incorporated into the fishway surfaces. The textures were smooth PVC (no texture added), 1-2 mm diameter coarse sand, 6-10 mm diameter pea gravel, and 19-31 mm diameter small cobble. The four size ranges were chosen from the smallest available up to $^1/_3$ the size of previous studied roughness elements (Swarr 2018) to prevent interference with the hydrological advantages provided by the larger roughness elements. Surface textures were applied to the floor and side walls of the fishway between the roughness elements using waterproof adhesive. For all experiments, the flume was set at a 6% slope and the flow was set at 1325 lpm (350 gpm; 0.78 cfs). Slope and flow were chosen based on the finding by Swarr (2018) that a 6% slope and smooth substrate with a flow of 1325 lpm resulted in 100%, 5%, and 0% passage success for Flathead Chub, Stonecat, and Arkansas Darters, respectively. We assumed that it would be possible to detect improvements or impairments in passage related to surface texture under these conditions.

Arkansas Darters and Flathead Chubs were tested in groups of ten individuals per species due to their smaller size, schooling tendencies, and availability. Stonecats were used in groups of five individuals per trial because of their larger size and limited availability. Individual fish were tested three times at each surface texture, for a total of three trial groups, to minimize the number of fish needed for the study while providing information on potential learned behavior. Combining both initial and replicate trials, a total of 90 samples were collected for Arkansas Darters (ARD) and Flathead Chub (FHC) and 45 samples were collected for Stonecats (STP) at each surface texture. It is important to run fish passage studies under both light and dark conditions, and, preferably, overnight, because the behavior of different species makes them more active and perhaps more likely to pass during light or dark periods. Each trial lasted 20 h and encompassed a 10L:10D photoperiod. This photoperiod, with dark extending from 19:45 h to 05:45 h, mimics the natural daytime length encountered by these fish during part of their presumed migratory seasons — it also allowed us to see whether there were differences in passage rates and success under dark or light conditions. Fish in the holding tanks experienced the same photoperiod.

Fish locations were monitored by Oregon RFID multiplexer readers connected to four custom FDX antennas mounted under the floor of the flume at 1.5-m intervals to detect entrance to, passage along, and exit of the fishway. A Flowtracker2® Acoustic Doppler Velocimeter (ADV) was used to take velocity measurements inside the fishway for all four substrates. Velocity profiles and depth measurements were compared for each surface texture along 17 transects spaced 0.37-m apart, with 8 point measurements taken across the width of each transect.

Data Analyses

Fish passage success was defined as the detection of a fish at the uppermost antenna (A4), indicating that it had successfully negotiated the fishway. Passage success was used as a binary variable (detected or not detected) and was calculated for each species based on individual performance. We used a multivariate approach to identify key predictor variables by selecting the top model using Akaike's information criteria (AIC) (Table 2). The response of each species' passage success to substrate type was then analyzed using a Kruskal-Wallis test on median passage success rates; Dunn's tests were used to identify differences among pairwise comparisons. Nonparametric tests focusing on median responses were required due to the binary responses resulting in both skewed and normal distributions, however descriptive statistics revolving around the mean were more insightful and thus were included. We also compared the effects of substrate type on time of travel between A2 and A4 (a distance of 4.06 m) by looking at the distribution of the time-of-travel data. We calculated two time of travel metrics that helped illustrate the effort an individual must exert to successfully pass – mean time of time travel (TOT_{avg}; in hours) and minimum time of travel (TOT_{min}; in hours). Because we had a range of sizes in our fish, we included a qualitative examination of the effect of fish size on passage success, as our small sample size and unequal size distributions precluded a more robust quantitative approach.

Hydraulic data were evaluated in terms of velocity, depth and turbulence at a constant flow. The mean and distribution of velocity measurements was taken across all surface textures. Mean water depth for each surface texture was also calculated to explore the relationship between texture and velocity. Turbulence was qualitatively analyzed by observations of wake size. Shallow turbulent water prevented velocity measurements at each depth that would have helped clarify discrepancies between depth and velocity.

Results

Effects of Surface Texture

The size of the surface texture materials was positively correlated with fish passage success for Arkansas Darters (Figure 2) and Stonecats (Figure 3), increasing from 0% and 31% for the control substrate to 32% and 87% for the cobble texture, respectively. Arkansas Darters and Stonecats showed significant increases in passage success from the control surface texture to the small cobble. Arkansas Darters did not successfully ascend the fishway with the smooth or coarse sand texture. Flathead Chub passage success was uniformly high (> 94%) for all substrate textures and was unaffected by texture treatment (Figure 4).

Hydraulics

Hydraulic measurements showed that the addition of surface texture material resulted in a decrease in average velocity for all surface textures except small cobble (Figure 5). Average water depth within the fishway increased as surface texture size increased from 0.06 m for the control to 0.11 m for small cobble in areas located above three meters from the downstream end of the fishway (Figure 6). To eliminate backwatering effects of the downstream pool evidenced by depth measurements, velocity comparisons were made for stations located above the three meter mark (Table 3). The average velocity for stations above three meters decreased from 0.60 m/s for the control to 0.50 m/s for small cobble (Table 3). There was also a decrease in average velocity for the side margins of the trapezoidal fishway as surface texture increased. The slow velocity boundary layer on the side margins of stations upstream of the three-meter point decreased from 0.38 m/s for the control substrate to 0.20 m/s for the small cobble treatment.

Effects of Behavior

There was evidence of a learning effect in the Arkansas Darter and Stonecat experiments using the more textured surface treatments (Figure 7). Passage rates for a given substrate treatment tended to increase from the initial trial to the subsequent replicates by the same cohort of fish. Flathead Chubs did not show a learning effect, but they already exhibited high overall rates of passage success in their first trials. A non-parametric statistical analysis (Kruskal-Wallis and Dunn's Test) did not reveal a significant difference ($P < 0.05$) between initial and final replicate trial group performance for either Arkansas Darters ($P = 0.14$) or Stonecats ($P = 0.15$).

Our metric for effort, time of travel (TOT) between A2 and A4 for the first successful passage for each fish, varied widely between species. However, both the Arkansas Darter and the Flathead Chub showed a decrease in average TOT (TOT_{avg}) and minimum TOT (TOT_{min}) as surface texture size increased. Stonecats showed very little variation between TOT_{avg} across surface textures, but TOT_{min} decreased as surface texture size increased. Arkansas Darters decreased in TOT_{avg} from 6.51 h on smooth surface texture to 2.77 h on the small cobble surface texture (Figure 8). Flathead Chub showed a decrease in TOT_{avg} from 0.78 h on the smooth surface texture to 0.31 h on the small cobble surface texture (Figure 9). Stonecats TOT_{avg} increased slightly from 0.22 h on smooth surface texture to 0.23 h on small cobble, although TOT_{min} decreased as surface texture size increased (Figure 10).

There were substantial differences in the proportion of successful fishway ascents completed during light and dark periods (Figure 11). Arkansas Darters completed 100% of their successful passages during daylight hours, while Stonecats completed 87% of their successful attempts in the dark; Flathead Chub completed 65% of their successful ascents in the dark.

There appeared to be a relationship between total length (TL) and passage success for Stonecats and Arkansas Darters, wherein smaller fish had higher passage success; no such trend was observed for Flathead Chub. Dividing the fish of each species equally into 10 size categories revealed interesting patterns related to passage success but uneven distributions prevented statistical analyses. For surface textures that Arkansas Darters successfully ascended, 46-mm darters had a successful passage rate of

56% compared to 55-mm darters that successfully passed at only a 6% rate (Figure 12). Stonecats showed similar results across all surface textures, yielding a 100% success rate for individuals between 100-109 mm compared to only a 25% success rate for the largest cohort, >200-mm (Figure 13).

Discussion

Increasing the size of surface texture between large roughness elements on a rock ramp fishway increased the passage success of small-bodied, poor-swimming species that had low or no success with smooth textures. The largest surface texture, small cobble, provided the highest rates of passage success for all species, but appreciable increases in passage success were also observed in Arkansas Darters and Stonecats for the pea gravel treatment. Although previous studies (Bestgen et al. 2010; May and Kieffer 2017; Rodgers et al. 2017) have documented an improved swimming capacity and altered swimming behavior of various sized fish species after increasing surface texture, this study is the first to document the positive effects of surface texture on fish passage success rates in a full-scale rock ramp fishway.

