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Evaluation of a Prefabricated Fish Passage Design for Great Plains Fishes

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Abstract: Connectivity is critical for stream fish persistence, and fish passage structures are a useful conservation tool to reconnect fragmented systems. The design of fish passage structures is a tradeoff between the area available for construction, slope, and costs associated with the structure. The Longrie–Fecteau fish passage structure was designed to be modular, adjustable to barrier-specific needs, and to have a low slope (2%) to pass small-bodied fishes. We evaluated fish passage through this structure in Fountain Creek, Colorado, USA, via a PIT tag mark–recapture study. We documented four native Great Plains fish species successfully ascending the passage structure, with most passage occurring at night. We estimated a 3% probability of a released fish entering the structure, then 89% and 99% passage to the midpoint and exit of the 123 m structure, respectively. Low entrance efficiency was due to low recapture probability of small-bodied study organisms in a relatively large system, and the low percentage of space of the entryway on this barrier (<3% of the length of the barrier). Fish that entered the structure ascended quickly, with median time for successful ascent of 19 min, and minimum time of 6 min. The Longrie–Fecteau fish passage structure is a conservation tool that may broaden the adoption of fish passage structures for small-bodied fishes due to its modularity and low slope.

Keywords: barriers; connectivity; fish passage structure; Fountain Creek, Colorado; Great Plains fishes

Key Contribution: The Longrie–Fecteau fish passage design is modular to adjust to barrier specific needs, with a low slope (2%) to pass small-bodied fishes, and although it had low entrance efficiency in this study, it had high rates of passage once fish were in the structure.

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1. Introduction

Freshwater stream fishes require a mosaic of habitats to complete their life cycle, and restoring connectivity among these habitats with fish passage structures is vital for conservation in fragmented systems [1,2]. Connectivity is necessary for the maintenance of metapopulation dynamics, such as genetic flow, recolonization of areas of extirpation, and refuge from extreme abiotic conditions [3–5]. Unfortunately, barriers are common in freshwater streams [6], and fragmentation is especially prevalent in arid regions, such as streams in the Great Plains ecoregion [7–9]. These barriers can take the form of dams, drop structures, weirs, and culverts under road crossings [10–12], with each presenting unique challenges to passage. With the increase in impassable structures present on streams and rivers in the Great Plains, habitat connectivity has become a critical issue surrounding the conservation of taxa native to this ecoregion [9,13,14]. Fragmentation is especially detrimental to fishes that require long, unimpeded reaches to complete their life cycle, such as a suite of Great Plains species that rely on the transport of semi-buoyant eggs that may require long distances for their development [13,15,16]. Unfortunately, these species are not effective at jumping over instream structures, making even small vertical drops potential barriers [17,18]. A relatively high proportion of species within this ecoregion are listed as threatened or endangered [16,19]; therefore, the development and use of effective fish passage structures to increase connectivity for this assemblage has the potential to aid in the conservation of a suite of small-bodied native fishes.

Historically, the research and design of fish passage structures has primarily focused on taxa of economic importance [20], leading to a deficiency of insight into the passage of small-bodied fishes [21]. Design for the passage of small-bodied, and therefore weaker-swimming [22] fishes often focuses on vertical-slot and rock-ramp fishways [23,24] and has allowed for successful passage, thereby expanding stream connectivity [25]. However, many of these structures can be economically infeasible. Considering the vast amount of instream structures affecting small-bodied fishes, this limitation may ultimately hinder progress towards the reinstatement of ecologically linked reaches.

The design of fish passage structures is a tradeoff between the space available for construction, slope, and costs associated with the structure, as well as the migration ecology, swimming performance, and body size for the target species [20,26]. The structure needs to be able to pass fish, transport sediment, and be able to physically withstand the flow regime it will encounter [27,28]. In order to reclaim connectivity at the watershed scale, a fishway design that is readily deployable, has a slope low enough to pass the weakest swimming species in the assemblage, and is economically feasible would be useful for stream fish conservation. However, its efficacy in fish passage must first be evaluated [29,30].

In addition to fishes' physical ability to pass a structure, they also need to be able to locate the entrance [31–35]. This is a function of attraction flows, the size of the entrance relative to the size of the barrier, and the location of the entrance. Assessing the temporal variation in use is also important to guide operations of the structure. For example, the timing of gate operation on water diversions could be altered to minimize the risk of fish being trapped and desiccated in the passage structure during operation. In addition, if the majority of movements occur at night, artificial lighting may affect the probability of a fish using the passage structure [36]. Depending on when fish use a fish passage structure, they could be at risk of avian, mammalian, reptilian, or fish predators [37]. Inference regarding when most usage of a fish passage occurs, and how long it takes to successfully ascend, will help guide diversion operations to minimize fish mortality near and in the structure.

This study aimed to assess passage of the Longrie–Fecteau fish passage structure (LFFPS) located on a weir/small dam by small-bodied, Great Plains fishes through a mark–recapture study. Results are discussed in the context of current fishway designs and how the design may provide a more readily deployable and economically viable option for increasing stream connectivity, which would be useful where passage of small-bodied fishes is a conservation priority. The objectives of this study were to (1) provide information regarding the LFFPS as a prefabricated design, and (2) evaluate the effectiveness of this structure for Great Plains fish passage.

