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A low-water crossing impacts Northern Hog Sucker *Hypentelium nigricans* movement in an Ozark stream

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ABSTRACT

Streams are complex systems that rely on connectivity to maintain natural ecological function. Low-water crossings are common in small-intermediate sized streams and can restrict longitudinal movement of fishes. The Current River in Missouri (USA) contains a single anthropogenic barrier to longitudinal connectivity: the Cedar Grove low-water crossing, which spans the main channel (10 culverts) and a side channel (4 culverts). In July 2017, we radio-tagged Northern Hog Sucker *Hypentelium nigricans* upstream (henceforth 'above'; N = 24) and downstream (henceforth 'below'; N = 26) of the crossing and followed their movements monthly for a year to assess fish passage and maximum displacement. Passage was limited to four below-tagged fish passing upstream of the crossing with one fish making an additional downstream and then upstream passage. Passage was more likely to occur during high flow. On average, below-tagged fish exhibited more than seven times greater maximum displacement (Mean (M) = 6.55 km, Standard Error (SE) = 2.91 km) than above-tagged fish (M = 0.92 km, SE = 0.33 km). The majority (71%) of fish exhibited stationary behavior (<1 km) compared to mobile behavior (>1 km). Among mobile individuals, maximum displacement was greatest away from the crossing, with above-tagged fish favoring upstream movements (100%) and below-tagged fish favoring downstream movements (67%). Our results suggest the crossing is a semi-permeable barrier in which fish passage primarily occurs during high flows. Alternatives to the low-water crossings at Cedar Grove should be considered to promote natural longitudinal movement of fishes. The side channel provides a potentially impactful and economically feasible management opportunity to act as a fish bypass channel on the Current River.

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Introduction

Longitudinal connectivity provides material resources from upstream to downstream as well as a migration corridor for aquatic organisms to essential habitat (Ward and Stanford 1995; Ensign and Doyle 2006; McIntyre et al. 2008). For fish, longitudinal connectivity is critical for promoting movement to feeding, spawning, and seasonal habitats that are often distantly distributed within stream networks (Calles and Greenberg 2009; Armstrong and Schindler 2013; Ettinger-Dietzel et al. 2016; Wells et al. 2017). For example, Armstrong and Schindler (2013) found that juvenile Coho Salmon *Oncorhynchus kisutch* use the spatial heterogeneity in diel water temperature by feeding on salmon eggs in colder water before dispersing up to 1 km upstream to warmer headwater reaches to promote digestion. Several sucker species, (White Sucker *Catostomus commersonnii*, Black Redhorse *Moxostoma duquesnei*, Greater Redhorse *Moxostoma valenciennesi*, and Razorback Sucker *Xyrauchen texanus*) have been documented migrating from 6 to 50 km to reach spawning grounds (Raney and Webster 1942; Bowman 1970; Modde and Irving 1998; Bunt and Cooke 2001).

A major anthropogenic effect on longitudinal connectivity and fish movement in lotic systems worldwide is the construction of barriers (e.g. dams, weirs, and road crossings). The United States alone has approximately 82,000 dams over 2 m in height and 2,000,000 smaller structures that disrupt longitudinal connectivity (Baker et al. 2011). Huusko et al. (2018) followed the downstream migration of juvenile Atlantic Salmon *Salmo salar* in both a regulated (five dams) and adjacent free-flowing river and found six times greater survival of smolt in the free-flowing system. Anadromous salmonids have received the bulk of research attention regarding barriers due to the clear importance of longitudinal connectivity in their life histories and the economic importance of these taxa (Gowans et al. 1999; Scruton et al. 2007; Davis and Davis 2011). However, smaller barriers (e.g. weirs and road crossings) and less economically important stream fishes such as *Campostoma* spp., *Cyprinella* spp., and *Cottus* spp. have received more attention over the past decade (Benton et al. 2008; Helms et al. 2011; Mueller et al. 2011). Smaller barriers are often considered semi-permeable in which fish passage is enhanced during high flow events. For example, high flows may temporarily reestablish stream connectivity through perched culverts or provide alternative pathways around barriers of other types (Perkin and Gido 2012).