Increasing surface texture size within the fishway appears to confer two principal hydraulic advantages from a fish passage standpoint: the enhancement of instream refuge areas for small bodied fish (Bestgen et al. 2010), and the enhancement of low velocity side margins. Although unmeasured, the thickness of the low velocity layer along the floor of the fishway likely decreased as surface texture increased in size. The increase in water depth with surface texture size showed evidence for the presence of the slow velocity boundary layer on the bottom of the water column, but the shallow nature of the fishway only allowed the top half of the water column to be measured. It should be noted that the decrease in velocity does correspond with an increase in water column depth, as would be expected under the principle of continuity (Vogel 1981). The increase of successful fish passage also suggests the presence of the lower velocity boundary layer. Shallow side margins, formed along the angled portions of the trapezoidal cross-section of the fishway, create low velocity regions that fish could use to ascend. By increasing surface texture size on both the floor and side walls of the fishway, the side margins decreased in velocity. Visual observations confirmed that some fish, including Arkansas Darters, used the margins to ascend the fishway. A decrease in TOT_{min} was strongly correlated with passage success rates for both species that had more difficulty moving upstream, the Arkansas Darter and Stonecat. Although migratory energetics were not calculated for these fish, it is common to assume that finding the path of least resistance is a mechanism for conserving energy (Crossin et al. 2003; Pon et al. 2009) by the reduction in effort. Therefore TOT_{min}, relative to the species, could be a surrogate metric for effort. If fish are indeed expending less energy in moving upstream, the savings could potentially be reallocated to locating and utilizing velocity refuges, or to making repeated attempts at passage, all of which could additionally contribute to increasing passage success.

Surface texture appears to enhance passage success by creating hydraulically favorable conditions that allow fish to use both physiological and behavioral adaptations to move upstream. If a fishway were being designed for all three species used in this study, Arkansas Darters could be considered the limiting species due to their size and reduced swimming abilities relative to Stonecats and Flathead Chub. Due to the absence of slow-twitch muscles within the mid-section (Ficke 2015), an Arkansas Darter's swimming style is reliant on small bursts of speed, <0.7 m/s. This musculature prevents darters from sustained swimming for long periods of time, which makes station holding, as pelagic species do, difficult for darters. However, darters can use their prominent pectoral and pelvic fins to hold their position on the substrate or vegetation while in current, similar to the approaches used by Mottled Sculpin (*Cottus bairdi*) described by Webb et al. (1996) and of four species of sucker (Catostomidae) described by Underwood et al. (2014). We observed that darters were able to use their pectoral fins to hold their position on the sides and bottom of the fishway in the pea gravel treatments, while they positioned their whole bodies in the larger interstitial spaces in the small cobble treatment. Interestingly, despite the texture provided by the sand treatment, passage success of darters was not enhanced, perhaps because the size of the sand grains was insufficient to allow them to create a firm hold at the 6% slope, or, perhaps, because the reduction in velocity was insufficient to constitute a velocity refuge of sufficient depth. A passage study on Rio Grande Silvery Minnows *Hybognathus amarus*

(Bestgen et al. 2010) using a 0% slope documented the fastest TOT_{avg} on sand, as opposed to larger surface textures. It was determined that constant swimming and seeking velocity refuge was less energy efficient than sprinting to the top when possible. Even though the flume was similar in length for our study, the 6% slope prevented Darters from sprinting to the top. This indicates that coarse sand was not large enough to provide velocity refuge for species lacking sustained swimming ability, since Arkansas Darters were unable to successfully pass.

In addition to the major effects of surface treatment on passage success, we also noted interesting influences of three other variables: light, TOT, and fish size. All successful passage attempts by Arkansas Darters happened when the flume was illuminated during the 10-h light period, which was in stark contrast to the Stonecats and Flathead Chub that made the majority of their successful passage attempts during the 10-h dark (nighttime) periods. These results are very similar to those reported by Swarr (2018) for the same fish species in a smooth rock ramp fishway set to slopes of two to ten percent. The reaction to light could be attributed to a number of factors, including a behavioral response to minimize predation risk. Arkansas Darters are small and cryptically colored, with large eyes and burst swimming abilities that would help enhance predator avoidance. Making movements during periods where they can visually detect predators, especially if moving in the shallow margins, is one hypothetical strategy. However, their avoidance of dark could be a concern for fisheries managers, as other instream structures that have low or no illumination (e.g., culverts) may represent a behavioral barrier even when the hydraulic conditions are passable, as noted by Swarr (2018). Stonecats are also a benthic-dwelling species, but their coloration is less cryptic and their larger size could make them more vulnerable to predators under low turbidity conditions during daylight hours. They are moderately good swimmers and their swimming mode is more anguilliform – good for negotiating complex habitats but not necessarily optimized for high velocity movements (Gillis 1996). Like most other ictalurid catfish, they are most active under low-light conditions and appear to more frequently choose such conditions for negotiating the fishway, thereby reducing the risk of detection by visual predators. Flathead chubs reside in the pelagic region of the stream, unlike Stonecats and Arkansas Darters, which increases their likelihood of being detected by potential predators. Their preference to move during darkness, especially through the shallow water of the fishway, could reduce the probability of predator detection, though their strong swimming performance (Ficke et al. 2012) and fast burst speeds would make them harder to capture.

The Stonecats consistently achieved the fastest TOT_{avg} across all surface textures for all three species. Due to their ability to sprint to the top of the flume for all surface textures, sprinting may have been more energy efficient than sustained swimming or utilizing velocity refuges due to their relatively large body size and anguilliform swimming style. Although their passage success increased 55.6% from smooth to small cobble surface texture, the TOT_{avg} only increased by 1 minute. Giving similar effort metrics across all velocities and surface textures implies they were continuously trying to pass as quickly as possible. This was corroborated by their decrease in TOT_{min} as surface texture increased, agreeing with results for the other two species that surface texture can positively affect passage effort.

Arkansas Darters had their fastest TOT_{avg} and TOT_{min} for small cobble. Arkansas Darters were unable to sprint to the top of the fishway as their fastest TOT_{min} was 23 minutes, compared to TOT_{min} <10 sec for Flathead Chubs and Stonecats with the small cobble surface texture. The maximum sprint speed for a similar species, the Johnny Darter (*Etheostoma nigrum*), is 65.4 ± 20.5 cm/s (Ficke 2011). Since the average downstream water velocity for small cobble was 0.46 m/s, a darter could theoretically ascend the 4.06-m fishway in 20.93 seconds if they were moving at the maximum sprinting speed of Johnny Darters. This helps illustrate why it is necessary to provide velocity refuge areas, via roughness elements, for Arkansas Darters to recover within the fishway. Species that are unable to sprint to the top of the fishway will utilize velocity refuge areas to recover and successful ascend (Bestgen et al.

2010). The larger surface textures allow Arkansas Darters to exploit velocity refuge areas both within the surface texture and behind the roughness elements more efficiently and effectively.

Our Arkansas Darter and Stonecat results suggest that the size of the fish relative to the size of the material used for the surface texture and roughness elements in the flume may play an important role in determining passage success. We observed a trend wherein smaller individuals of both species had higher passage success rates than their larger sized conspecifics. Larger fish were initially expected to have higher passage rates due to the absolute swimming velocity of larger fish compared to small fish, but their passage success rate was lower than that of the smaller individuals. This interesting observation could be the result of the interaction of fish size and their ability to take advantage of the localized velocity refuges created by the roughness elements and larger surface treatments. The low velocity eddies behind the 91-mm roughness elements are cone shaped. The width consistently shrinks from 91-mm to zero over a distance just larger than 150-mm, depending upon the flow. These dimensions provide low velocity areas for smaller fish to exploit whereas larger fish may not be able to fit, and thus are at a disadvantage. This observation warrants further investigation, because if there is a relationship between roughness element sizing and the size of the fish, it would be important to identify the threshold element sizes needed to maximize passage success of the target fish community.

The behavior of the species should also be considered. In our study, Arkansas Darters (maximum TL: 54 mm) only passed at a rate of 6.7%, while Stonecats (minimum TL: 103 mm) passed at a rate of 100%. Visual observation confirmed that the species used the velocity refuge area differently: the Arkansas Darter's smaller size allowed their body to be oriented perpendicular to the flow directly behind the roughness elements. Stonecats were unable to utilize the refuge area in this manner due to their size, but were able to shelter behind the roughness elements by aligning their body parallel with the flow. Flathead Chub (TL range: 87-152 mm) passage success was unaffected by size and was uniformly high. We did not test smaller sizes (e.g., similar to the size of Arkansas Darters) for either

Flathead Chub or Stonecats, so a direct comparison across species was not possible. Interestingly, the Flathead Chub used the roughness elements in a similar manner as the Stonecats. These observations suggest that the size of the roughness element contributes to the successful passage of certain species, and even specific size cohorts within those species.