2. Materials and Methods

2.1. Study Area

This study was conducted on Fountain Creek, CO, USA, which is a 120 km tributary of the Arkansas River that is representative of similar low-gradient reaches in the Great Plains ecoregion (Figure 1). In its lower reaches, Fountain Creek is characterized by wide, sandy channels with a high sediment load that are prone to morphological fluctuation within the flood plain due to an extremely flashy hydrograph (range over study period = 0.3–32.8 m^3/s; USGS gage station 07106500; Figure 2) [38,39]. Between its headwaters and confluence with the Arkansas River, Fountain Creek has 18 potentially impassable instream structures ranging from small, rock-fill dams to concrete diversion structures spanning the entire width of the channel. A motivating factor for this project was to design a fish passage structure that could be used as a template for other barriers in the system to increase connectivity upstream, and hopefully in other systems where passage of small-bodied fishes is a conservation priority.

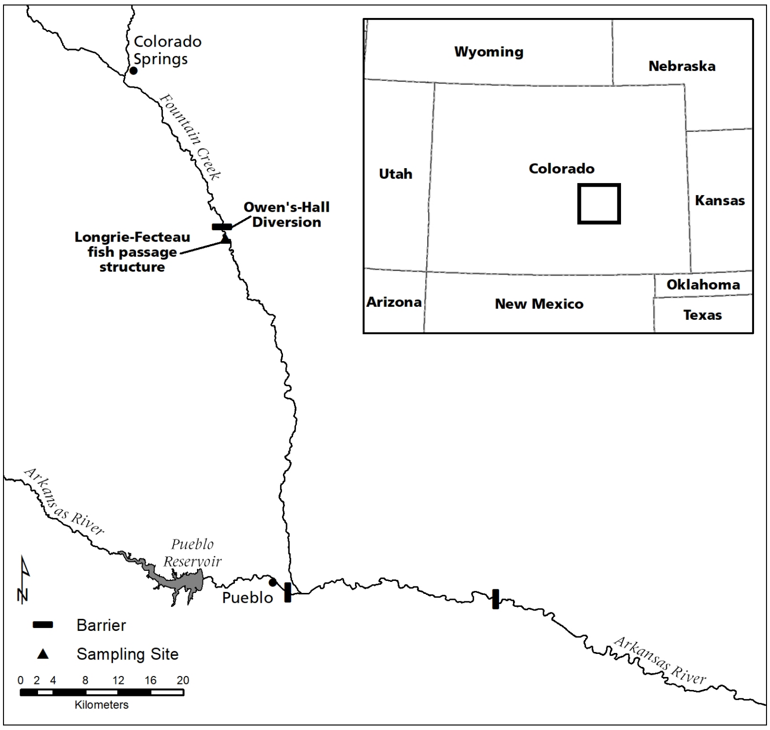

Figure 1. Fountain Creek is located in south-central Colorado, USA along the Front Range of the Rocky Mountains. The study site was between Colorado Springs and Pueblo (UTMs for Owens-Hall Diversion Zone: 13 E: 526847 N: 4277740).

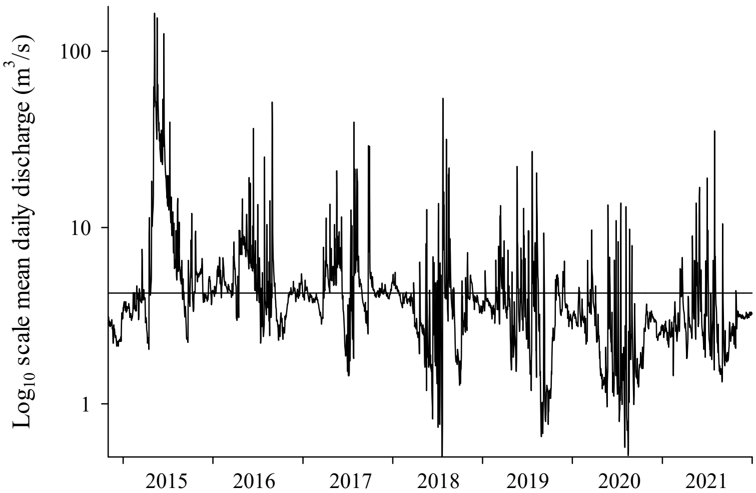

Figure 2. Flow regime experienced by the Longrie–Fecteau fish passage structure. Log scale mean daily flow to display flows under 4.25 m^3/s, which is where the fish passage structure is operational. This passage study was conducted July–November 2020.

Fountain Creek's native fish community is mostly intact, with an average abundance of 93% native taxa observed over the past decade [40]. The fish assemblage in the lower portion of the basin is dominated by the State of Colorado species of special concern flathead chub (*Platygobio gracilis*) (48%) and includes the state threatened Arkansas darter (*Etheostoma cragini*) [41]. This lower, native species dominated section represents the longest unimpeded reach within the drainage (58 km), and fish have access to another 35 km of unimpeded stream on the main-stem Arkansas River [42,43] (Figure 1). The first upstream barrier that fish encounter from the confluence with the Arkansas River is the Owens-Hall irrigation diversion (Figure 1). This structure, rebuilt in 1999, spans the entire width of the channel. There are two time periods that are important to understand regarding potential passage of the Owens Hall diversion. The first is when the sluice gate is closed and the fish passage structure is operational. During this time (which is the vast majority of the time) there is no passage through the barrier as it is a 2.8 m high concrete barrier with 74% slope. The next are short time periods that occur every week or two, when the sluice gate is open. During this time, the fish passage structure is not operational, but there is the potential of fish moving through the sluice gate and increasing connectivity. Walters et al. [42] conducted a mark–recapture study at this barrier and found 0.017% movement upstream of the diversion structure. Therefore, even when the sluice gate is open and there is potential for passage, there is little movement through it. As a spatial control to compare the results of this study, a previous PIT study in the same river section showed high movement of flathead chub (Ryan Fitzpatrick, unpublished data), which indicates if the barrier was not present that there would be high rates of fish movement through this study area. To increase the stream reach available to native plains fishes, Colorado Springs Utilities designed, built, and installed the LFFPS on the diversion in 2014 (Figure 3). Fountain Creek is a unique system due to its native species dominated fish assemblage [42–45], the high amount of sediment in the system [39], and the highly fluctuating flow regime [38] that the structure needs to withstand and operate within.