Low-water crossings are common in low order streams and range in size and complexity. Crossings containing pipe culverts appear to have a greater negative impact on fish movement than box culverts, open span bridges, and natural reaches (Warren and Pardew 1998; Benton et al. 2008). Pipe culverts primarily inhibit fish movement by creating jump, velocity, and depth barriers (Benton et al. 2008; Hansen and Reeves 2008; Bouska and Paukert 2010; Eisenhour and Floyd 2013). Studying the impacts of low-water crossings on a variety of fishes can provide important information on how these barriers affect the longitudinal distribution of understudied, common stream fishes and associated ecosystem processes.

The Northern Hog Sucker *Hypentelium nigricans* is widely distributed throughout much of the Mississippi River Basin where it inhabits riffle, run, and pool habitat in streams with permanent flow and clean gravel substrate (Pflieger 1997). Adults commonly reach 203–381 mm in length and weigh between 136–635 g (Pflieger 1997). The Northern Hog Sucker is a benthic species and can exhibit mean daily movements of at least 425 m (Matheney and Rabeni 1995). In the Missouri Ozarks, it is an abundant game fish and is commonly found in loosely organized schools of conspecifics and heterospecifics (e.g. *Moxostoma* spp.). Spawning in Missouri occurs during spring (April–May) when fish

move into the heads and tails of pool habitat with moderate velocities and depth (Matheney and Rabeni 1995).

Velocity barriers, such as those commonly associated with low-water crossings containing pipe culverts, may negatively impact the longitudinal movements of Northern Hog Suckers. For example, juveniles (25 mm TL—total length) have a FV50 (velocity in which 50% of fish fail to maintain their position in a 30-minute period) of 0.142 m/s with adults (330 mm TL) projected to have a FV50 of 1.485 m/s (Ivasauskas 2017). Additionally, Northern Hog Suckers, like many other stream fishes, have been found to exhibit both mobile and stationary behaviors (Matheney and Rabeni 1995; Radinger and Wolter 2014). Movements necessary for this species to reach suitable habitats during different life stages (juveniles vs. spawning adults), seasons (summer vs. overwintering habitat), or mobility types (mobile vs. stationary) make Northern Hog Suckers vulnerable to high velocity barriers that restrict longitudinal movement.

We investigated potential differences in movement behavior of Northern Hog Suckers located upstream (henceforth 'above') and downstream (henceforth 'below') of a large, pipe-culvert lined low-water crossing in a third-order Ozark river. To assess differences in above and below-tagged fish, we tested four hypotheses. H1) The crossing limits fish passage to periods of high flow. H2) Velocity barriers caused by the pipe culverts (frequently > FV50) restrict upstream-directed passage. H3) Maximum displacement in above vs. below mobile fish is similar; however, (H4) the direction of displacement is upstream-directed in above-tagged fish and downstream-directed in below-tagged fish.

Materials and methods

Study site

The Current River is located within the Ozark Plateau of Southeastern Missouri, USA. The Ozark region consists of karst topography which includes shallow, porous soils over cherty limestone and dolomites as well as numerous caves, sinkholes, and springs (Matheney and Rabeni 1995; Orndorff et al. 2001). Channel gradient of the Current River averages 0.74 m/km (Ettinger-Dietzel et al. 2016). The river's baseflow is primarily spring-fed, but the flow regime is strongly influenced by rainfall events with highest flows occurring during spring months, on average (Leasure et al. 2016). Ozark National Scenic Riverways (OZAR, National Park Service) encompasses 5% of the river's watershed and helps protect over 100 species of fish along much of its 296 km length (Dodd 2009, 2013). The river is free flowing with the exception of a single low-water crossing 17 km downstream of the river's source (Wilkerson 2003; Figure 1).