Roughness element size selection should be considered in tandem with surface texture size. An increase in surface texture size will decrease the protrusion of the roughness element from the surface. The largest surface texture, small cobble, began to negatively impact the roughness element's ability to decrease velocity due to the decrease in protrusion. The ratio between roughness element and surface texture size underlies an important relationship between hydraulics and habitat that needs to be maintained while constructing a fishway. Coarse Sand resulted in the slowest average velocity, but also had a surface texture size that was too small to benefit all species. Small cobble resulted in the third fastest average velocity, but the habitat it provided outweighed its negative impacts on velocity to achieve the best passage results. Increasing the size of the roughness elements, relative to the surface texture, would create slower average velocities within the fishway. On the other hand, the current size of roughness elements used in this experiment allowed successfully passage of smaller sized cohorts within species. These results suggest it would be prudent to deploy a range of roughness element sizes, with a minimum of 95-mm diameter, to improve success rates for all sized cohorts across all species. Determining the effects of a more heterogeneous manufactured rock ramp may be an avenue for future research.

It is important to note that this study was not designed to determine whether one could trade a lower fishway slope with a smooth surface for a steeper fishway with a rough surface. The fishway slope chosen for this study (6%) was selected to make it easier to determine whether adding surface texture would increase passage success, but not to explicitly determine whether a 6% ramp with texture had performance equivalent to a lower slope ramp without texture. There is evidence that surface texture could help mitigate the effects of a steeper ramp, but further research would need to be completed to better understand the slope and surface texture relationship, and for a wider array of species. One concern with adding surface texture is that the rougher texture and slowing of the boundary layer velocities would potentially make such ramps more prone to issues with turbulence and sedimentation. Based on the information in Julien (2010) it might be possible to identify threshold conditions where the sediment of concern (e.g., silt to coarse sand) is mobilized and less likely to deposit within the fishway.

Tables

Table 1 – Fish sizes and state of Colorado conservation status of the three species of Great Plains fish used in this study.

Species	Size Distribution (total length; mm)	Colorado Status
Arkansas Darter	46-54	Threatened
Stonecat	103-207	Special Concern
Flathead Chub	87-152	Special Concern

Table 2. – AIC model selection results for successful passage over three predictors including their interactions: Species, Surface Texture (ST), and Trial.

Model	(Int)	Species	ST	Trial	Species:ST	ST:Trial	Species:ST:Trial	df	Loglik	AIC	ΔAIC	weight
16	-22.52	+	+	+	+			14	-48.29	124.6	0	0.475
32	-22.49	+	+	+	+	+		18	-44.96	125.9	1.32	0.245
12	-22.14	+	+		+			12	-51.32	126.6	2.05	0.17
64	-23.52	+	+	+	+	+	+	24	-40.27	128.5	3.94	0.066
48	-23.81	+	+	+	+		+	20	-44.68	129.4	4.77	0.044
8	-3.418	+	+	+				8	-61.72	139.4	14.85	0
24	-3.36	+	+	+		+		12	-58.40	140.8	16.2	0
56	-3.298	+	+	+		+		18	-52.46	104.9	16.32	0

Table 3. – Water velocity and depth measurements for all surface textures. Velocity measurements are represented as the average velocity for the entire fishway (average), and for the longitudinal side margin (SM) of the fishway. Side margin velocity was measured 0.23-m from edge of water.

		Stations > 3 m			
	Velocity Average (m/s)	Velocity Average (m/s)	Side Margin Velocity (m/s)	Ratio V = SM/Average	Depth Average (m)
Control	0.41	0.60	0.38	0.64	0.06
Coarse Sand	0.33	0.46	0.24	0.51	0.07
Pea Gravel	0.38	0.48	0.22	0.46	0.08
Small Cobble	0.46	0.50	0.20	0.39	0.11

Figures

Figure 1. 95-mm roughness elements were spaced one diameter apart in a chevron pattern. The surface texture treatment shown in this image is the sand (1 – 2 mm diameter) treatment.

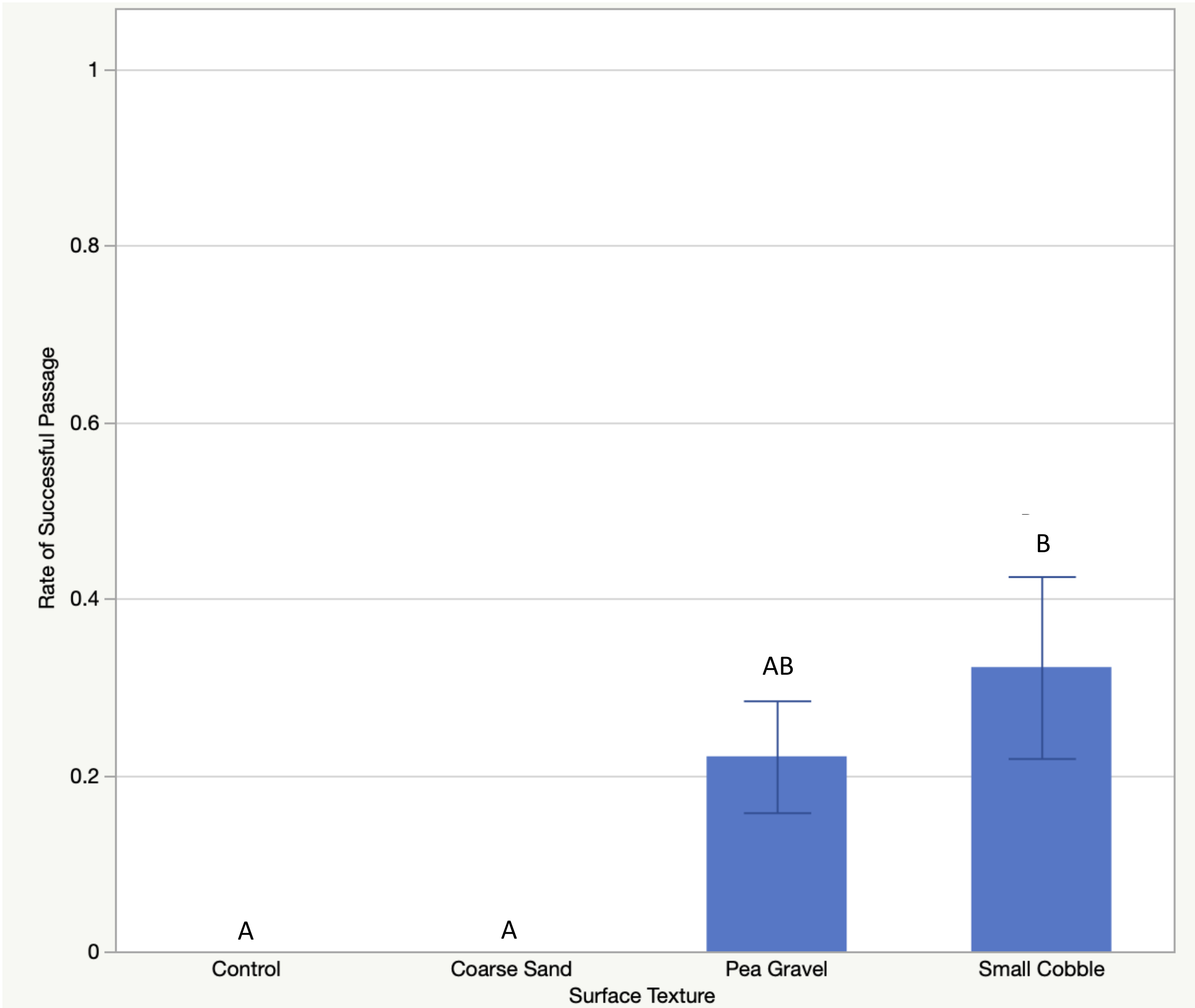

Figure 2. Effects of surface texture on the passage success rate of Arkansas Darters in a 6.1-m long rock ramp fishway set to a slope of 6%. Reported values are means, and error bars represent the 95% confidence intervals. No Arkansas Darters successfully negotiated the fishway in the control or coarse sand treatments. Passage rates that are significantly different from each other are denoted by different letters.