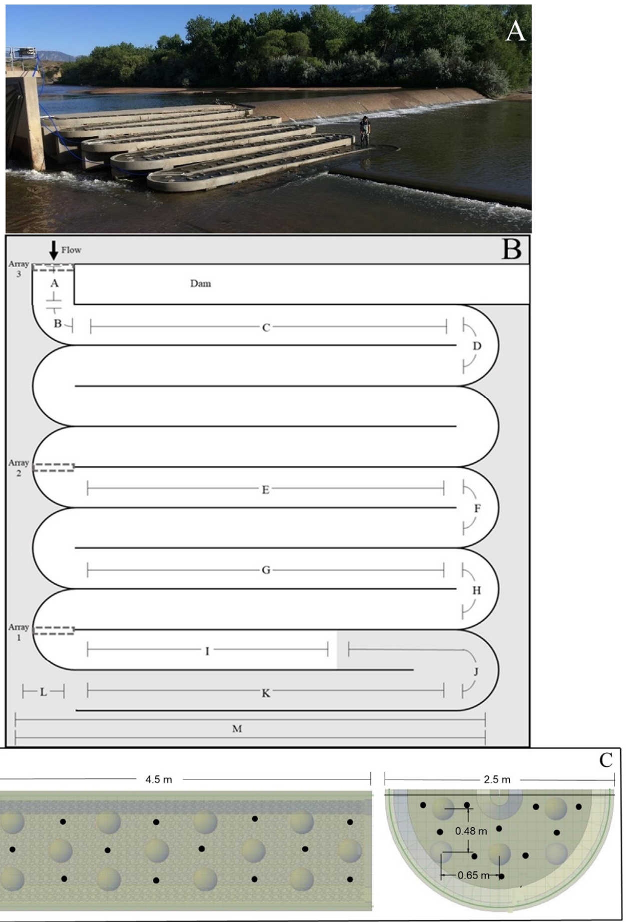

Figure 3. Scaling images for the Longrie–Fecteau fish passage structure on Fountain Creek, CO, USA. (**A**) Large-scale, upstream view of the structure noting potential attraction flows in areas away from the passage entrance. For scale, note the technician standing at the first corner of the structure. (**B**) Mid-scale, plan view of sections for hydraulic measurements (see Table 3 for results). Note: section M contained six transects, though only two are displayed to conserve space (**C**) Small scale view showing detailed view of representative roughness elements. Dots indicate locations of flow measurements.

2.2. Fishway Design and Construction

The LFFPS is a rock ramp fishway, and a limitation with this type of fishway is to maintain a low enough slope to ensure fish passage while still fitting in the available space for the structure (technical plans can be found in the Supplementary Materials). Since the Owens–Hall diversion is such a high barrier (2.8 m), the serpentine design was needed to maintain the slope at 2%, which is within the swimming capability of the poorest-swimming species in the assemblage (Arkansas darter), and to limit the physical footprint of the structure [18,46]. An additional focal species for the design of this structure was the flathead chub, but this species has higher swimming capabilities than the Arkansas darter [46,47].

The LFFPS was constructed with pre-cast reinforced concrete. The substrate was molded with small pebbles (various sizes up to 25 mm) to create a roughened surface, and larger molded concrete rocks spaced along the passage in a chevron pattern to provide refuge (Figure 3C). Areas of cast-in-place concrete were required when pre-cast sections were not feasible. This included the passage exit, diversion cap, and closure pours. Construction of the passage structure took three months and was performed from October to December to reduce the risk of high-flow monsoonal storm events. This timeframe included two weeks to divert the creek, time to recover from a large storm event that destroyed some of the completed work, snow delays, and a contractor having to re-pour one of the foundation walls that did not meet the required strength. The first step for construction was to divert water from the work area and prepare the diversion structure. The piers for the foundation walls were poured followed by the foundation walls. The precast sections were placed. Finally, the pre-cast closures, fish exit, curb, and diversion cap were poured. Water was then returned to the structure. Ideally, the only attraction flows that fish experience would be from the fish passage structure itself. However, the physical makeup of this particular barrier included other areas along the structure that have potential attraction flows, including the vertical drop, and the diversion gate, as there is minimal flow through the gate even when it is closed (Figure 3A). An important caveat with this design on this particular barrier was that the entrance was 1 m, which is only 2.9% of the length of the barrier. This small entrance reduces the probability of fish encountering the entrance compared to the other areas of the barrier.

The passage structure was designed to create velocities no greater than 0.3 m/s with rest intervals spaced every 0.2 m to meet the swimming characteristics of the poorest swimming species in the assemblage [46,47]. When flows increase and submerge the structures channels, which occurs at approximately 4.25 m^3/s, flow becomes perpendicular to the direction of the channel and likely restricts passage. Since construction, mean daily flows have been below this level 67% of the time and 82% of the time since 2018 (which were more normal water years).