The Cedar Grove low-water crossing (Figure 1; henceforth 'the crossing') consists of two structures, one spanning the main channel (Figure 2: A and B; Table 1) and another spanning a side channel (Figure 2: C and D; Table 1). During baseflow, all flow is forced through corrugated pipe culverts (Table 1). The culverts are non-perched year-round, due in part to stable baseflow. Both structures create upstream impoundment pools with moderate to heavy sediment deposition and scoured downstream plunge pools followed immediately (<10 m) by natural riffle-pool sequence (Figure 2; Table 2).

Sampling design

In July 2017, Northern Hog Suckers were collected using boat electrofishing procedures outlined in Peterson et al. (2008). We anesthetized fish using a solution of river water and
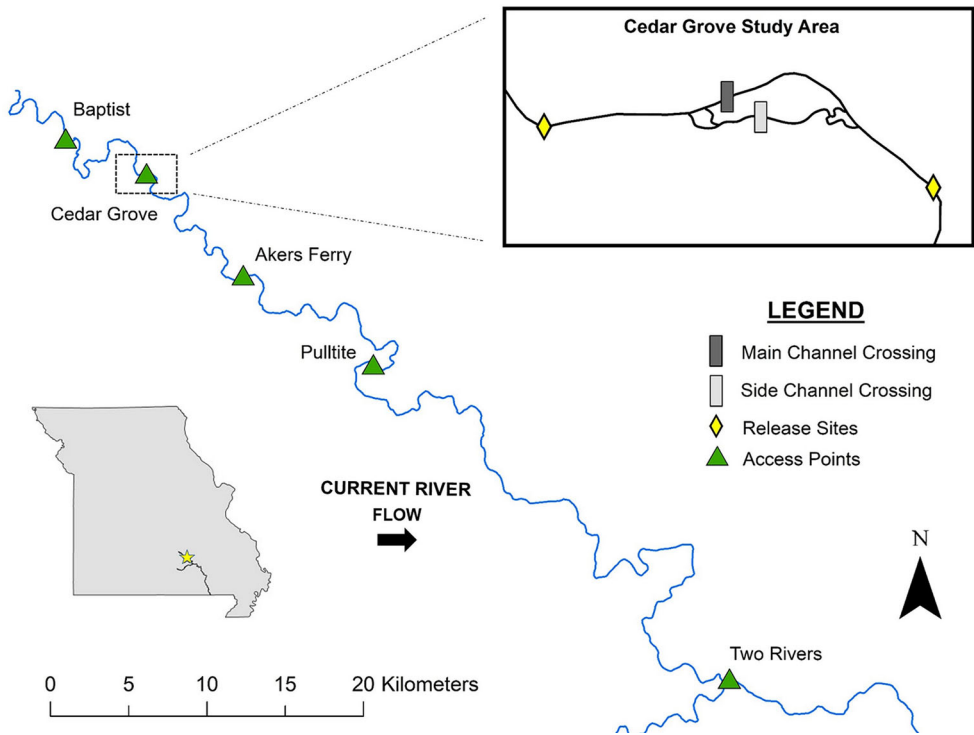
Figure 1. Map showing the headwaters of the Current River and the Cedar Grove study area (37°25′19″ N, 91°36′30″ W). Northern Hog Sucker release sites (diamonds), low-water crossings (dark and light rectangles), and commonly used access points (triangles) are represented. Main tracking efforts were conducted between Baptist and Akers Ferry access points with periodic extended surveys to Two Rivers.

Figure 2. (A) Downstream view of the main channel crossing at Cedar Grove. (B) Upstream view of the main channel crossing showing heavy amounts of sediment deposition. (C) Downstream view of the side channel crossing at Cedar Grove. (D) Upstream view of the side channel crossing showing lighter sediment deposition. Pictures were taken February 9, 2018. Discharge at the Cedar Grove low-water crossing is 2.33 m³/s (Akers Ferry = 5.10 m³/s).

seltzer water (H_2CO_3) in a holding container, maintaining a CO_2 concentration of 400 mg/L and dissolved oxygen concentration around 5 mg/L (Summerfelt and Smith 1990). This study evaluated individuals >181 g that were surgically equipped with radio transmitters with a trailing whip antenna (Advanced Telemetry Systems, F1580, 3.6 g, 441-day battery life, Frequencies: 164.013–165.692 Hz), such that tags were less than 2%

Table 1. Physical characteristics of the main and side channel crossing and associated culverts.