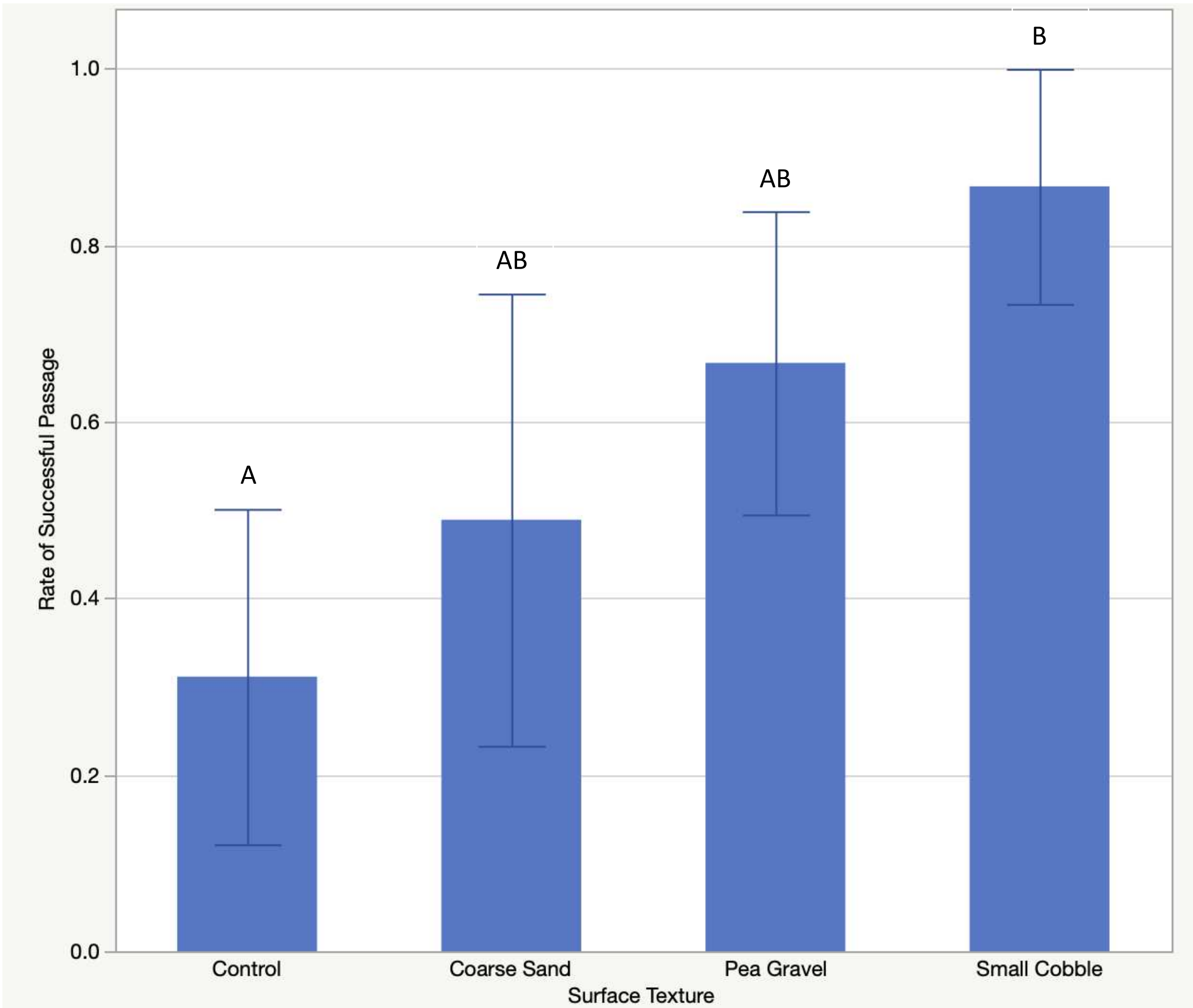

Figure 3. Effects of surface texture on the passage success rate of Stonecats in a 6.1-m long rock ramp fishway set to a slope of 6%. Reported values are means, and error bars represent the 95% confidence intervals. Passage rates that are significantly different from each other are denoted by different letters.

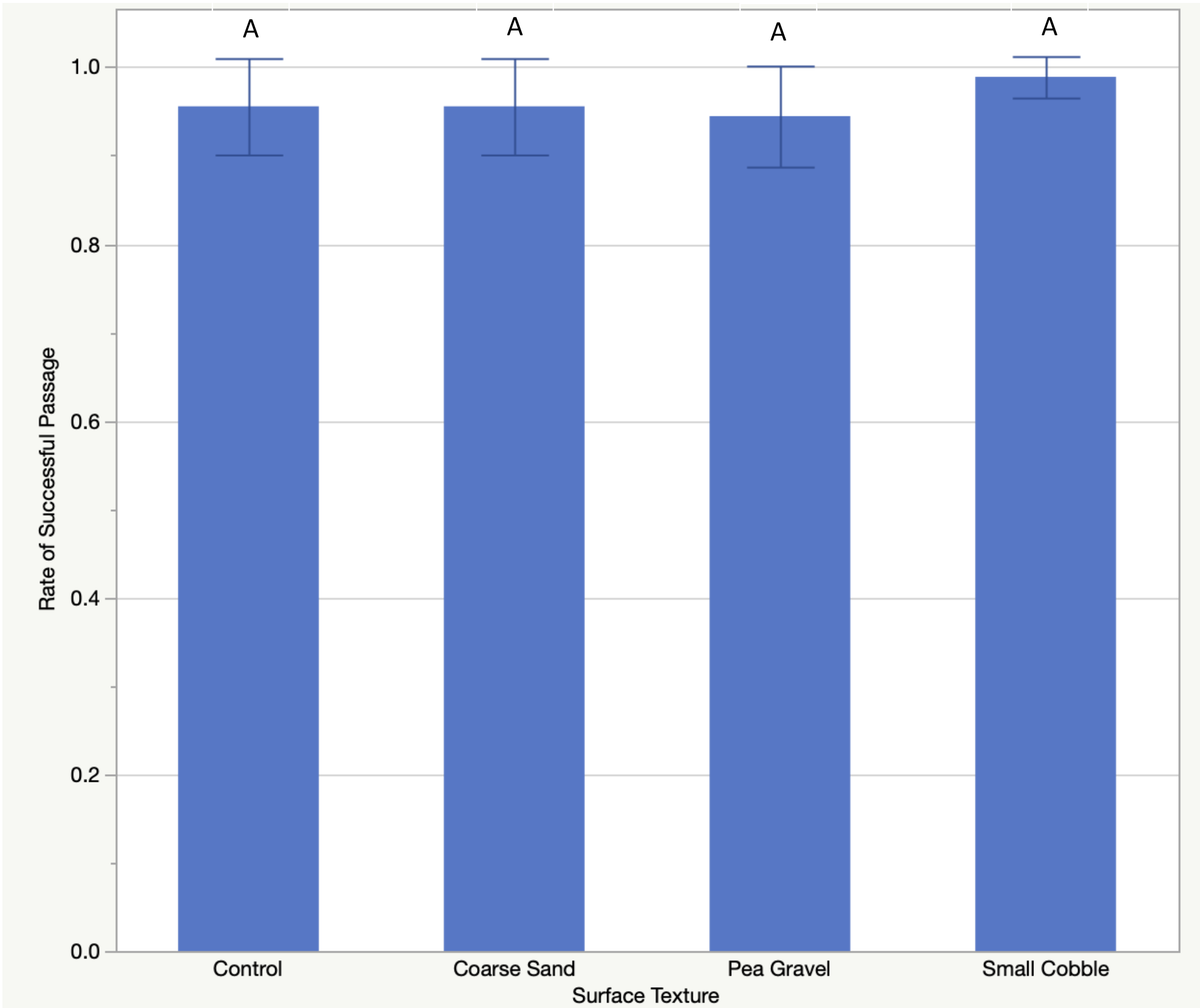

Figure 4. Effects of surface texture on the passage success rate of Flathead Chub in a 6.1-m long rock ramp fishway set to a slope of 6%. Reported values are means, and error bars represent the 95% confidence intervals. Passage rates that are significantly different from each other are denoted by different letters.