2.3. Fish Sampling Methods

Fishes were collected by 12 weekly sampling events from July to November 2020 using backpack electrofishers (LR-24, Smith-Root, Inc., Vancouver, WA, USA) and 2-person pull seines (1.2 $\times$ 3.7 m seine with 9.5 mm mesh). Due to high turbidity at the site, collection was primarily accomplished by electrofishing downstream into a seine. Fishes were collected within 350 m downstream of the structure. All previously untagged fishes that were large enough to receive a PIT tag (>59 mm) were anesthetized with tricaine mesylate (MS-222), measured, and PIT tagged. Deploying PIT tags consisted of creating a ventral incision into the fish's body cavity just posterior to the left pectoral fin. The 12 mm half-duplex PIT tag (Oregon RFID, Inc., Portland, OR, USA) was inserted and one Braunamid suture (3/8 circle, 3/0) (Aesculap AG & Co, Tuttlingen, Germany) was applied with two half-hitch knots. All surgical tools and tags were sanitized in ethanol prior to use. Fish were allowed to recover equilibrium before being released approximately 7.5 m below the fish passage structure.

2.4. Antenna Construction and Operation

Three passive PIT tag reading antennae were placed across the width of the fish passage structure, which allowed for the detection of movement and direction of tagged fish within the structure (Figure 3B). Antennae were installed at the second and sixth turn as well as the upstream exit of the structure (termed A1, A2, and A3, respectively; Figure 3B). Depending on flow, lower areas of the structure may be submerged, but this placement of A1 ensured that all fish detected were in fact in the fish passage structure. We were interested in deploying an array below the structure to estimate attraction efficiency [32,48], but it was only possible to deploy arrays on the large concrete passage structure due to the shifting substrate and extreme flow events of Fountain Creek. Array construction followed protocol set forth in Richer et al. [25], with the exception of using four loops of wire, and housing wiring from the detection arrays to the tuning box in 2.54 cm CE Blue CTS SDR 9 plastic polyethylene pipe (Creslin Plastic Pipe, Co., Inc., Evansville, IN, USA). Read ranges of antennae were 31, 27, and 20 cm for A1, A2, and A3, respectively. Data were collected from the Oregon RFID Multiple Antenna PIT Tag Reader approximately once per week from July to November 2020.

The range of operation for the arrays was below approximately 8 m^3/s, as flows above this level caused water to inundate the structure with flows at a 90-degree angle to the fish passage structure. However, when there was an increase in flow over 10 m^3/s, the arrays were checked for function. Other operational limitations could have occurred if electricity was lost at the site. We were not aware of this occurring during our study.

2.5. Cormack–Jolly–Seber Model

The goal of model development was to test hypotheses regarding fish movement to and through the LFFPS, as well as estimate the detection probability of all arrays. Program MARK [49] was used to fit all models and obtain parameter estimates and an information-theoretic approach was used for model selection [50,51]. Parameters estimated included apparent survival (ϕ), which was used to estimate movement in this analysis, and detection probability (p) for each of the three arrays (Figures 3 and 4). Three movement parameters were estimated, including movement from release to A1 (ϕ_1), movement from A1 to A2 (ϕ_2), and movement from A2 to A3 (ϕ_3) (Figure 4). A key parameter estimated is ϕ_1, which incorporates survival over a longer time period than ϕ_2 or ϕ_3, a decision to move, the ability to find the entrance to the structure, and then a choice to enter and ascend the fish passage structure. Total travel distance from the entrance of the fishway to its exit was 123.3 m (structure entrance to A1 = 22.3 m; A1 to A2 = 49.7 m; A2 to A3 = 49.7; A3 to structure exit = 1.6 m).

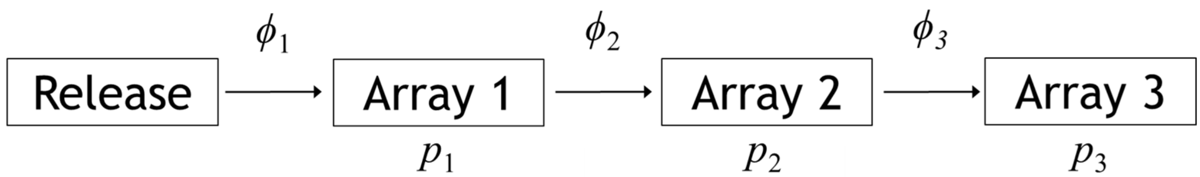

Figure 4. Conceptual model of the Cormack–Jolly–Seber analysis for Great Plains fish movement through the Longrie–Fecteau fish passage structure in Fountain Creek, CO, USA.

Encounter histories were constructed for each fish starting with the initial release. A total of three sampling occasions were included, consisting of detection at A1, A2, and A3, respectively. Therefore, the encounter history for a successful ascent was 1111, and for a fish that was released and never detected again was 1000. Fish total length was added to the end of the encounter history as an individual covariate. Movement and detection probability covariates included fish total length (TL; mm) and array number. All combinations of intercept, individual, and additive models were run, resulting in a model set consisting of 16 models. Models were ranked by the AICc values and all parameter estimates were model averaged [50].

2.6. Timing of Movements

For each detection, time of day was recorded to determine if the movement was during day or night. Since this study encompassed July–November, times of sunrise and sunset varied, which was accounted for in our analyses. Time spent in the LFFPS was estimated by using the first time a fish was detected by A1, and then the latest time they were detected by A3.

2.7. Hydraulic Measurements

Point measurements for depth and velocity were collected at the bottom and 60% depth with a Marsh–McBirney Flo-Mate 2000 at 248 locations to evaluate hydraulic conditions within and just below the fishway (Figure 3C). These data were used to calculate the Froude number (F), with the following equation:

$$F = \frac{V}{\sqrt{\mathrm{gh}}} \quad (1)$$

where V is depth-averaged water velocity, g is the gravitational constant (9.81 $\mathrm{m/s^2}$), and h is water depth [25,52,53]. Since the LFFPS passes a set volume of water, hydraulic measurements were made once as hydraulic conditions will be consistent as long as the fish passage structure is operational (below 4.25 $\mathrm{m^3/s}$). Measurements were taken 10 June 2022 when the discharge was 2.27 $\mathrm{m^3/s}$.