	Width (m)	Number of culverts	Culvert description		
			Length (m)	Diameter (m)	Velocity range (m/s)
Main channel	60	10	9	0.7	0.87–2.57
Side channel	24	4	11	0.5–0.7	0.31–0.75

Velocity range is during baseflow conditions and was taken at the culvert outflows.

Table 2. Physical characteristics of the upstream impoundment pool and downstream plunge pool associated with the main and side channel crossing at Cedar Grove.

	Length (m)	Width (m)	Mean depth (m)	Substrate
Impoundment pool				
Main channel	400	33	1.5	Sand - cobble
Side channel	100	9	0.6	Sand
Plunge pool				
Main channel	15	38	1	Cobble
Side channel	10	10.5	1	Cobble - boulder

of the body weight (Matheney and Rabeni 1995). We tagged 24 fish above and 26 fish below the crossing and allowed fish two hours to recover before releasing them centrally within the two sample reaches, approximately 600 m upstream and downstream of the crossing (Figure 1). Initial mortality was high (N = 17) and likely associated with tagging stress, warm water temperatures, and predation. To recover the sample size, we conducted a second tagging event above (N = 8) and below (N = 9) the crossing in November 2017.

We conducted 14 surveys between July 2017 and June 2018 (Figure 3). A 40 km stretch of the Current River, between Baptist Access and Pulltite Campground (Figure 1) was searched during each tracking event. Extended surveys were conducted downstream to Two Rivers in March and December 2017 to search for fish previously undetected within the main sample stretch (Figure 1). We surveyed monthly during periods of low flow (summer: June–August, fall: September–November, winter: December–February) and increased survey frequency during periods of higher flow and spawning season (spring: March–May, Figure 3). We assessed fish position by first floating the study area with a receiver (Lotek Wireless, Biotrack Reciever, 3-element Yagi Antenna) until we were within close proximity of a tagged fish. We then determined individual fish locations with triangulation from river's edge, as to not disturb the fish. The position of each fish was then recorded using a Trimble Geo7x GPS unit with sub-meter accuracy. If tagged fish were not visible during data collection, fish were temporarily monitored to ensure tags were not shed.

In order to monitor key water levels associated with the crossing, we deployed a series of iButtons (Maxim Integrated) that logged temperature every two hours and were placed downstream of both main and side channel crossings at four vertical levels: 1) near the stream bed in deep water (water temperature control); 2) at the top of the culverts (high flow); 3) at the top of the crossing (inundation of the crossing); 4) above a floodplain terrace lateral to the channel (air temperature control). Because air temperature fluctuates more rapidly than water temperature, due to water's higher heat capacity (Perlman 2018), we were able to determine if the water column reached these vertical stages by evaluating temperature differences between the two mid-level loggers (culverts and top of crossing) and the controls for water and air temperature throughout the study period. As such, we could ask whether fish passage events were associated with high flow events at the crossing, and we could approximate stream discharge during these events, as recorded by a US Geological Survey (USGS) gauge station (07064533, Akers Ferry) approximately 13 km
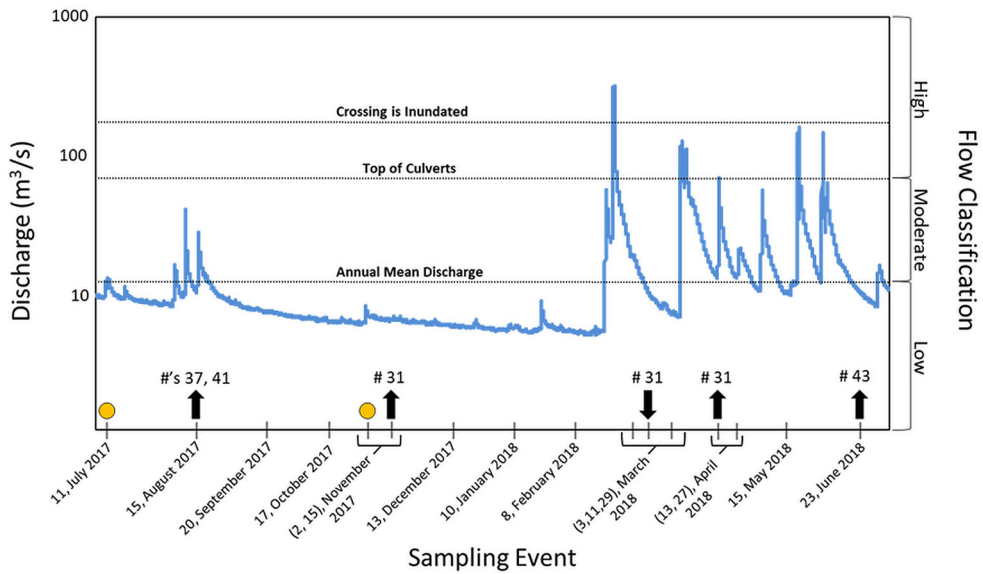
Figure 3. Stream discharge at USGS gauge station 07064533 during the study period. The gauge is approximately 13 Km downstream of the crossing near Akers, MO. Sampling events are represented on the x-axis with the two tagging events indicated by circles. Arrows indicate when a fish passage was detected and the direction of that passage (upstream/downstream). Numbers above each arrow represent the ID of each fish which passed (Appendix). The 17 year annual mean discharge ($12\,m^3$/s) and point in which the water level at the crossing reached the top of the culverts ($70\,m^3$/s), and inundated the crossing ($300\,m^3$/s) are plotted on the hydrograph. Flow classifications used in the study are represented on the right side of the y-axis.