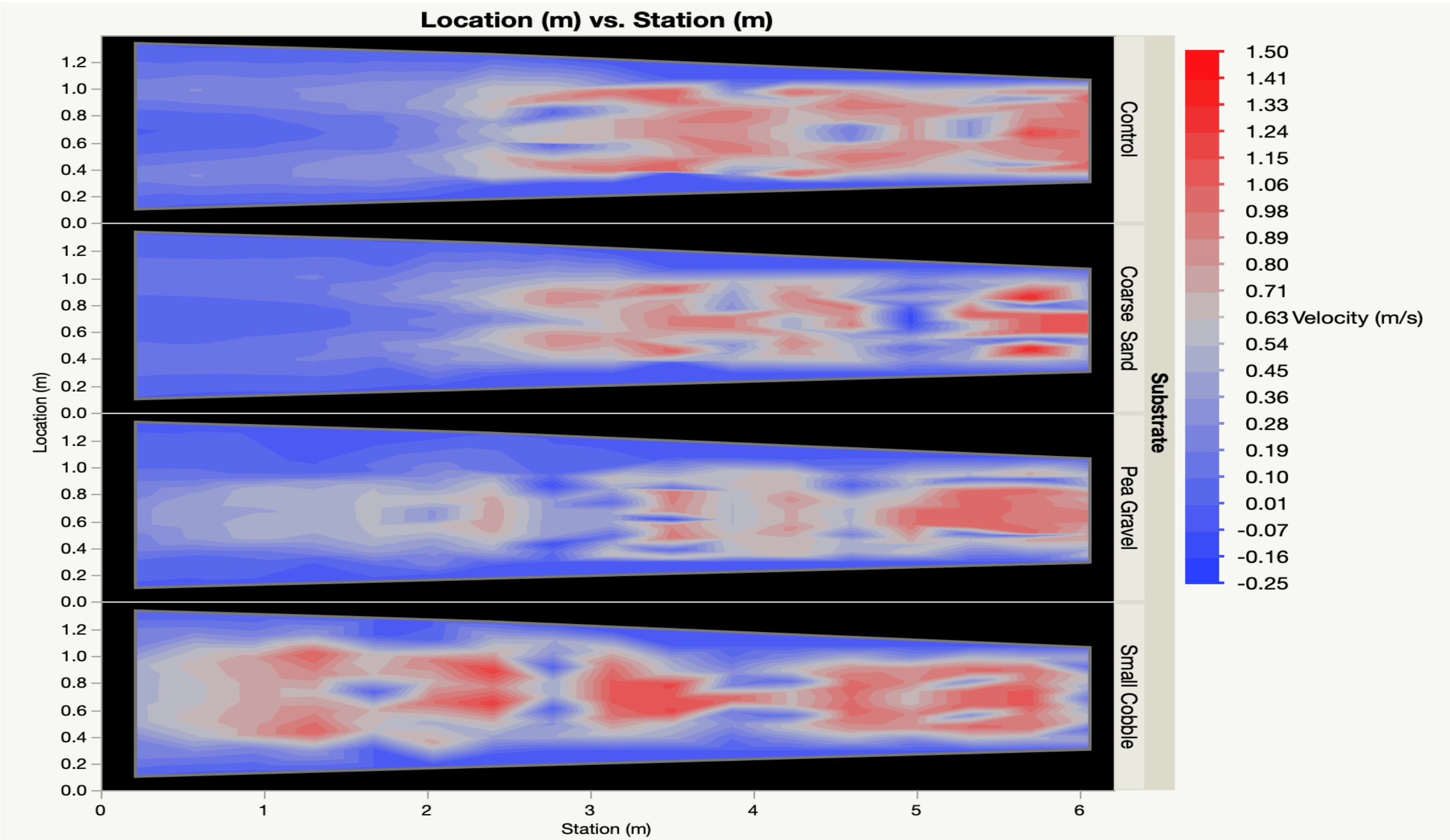

Figure 5. Velocity measurements repeated at 17 evenly spaced cross sections for all surface textures. The top of the fishway is on the right (6.1 m) and water flows downstream to the left (0 m).

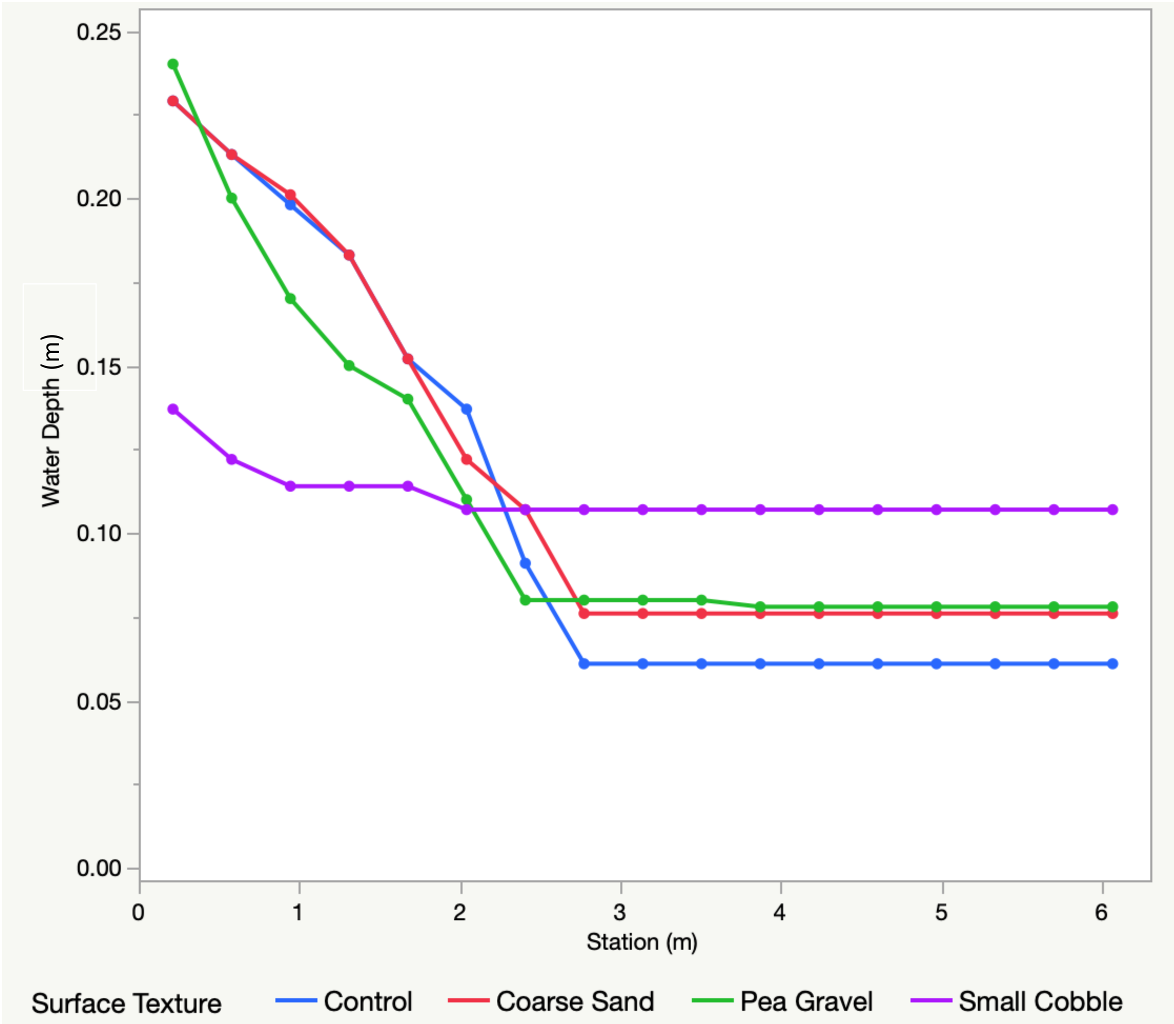

Figure 6. The effects of surface texture on average water depth within the fishway. Stations downstream of the 3-meter point show backwatering effects of downstream pool.