3. Results

3.1. Tagging Summary

Weekly sampling efforts resulted in a total of 1327 fishes from eight species being implanted with PIT tags (Table 1). The majority of these were flathead chub (n = 816; 61%), followed by white sucker (*Catostomus commersonii*) (n = 367; 28%). The average fish total length was 104 mm and ranged from 59 to 297 mm (Table 1). Four fish species were documented successfully ascending the structure, which were flathead chub, white sucker, central stoneroller (*Campostoma anomalum*), and creek chub (*Semotilus atromaculatus*). Passage efficiency was low and ranged from 0% to 3.1% for species with multiple PIT tagged individuals (Table 1).

Table 1. Summary of the number (#) of native Great Plains fishes PIT tagged below the Longrie–Fecteau fish passage structure in Fountain Creek, Colorado, USA.

Species	# PIT Tagged	# Detected	Passage Efficiency	% Nighttime Movement	Total Length (Mean (Range); mm)
Flathead chub (*Platygobio gracilis*)	816	24	2.9%	85%	100 (63–177)
White sucker (*Catostomus comersonii*)	367	10	2.7%	80%	117 (70–297)
Central stoneroller (*Campostoma anomalum*)	65	1	1.5%	100%	84 (67–144)
Longnose dace (*Rhinichthys cataractae*)	32	1	3.1%	100%	73 (61–99)
Creek chub (*Semotilus atromaculatus*)	1	1	100%	0%	109
Longnose sucker (*Catostomus catostomus*)	41	0	0%	-	113 (83–187)
Fathead minnow (*Pimephales promelas*)	4	0	0%	-	62 (59–66)
Sand shiner (*Notropis stramineus*)	1	0	0%	-	63
Total	1327	37		-	104 (59–297)

3.2. Cormack–Jolly–Seber Results

The top model from a Cormack–Jolly–Seber analysis included ϕ(array) and p(total length), which indicates differences in passage based on arrays (Table 2). The lowest movement probability was from the release point to the first antenna (ϕ_1 = 0.03; SE = 0.02–0.04), which was expected, as a released fish needed to find the 1.25 m entrance to the fish passage structure, and then, depending on the water level, ascend 22.3 m to reach A1 (Figure 3). However, once fish were in the structure, there were high rates of successful ascension, with ϕ_2 = 0.89 (SE = 0.73–0.96) and ϕ_3 = 0.99 (SE = 0.87–1.03). Specifically, there is a 3% probability of a released fish encountering the first array, but once in the structure, there is an 88% (0.89 × 0.99) probability that the fish will successfully ascend it.

Table 2. Cormack–Jolly–Seber models in Program MARK used to estimate movement (ϕ) and detection probability (p) for PIT-tagged Great Plains fishes in Fountain Creek, Co, USA. The top eight models selected by Akaike's information criterion (AICc) and model weights are shown for comparison. The maximized log-likelihood (-2log(L)), the number of parameters (K) in each model, and the small sample size-corrected values (AICc) are shown. Models are ranked by their AICc differences (ΔAICc) relative to the best model in the set and Akaike weights (w_i) quantify the probability that a particular model is the best model in the set given the data and the model set.

Model	AIC_c	ΔAIC_c	w_i	Likelihood	K	−2Log(L)
ϕ(array) p(TL)	389.1491	0.0000	0.36302	1.0000	5	379.1058
ϕ(array) p(.)	390.5102	1.3611	0.18381	0.5063	4	382.4815
ϕ(array + TL) p(TL)	391.1536	2.0045	0.13325	0.3671	6	379.0930
ϕ(array) p(array)	391.6376	2.4885	0.10461	0.2882	6	379.5770
ϕ(array + TL) p(.)	392.5174	3.3683	0.06738	0.1856	5	382.4742
ϕ(array + TL) p(array + TL)	392.5990	3.4499	0.06468	0.1782	8	376.4949
ϕ(array) p(array + TL)	393.3235	4.1744	0.04503	0.1240	7	379.2427
ϕ(array + TL) p(array)	393.6507	4.5016	0.03823	0.1053	7	379.5699

Detection probabilities for the three arrays were high, with the lowest detection probability being A2 at 0.97 (0.81–0.99). Detection probability for the top model included the fish total length covariate. The beta for this estimate was positive (0.093), indicating the detection probability for larger fish was greater than for smaller fish. However, the confidence interval overlapped zero (−0.025–0.211), indicating this was a weak relationship.

3.3. Timing of Movements

Most movement through the LFFPS took place at night, with 85% of flathead chub movements and 80% of white sucker movements occurring at night (Table 1; Figure 5). Although only one individual was detected per species, both the central stoneroller and creek chub ascents took place at night. Median time for successful ascent was 19 min across all species (range = 6 min–12 h). Fishes were detected using the LFFPS from initiation of this study in July, and the last detection was 21 October 2020 (Figure 6). Increases in movement through the structure occurred during August and early September, with another increase in use in October (Figure 6).

3.4. Hydraulic Measurements

Throughout the passage structure and immediately downstream of it, velocity measurements at the bottom of the channel and 60% depth averaged 0.19 m/s (range = 0.13–0.24) and 0.21 (range = 0.14–0.26), respectively (Table 3). As the discharge of Fountain Creek during the time of flow measurements was 2.27 m^3/s, the most downstream straight and curved sections were inundated (sections J, K, and L in Figure 3B). The structure has withstood a variation in flow of 0.3–523.9 m^3/s since construction (USGS gage station 07106500; Figure 2).