downstream of the crossing (Figure 3). For the purpose of this study, we classified flow magnitude in the following categories: low flow ($\leq 12\,m^3$/s, 17-year annual mean discharge (AMD) at gauge or bottom of culverts), moderate flow ($12–70\,m^3$/s, between bottom and top of culverts), and high flow ($>70\,m^3$/s, exceeding top of culverts, Figure 3). The crossing was completely inundated when flow was approximately $300\,m^3$/s at the Akers Ferry gauge.

Data analyses

Telemetry data were uploaded with GPS Pathfinder Office (Version 5.85) and imported into ArcMap 10.3 for analysis. Fish passage events were confirmed if a fish tagged downstream of the crossing was located upstream of the crossing during a later survey and vice versa. Passage events were then cross-referenced to flow magnitude. Movements were measured by snapping fish locations to a digitized midline of the stream channel and measuring the linear distances along the midline between consecutive fish locations. We determined the maximum displacement value for each fish by measuring the furthest distance a fish was located from its release site during the study. Fish were then classified as either exhibiting stationary (<1 km) or mobile (>1 km) behavior according to their maximum displacement (Matheney and Rabeni 1995; Radinger and Wolter 2014). We required individuals to be located at least twice following initial release to be included in further analysis.

Statistical analysis was conducted in RStudio with an alpha of 0.05. Maximum displacements were first analyzed without including the direction (upstream/downstream) of movements thus giving us the overall magnitude of maximum displacement in all fish

Figure 4. Image of the pseudo-fish ladder formed along the edge of the main channel crossing following heavy rainfall. The discharge at Akers Ferry is approximately 28 m³/s during this photo. Picture taken August 17, 2017.

(mobile and stationary) tagged above vs. below the crossing. We conducted a similar analysis that included the directional component of maximum displacement in all fish. Upstream-directed movements were assigned a positive value and downstream-directed movements a negative value. Maximum displacement data were non-normally distributed (Package: e1071, Function: skewness and kurtosis), so we cube-root transformed these data to meet the assumptions required for parametric statistical analysis. To test for differences in the magnitude and direction of maximum displacement between above (N = 22) and below-tagged (N = 23) fish, we conducted two separate two-way Analysis of Variance (ANOVA) tests with tagging location (above vs. below) and mobility type (mobile vs. stationary) as factors (Program: stats, Function: aov). Following each two-way ANOVA, we used Tukey's test (Program: stats, Function: tukeyHSD) for pairwise comparisons.