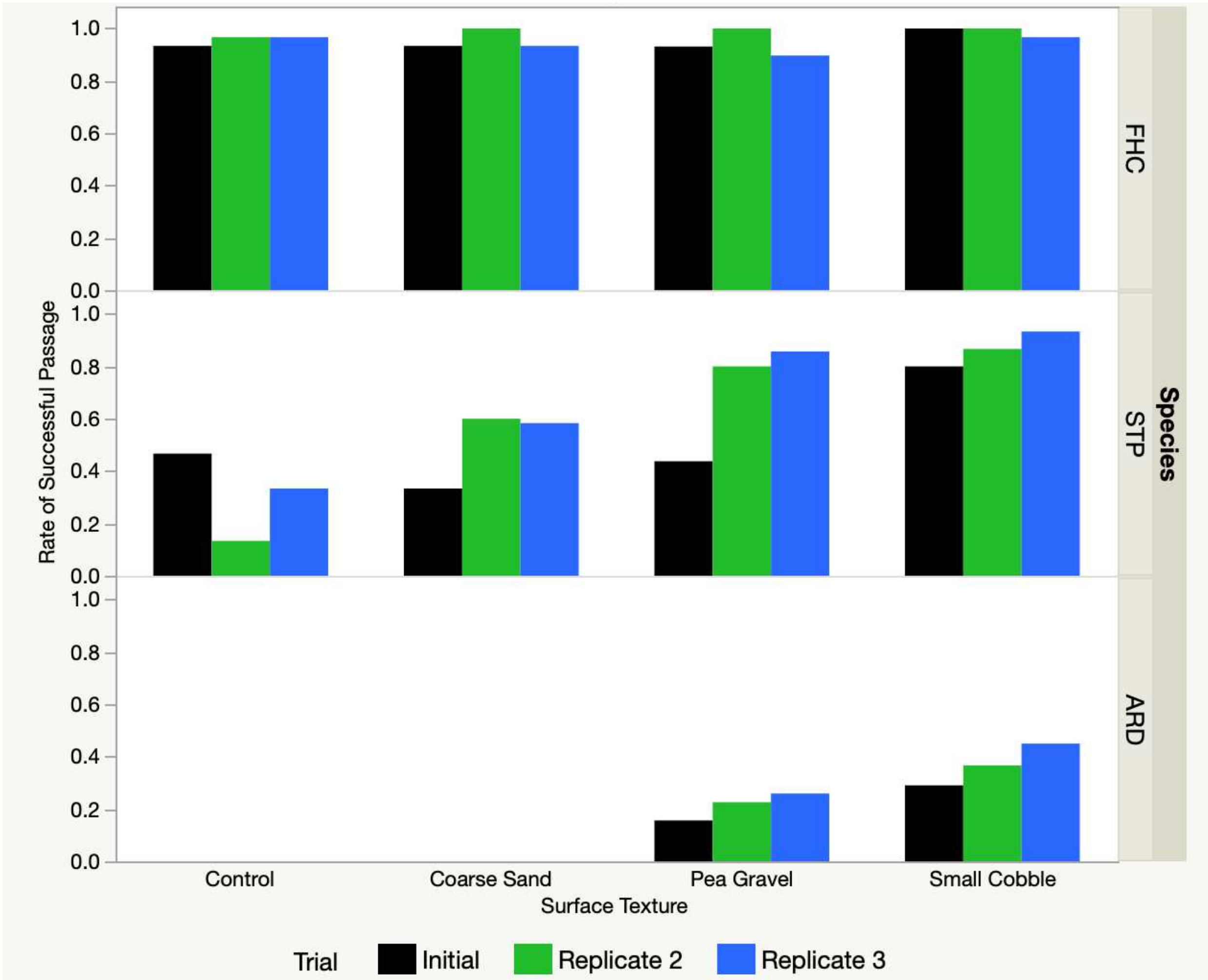

Figure 7. Evidence for learning as indicated by increased mean passage success rates with repeated passage trials for the three species (FHC = Flathead Chub; STP = Stonecat; ARD = Arkansas Darter) and four surface textures used in this study.

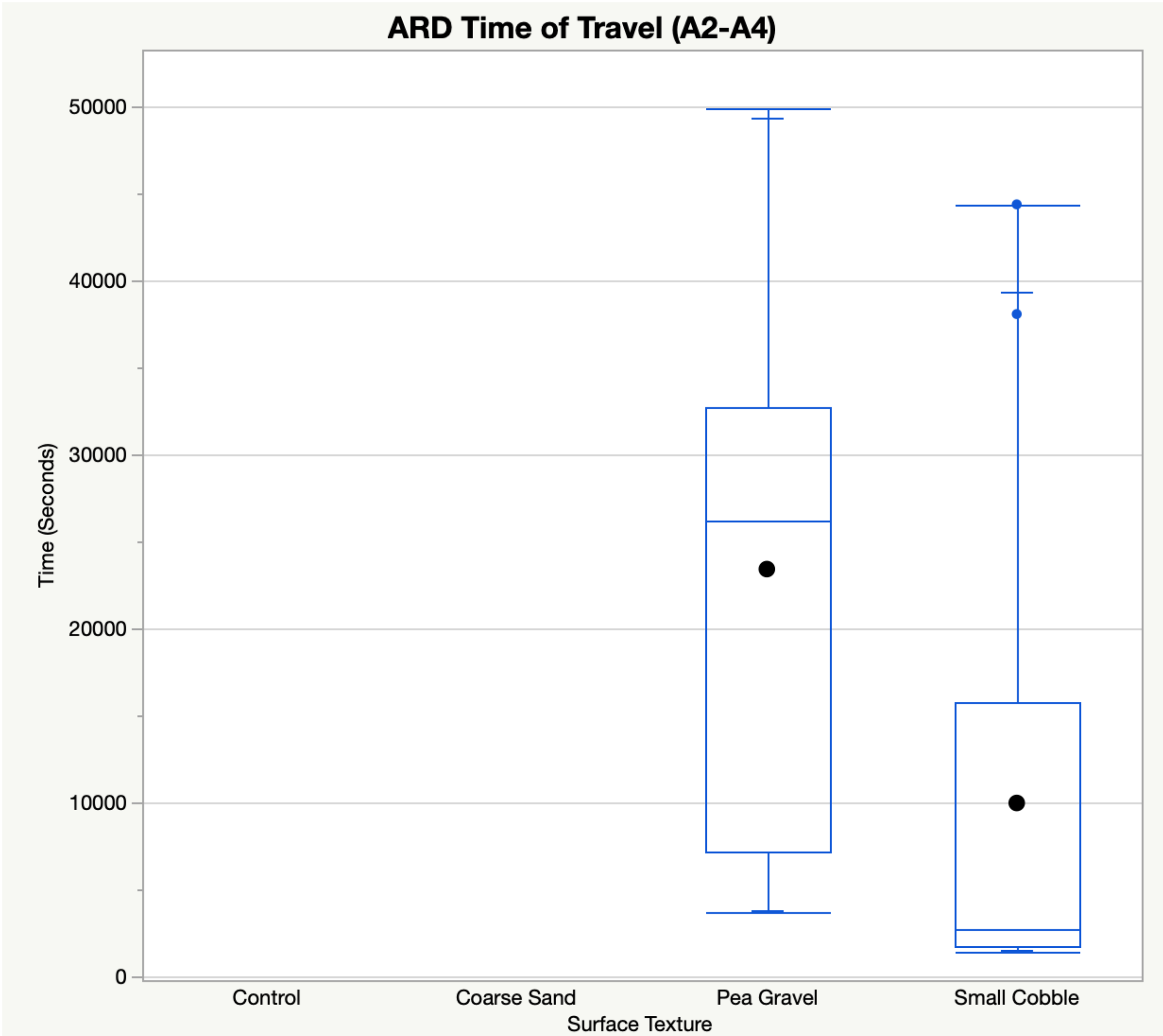

Figure 8. Time of Travel (TOT) between A2 and A4 (4.06-m) for successful passage by Arkansas Darters. The black points represent the mean travel time (TOT_{avg}) while the quantile plot overlay indicates the discrepancies between TOT_{avg} and TOT_{min}.

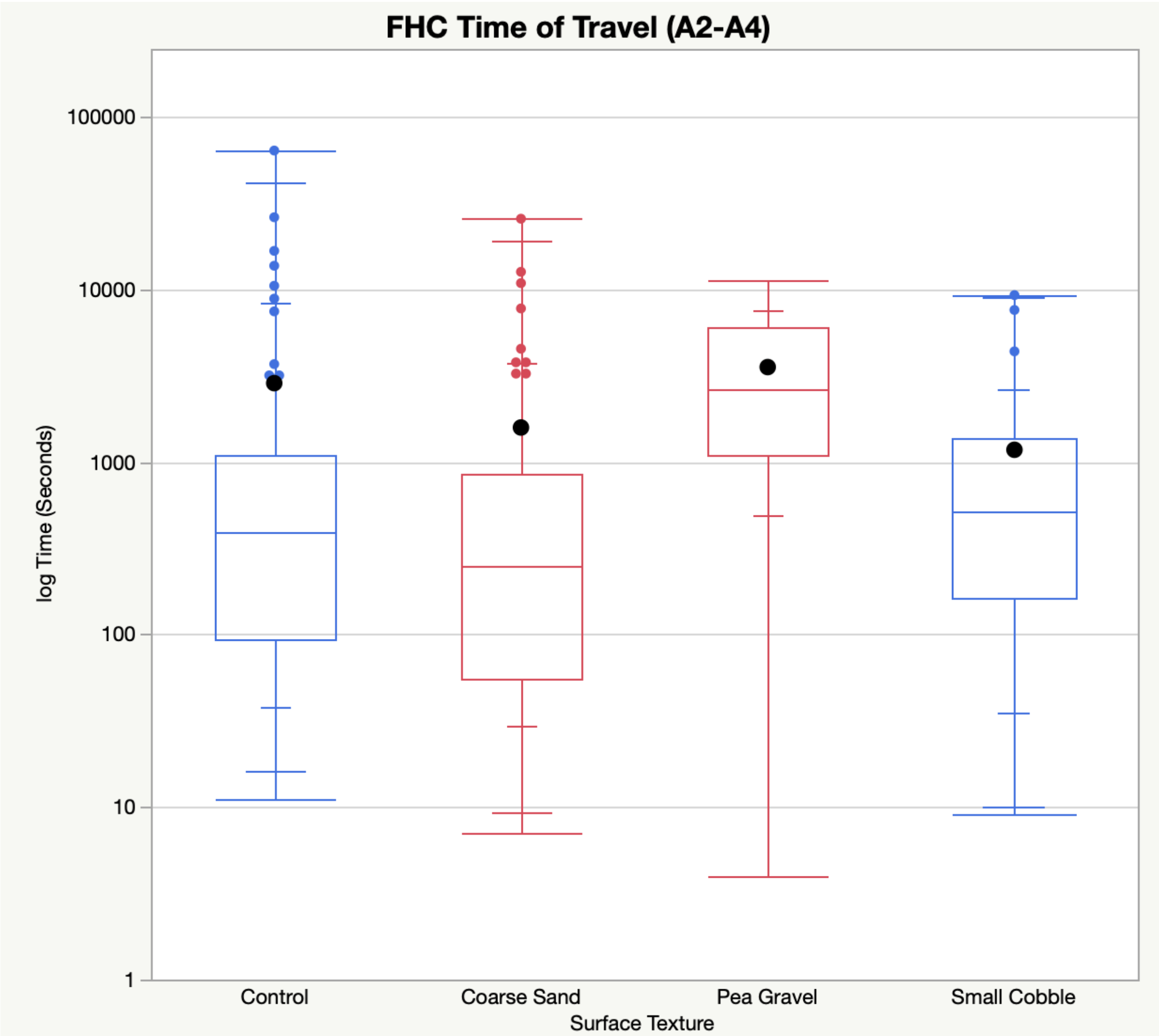

Figure 9. Time of Travel (TOT) between A2 and A4 (4.06-m) for successful passage by Flathead Chub. The black points represent the mean travel time (TOT_{avg}) while the quantile plot overlay indicates the discrepancies between TOT_{avg} and TOT_{min}. Blue bars have antenna detection rates >5%, while red bars have detection rates <5%.