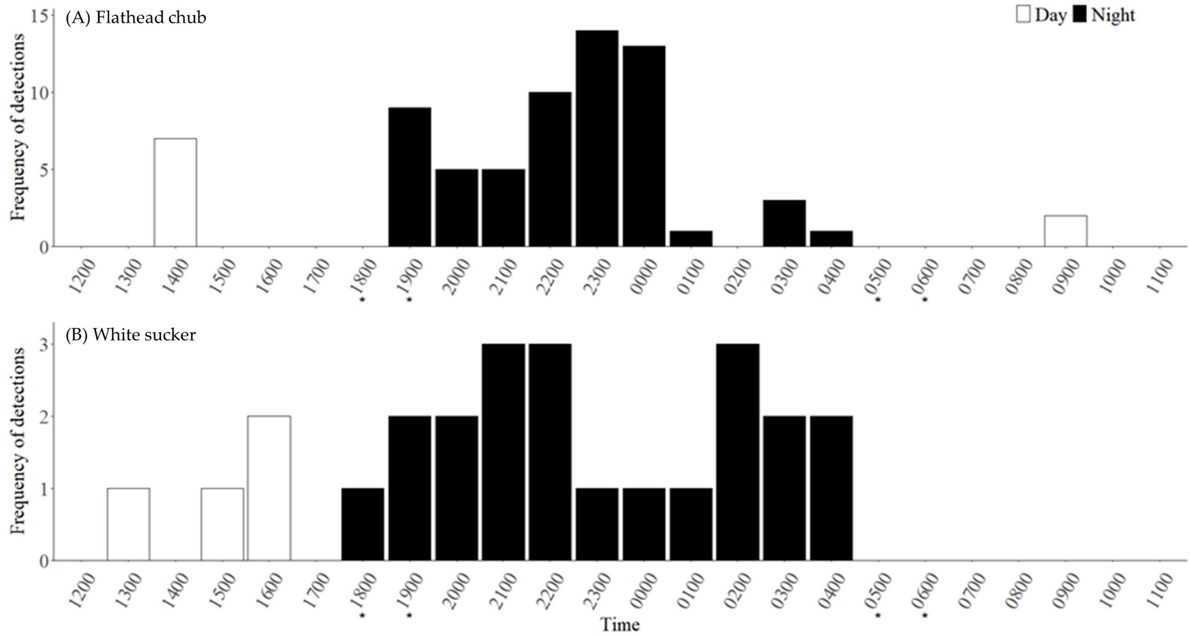

Figure 5. Frequency of PIT tag detections (pooled across all antennae) for (**A**) flathead chub and (**B**) white sucker moving through the Longrie–Fecteau fish passage structure on Fountain Creek, CO, USA. Asterisks indicate hours that differed in light levels due to seasonality. During the study period, sunrise and sunset ranged from 0554 to 0714 and 1811 to 2015, respectively. All detections occurring during hours of variable light (*) were at night.

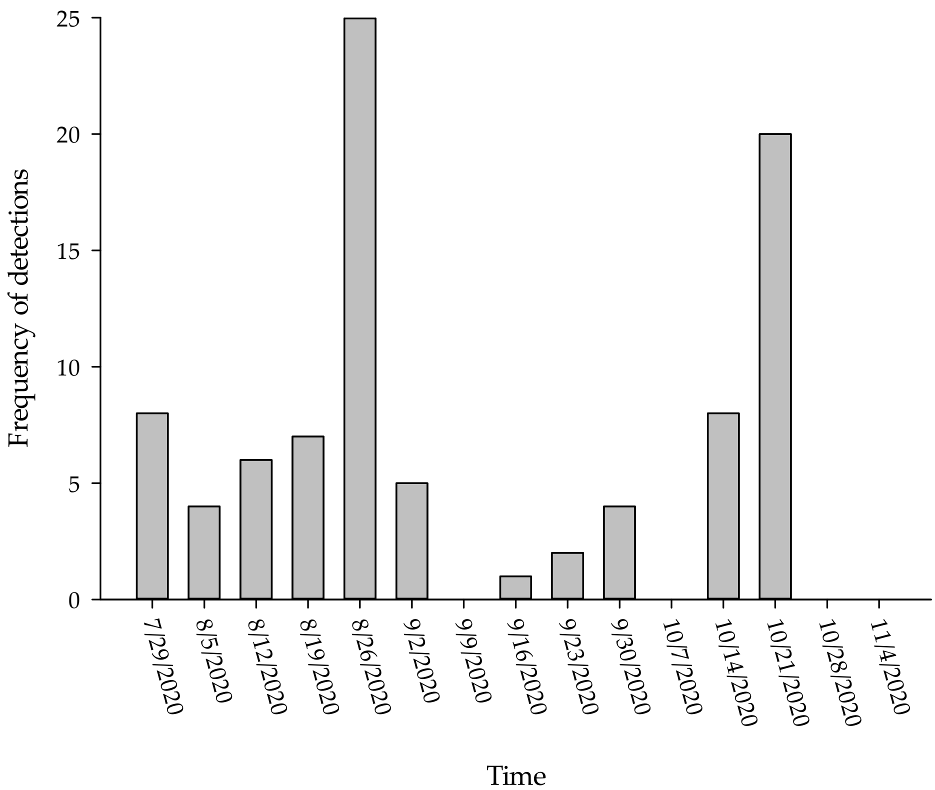

Figure 6. Weekly summary of the frequency of PIT tag detections (pooled across all antennae) for Great Plains fishes in the Longrie–Fecteau fish passage structure in Fountain Creek, CO, USA.

Table 3. The number (#) of hydraulic measurements collected throughout the Longrie–Fecteau fish passage structure on Fountain Creek, Colorado, USA. Definitions of locations can be seen in Figure 3.