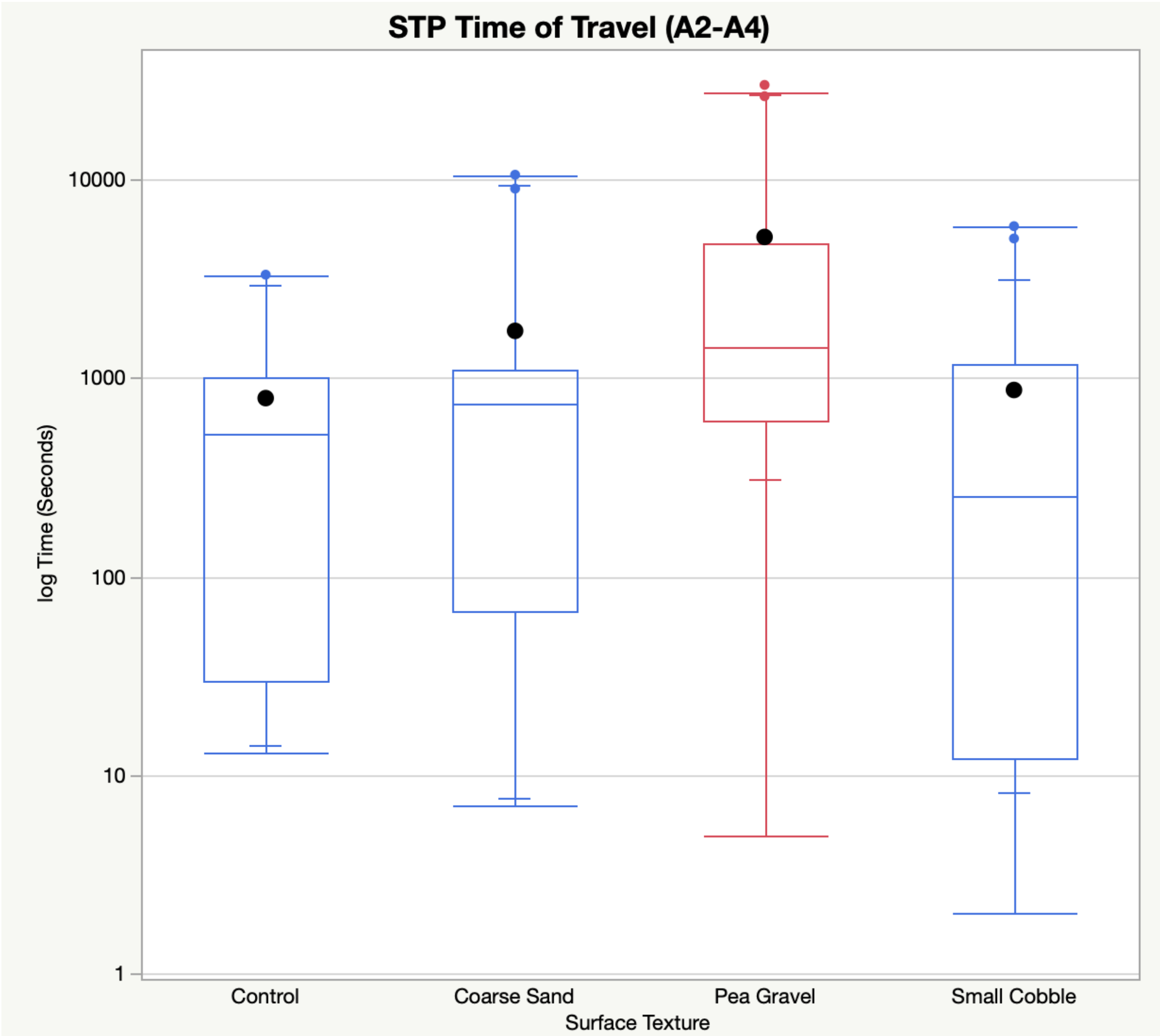

Figure 10. Time of Travel (TOT) between A2 and A4 (4.06-m) for successful passage by Stonecats. The black points represent the mean travel time (TOT_{avg}) while the quantile plot overlay indicates the discrepancies between TOT_{avg} and TOT_{min}. Blue bars have antenna detection rates >5%, while red bars have detection rates <5%.

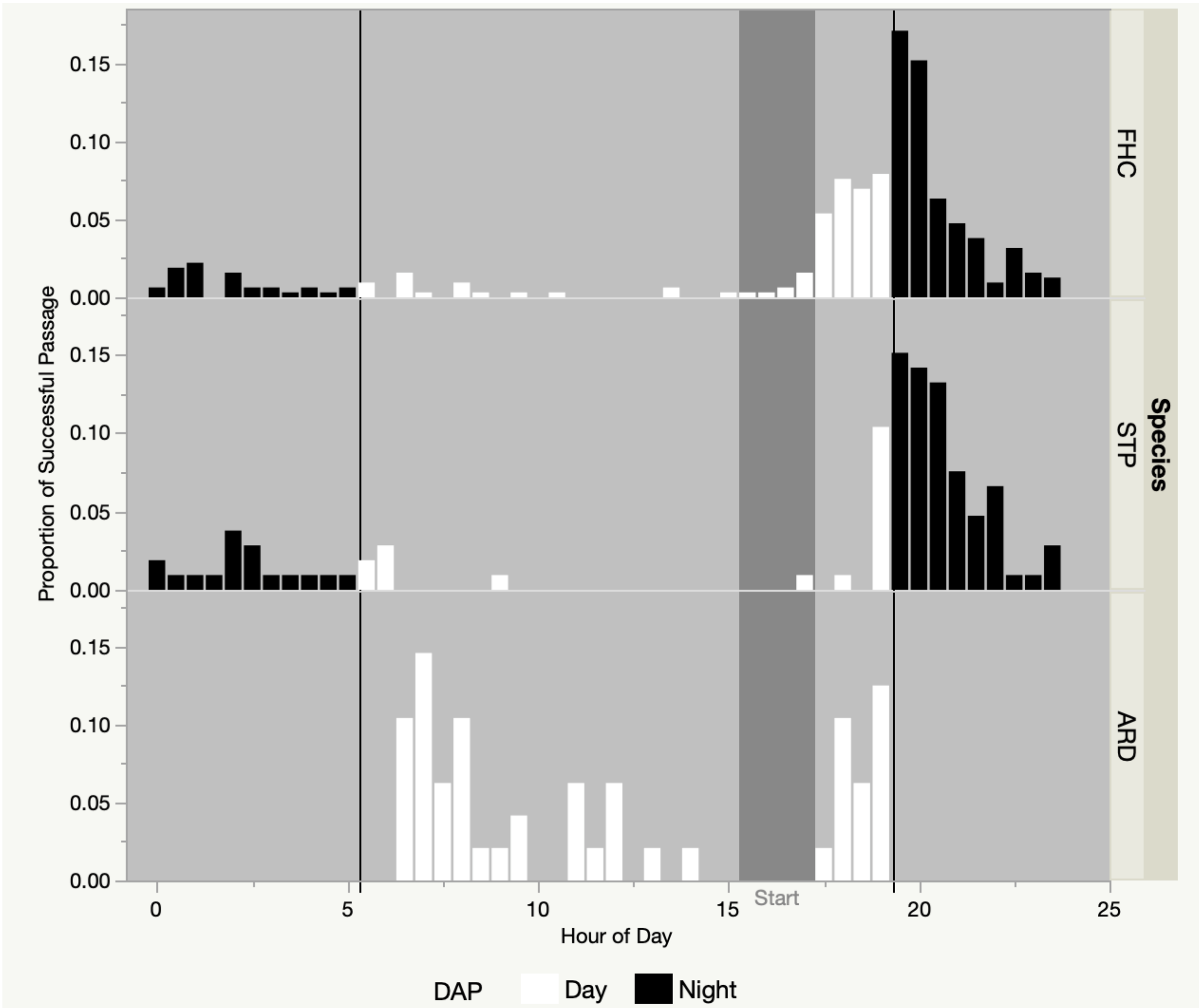

Figure 11. The proportion of total successful passages by hour of day for Arkansas Darter (ARD), Stonecat (STP), and Flathead Chub (FHC). Lights were set to turn on between 5:45-19:45 to create a 14L:10D photoperiod. Each trial commenced between 15:30 and 17:30 and lasted for 20 hrs.

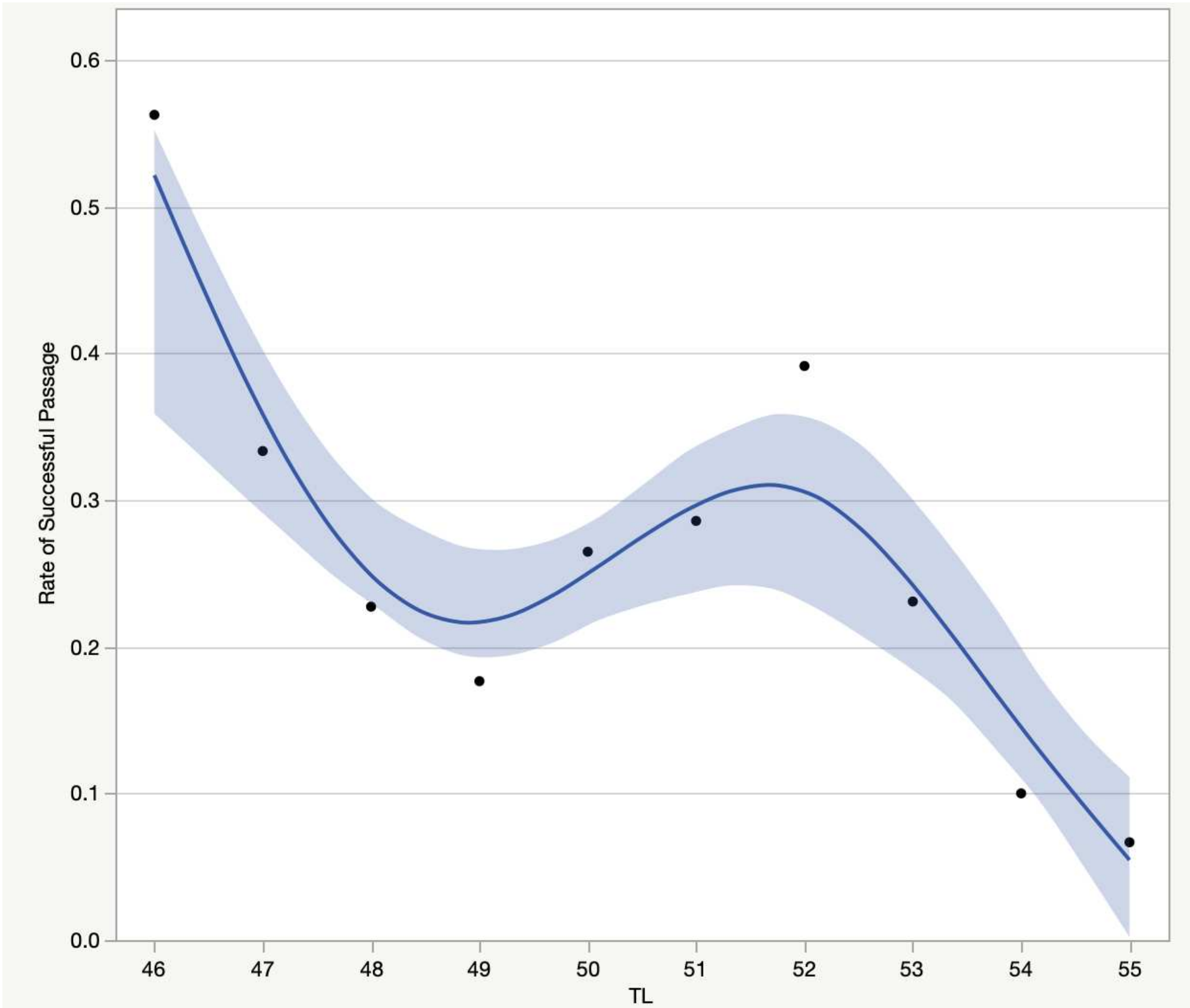

Figure 12. Passage success percentages for Arkansas Darters (n=180) by total length (TL) across only surface textures with successful passage, pea gravel and small cobble. Bootstrap confidence interval provided.

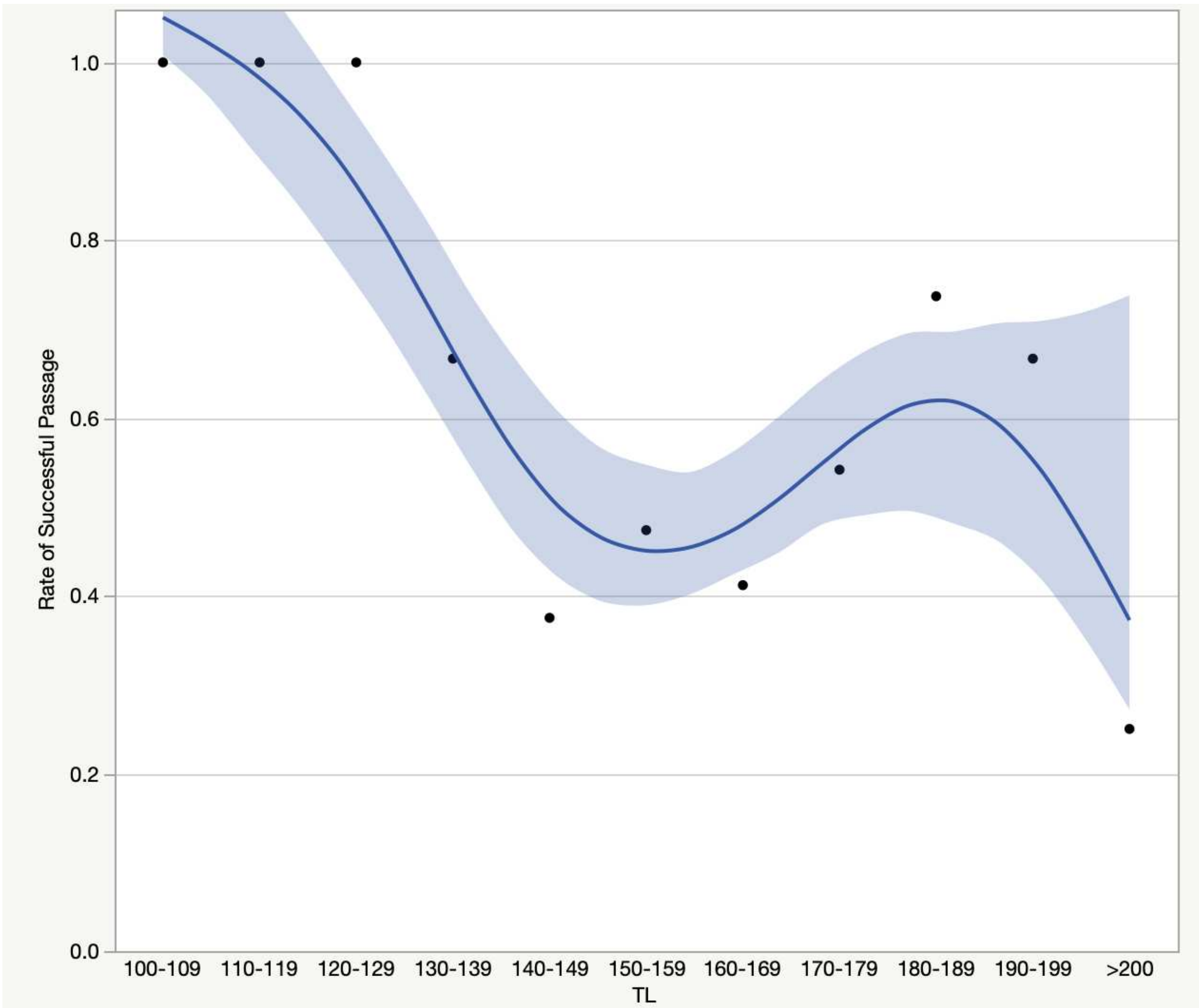

Figure 13. Passage success rates for Stonecats (n=152) by total length (TL) across all surface textures. Bootstrap confidence interval provided.

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