Label	Description	# of Point Measurements	Depth (m)	Bottom Velocity (m/s)	60% Velocity (m/s)	Froude #
A	Apron	42	0.28	0.27	0.33	0.20
B	Immediately downstream	12	0.37	−0.04	−0.04	−0.02
C	Submerged straight	28	0.14	0.08	0.06	0.05
D	Submerged corner	10	0.22	0.07	0.13	0.09
E	Entrance	28	0.12	0.13	0.14	0.13
F	Bottom corner	10	0.12	0.20	0.22	0.21
G	Bottom straight	28	0.12	0.22	0.23	0.22
H	Middle corner	10	0.12	0.22	0.26	0.24
I	Middle straight	28	0.12	0.20	0.21	0.19
J	Top corner	10	0.12	0.16	0.17	0.16
K	Top straight	28	0.12	0.20	0.22	0.21
L	90° corner	8	0.12	0.24	0.25	0.23
M	Exit	6	0.12	0.17	0.18	0.17

4. Discussion

Four species of small-bodied native Great Plains fishes were detected successfully passing the LFFPS, and the LFFPS has withstood a dynamic flow regime since initial construction. We acknowledge that entrance probability was low and was an issue at our site (3% from the release point to A1), but once in the structure, the probability of full passage was high (99% to A3), with most movement occurring at night.

Successful fish passage via this design is unique not only in that it is considerably longer than most fishways used to pass small-bodied fishes (123 m) [54], but that movement throughout its entirety requires nine, 180° turns. The number of corners was especially important as they allowed the structure to maintain a shallow gradient of 2%, known to increase the probability of passage, while decreasing the overall footprint and size of the apron required for installation [46,47]. The probability of successful passage once fish were in the structure was high and compares well with other studies of nature-like fish passage structures. Richer et al. [25] had successful passage (ϕP) that ranged from 0.22 to 1.00 depending on species, including 0.43 ± 0.19 for white sucker. Bunt et al. [55] documented passage success of nature-like fish passage structures with 3% slope, with a range = 0–100%, mean = 70%, and median = 86%. The probability of successful upstream passage, defined as entering and successfully ascending the structure (ϕE × ϕP), ranged from 0.05 ± 0.05 for longnose dace (*Rhinichthys cataractae*), to 0.51 ± 0.09 for brown trout (*Salmo trutta*). The common species between our studies was the white sucker, which has a total probability of successful passage of 0.17 ± 0.14.

While the LFFPS had a high passage probability and relatively little time needed to traverse the structure once fish were in it, the efficacy of any fishway is ultimately limited by the probability of fishes encountering and entering it [28]. The probability of fishes entering the fish passage structure in this study (ϕ_1 = 0.03) is low compared to other studies examining rock ramp fish passage structures. For example, Richer et al. [25], who also examined a rock ramp fish passage structure on the Front Range of Colorado, observed the probability of fish entering their fish passage structure (ϕE) ranged from 0.12 (longnose sucker (*Catostomus catostomus*)) to 0.51 (brown trout). The common species between our studies is the white sucker, which had ϕE = 0.40 ± 0.16, which is much higher than ϕ_1 = 0.03 for this study. Bunt et al. [55] observed attraction rates of nature-like fishways ranging from 0 to100% with a mean = 48% and median = 50%. As the attraction efficiency is so low, if this design were to be used on a series of barriers, the proportion of fish making it through all of the barriers would be effectively zero. Using this design as a template for other barriers in this area was a motivating factor for developing this design, which is why continued efforts must be deployed to improve the entry efficiency. These efforts may include reducing the attraction flows in other areas, especially any flows that may make it through the sluice gate. In addition, structures could be added to make hydraulic conditions unattractive in other areas below the barrier [56,57], which would guide fish toward the entrance. Auxiliary flows could also be added to increase attraction near the entrance of the passage structure [27,58,59]. Otherwise, other more tested designs may be more appropriate to be deployed [23,25,32,60,61].

The low entrance efficiency for the LFFPS can be attributed to three reasons. First, nonsalmonids have been shown to have lower passage efficiency than salmonids (21.1% versus 61.7%) [31]. Second, this is a mark–recapture study of a small-bodied organism in a relatively large system, making recaptures difficult. A series of events need to take place in order for fish to be detected at ϕ_1 (Figure 4), including the fish surviving a longer time period than during the other ϕ calculations, choosing to move, moving in the correct direction for detection, finding the entrance, and then choosing to ascend the structure. This series of events that must take place for the fish to be detected in the passage structure results in the low entrance efficiency. A third potential reason for low recapture rates was likely due to sub-optimal attraction flows near its downstream entrance and attraction flows in other areas of the barrier. One method to mitigate low entrance efficiency is to cage fish below the structure and see how many fish ascend the structure. However, this could result in unnaturally high densities of fish in the cages, as well as predator species with prey species, both causing additional motivation to ascend a barrier when under normal conditions those fish may not find the entrance or choose to ascend it. The leptokurtic distribution of many fish movement studies [62–64], indicates that although not as many fish move (or are detected as having moved) as fish that are collected at the same location, the fish that move are important for gene flow and recolonizing extirpated areas [3,4]. Based on the facts that this barrier is impassable when the sluice gate is closed (2.8 m high at 74% slope), there is low movement when the sluice gate is open (0.017%) [42], and there is extensive movement at sites that do not have a barrier (Ryan Fitzpatrick, unpublished data), we think our entrance efficiency is ecologically relevant even though it is low.

Detection probability (p) was an initial concern in our study, due to the large amount of metal (particularly rebar) in the passage structure potentially interfering with the read range of the PIT tag reading arrays. However, p was high for all three arrays (0.97–0.98), which compares well with other studies of fish passage structures that used PIT tag reading arrays. Richer et al. [25] used two arrays and had a p for white sucker of 0.99 $\pm$ 0.18. This was comparable to the other species in their study, which had a total detection probability that ranged from 0.80 to 0.99 among species.

Temporal use of the structure observed in this study (Figure 5) supports the literature on increased nocturnal movement by certain stream fishes [65] and specifically corroborate this behavior in flathead chub from Fountain Creek previously observed in a laboratory setting [46,66]. The increased movement at night has implications for fish passage structures in urban environments where there is the possibility of artificial light impairing nocturnally moving species [67]. However, differences in diurnal movement is species specific, as increased movement of stream fishes during the day has also been documented [68]. For example, Swarr [46] documented higher daytime movement of the Arkansas darter compared to night movements. There are also implications for diversion gate operation, as opening the gate temporarily dries the passage structure. Gate operation should avoid times of high fish passage for the species of highest conservation priority. An interesting result of the seasonal use of the LFFPS was that it increased in late September and mid-October (Figure 6). This is after the spawning migration for flathead chub [42,45], indicating the need for connectivity outside known periods of migration.

While flows near the entrance did not effectively attract fishes to the LFFPS, velocities within the structure promoted successful ascension once in the structure. Determining appropriate flow velocities within a fishway is vital to passage with the inclusion of multiple species requiring further refinement. One approach is to simply tailor velocities to the weakest swimming species [69]. Measured flow velocities in all but one portion of the structure met the initial design goal of a maximum velocity of 0.3 m/s (Table 3). As our measurements were collected during a period where flows partly submerged the structure, they represent peak velocities at which water can pass down the channels of the LFFPS. Compared to other passage structures designed for small-bodied fishes, the average velocity of 0.2 m/s observed across the structure is quite slow [54,69]. It is also important to note that observed velocities fall below the maximum swimming abilities reported for species tagged in this study (e.g., flathead chub, white sucker, creek chub, central stoneroller, longnose sucker, longnose dace, and sand shiner (*Notropis stramineus*)) [17,47,70–72], as well as native northern plains killifish (*Fundulus kansae*) that were not. As velocities of the LFFPS occur within the range of maximum swimming speeds for Arkansas darter, their passage may be discharge-dependent [18]. However, the capture of an individual within the LFFPS during the study period suggests use. In addition to the relatively low velocities observed, large roughness elements may create local, low-velocity zones, which provide refuge and are thought to promote successful passage [73]. As would be expected with low velocities, Froude numbers were low. Yu and Peters [53] found a Froude number greater than 0.3 could restrict Great Plains fish movement, but the LFFPS did not approach that level.

One of the primary limitations to any conservation or management action is the availability of funding [74]. Considering the immense number of impassable structures within lotic environments, an economically feasible option for fishways will be critical to broad scale implementation. A cost-efficiency of this design is the site-generic portions that simply need to be cast and installed. Approximate costs for each LFFPS casted portion were as follows in 2014: $6000 per corner portion, $9000 per straight portion, and $4000 for the foundation for each section. We acknowledge that these costs have likely increased in the time since construction. While these values do not factor in design, installation, or future maintenance, cost per linear meter of the LFFPS at the Owens Hall diversion is less than half of similar fishways [23,54,69,75,76]. All costs were compared in U.S. dollars reported from 2012 to 2021. As hydropower and agricultural development expands, any cost-efficiencies gained may improve the probability of inclusion of passage structures within the design of barriers as well as retrofitting passage to already existing barriers. Other financial considerations that will vary depending on the site include the passage entrance and exit, the cast-in-place cap to limit sheet flow over the passage structure, diverting and dewatering the creek during construction, and additional foundation construction to support the pre-cast sections.

Maintenance of the LFFPS has been minimal. An initial concern with the design was sediment transport, as the low velocity refuge areas required by fishes could allow sediment to deposit in the passage structure. Although sediment was not measured in this study, only a few minor areas of sediment deposition were observed. To aid in sediment transport, the passage exit and water entrance were placed near the diversion gate of the diversion and above the channel bottom to minimize sediment entering the structure. One maintenance issue has been large pieces of wood impinging on the structure during high flow events. Given the flashy flow regime of Fountain Creek, managers often waited for the next high flow event, which usually cleared the structure of any large wood. However, if this design is deployed in a system that is not as flashy at Fountain Creek, managers should have a plan to remove large wood from the structure.

5. Conclusions

The LFFPS has been shown to pass four species of Great Plains fishes and withstand an extreme flow regime. There was a low entrance probability due to the small-bodied study organisms in this study, the relatively large system in which the study took place, and other areas of the barrier that had attraction flows. However, even a small proportion of a population moving can potentially reinvade extirpated areas or provide gene flow. Future work needs to focus on improving the attraction efficiency of this structure by either reducing other areas that may have attraction flows, adding structures to make hydraulic conditions unattractive in other areas to guide fish to the entrance, or adding auxiliary flows at the entrance. Once fish entered the structure, there was high probability of passage success in a short amount of time, even though this structure is long (123 m). Other systems where this fish passage design would likely have higher entrance probability would be a narrow, non-migratory channel where there is a higher likelihood of fishes encountering the entrance, as opposed to the wide, migrating channel examined in this study. In addition, a relatively stable flow regime would increase the amount of time that the structure was functional.

Supplementary Materials: The technical plans can be downloaded at https://cpw.state.co.us/learn/Pages/RA-Owens-Hall-Fish-Passage-Structure-Evaluation.aspx.

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