Results

We located 46 of the 50 tagged fish at least once following release and collected a total of 317 fish locations (Appendix). There was no difference in the total length (t (44) = 2.015, $P = 0.4538$) or weight (t (44) = 2.015, $P = 0.8069$) of fish tagged above (Mean (M) = 341 mm, 406 g; Standard Error (SE) = 7.41 mm, 32.49 g) and below (M = 332 mm, 395 g; SE = 9.21 mm, 34.15 g) the crossing (Appendix). The temperature logger array at the crossing recorded one event in which water levels completely inundated the crossing (February 24–25, 2018; Figure 3). During the summer, fall, and winter discharge typically remained below the AMD with the exception of three moderate flow events in August, while discharge in spring typically consisted of moderate flow (Figure 3). During moderate flows, we observed a predictable formation of lateral overflow at the main channel crossing which acted as a pseudo-fish ladder for juvenile (non-tagged) Northern Hog Suckers to pass upstream over the top of the crossing (Figure 4).
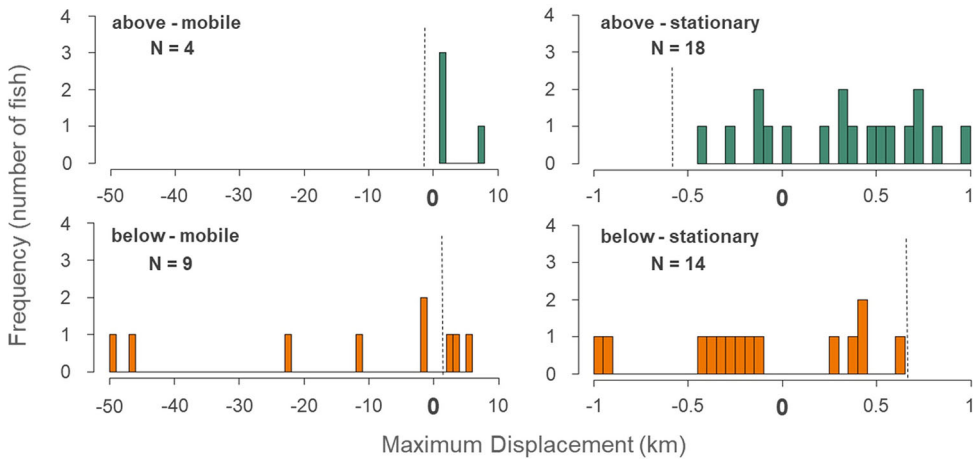
Figure 5. Frequency distribution representing the direction of maximum displacement of Northern Hog Suckers around the Cedar Grove low-water crossing. Mobile fish above and below the crossing are represented on the two left panels while stationary fish above and below the crossing are represented on the right panels. Release sites (0, bold) and the position of the crossing relative to release sites (dashed verticle line) are represented on the x-axis. Positive displacement reflects upstream movement and negative displacement reflects downstream movement.

Figure 3 and Appendix show detailed data on the timing and direction of all passage events during the year-long study. Four below-tagged fish (8% of tagged fish) successfully passed the crossing resulting in a total of six passage events. Five of these events were upstream-directed and one downstream. In August 2017, two individuals (fish # 37 and 41) passed upstream during a period of low to moderate flow. The third individual (fish # 31) passed upstream shortly after its release in November 2017 during low flow conditions. The same individual (fish # 31) passed back downstream in the early spring 2018, following our highest flow event in which the crossing was inundated, and again upstream in late spring during moderate to high flows. The fourth individual (fish # 43) passed upstream between late spring and early summer 2018 during a period of several moderate flow events.

River distances traveled by individual Northern Hog Suckers ranged from 0.3 to 49 km across the study year. The majority (71%) of suckers at Cedar Grove exhibited stationary behavior, although stationary behavior was more prevalent in above-tagged (82%) than below-tagged (62%) fish (Appendix). Forty-five fish were located at least twice following their release, therefore meeting our criteria for inclusion in the maximum displacement analysis (Appendix). The maximum displacement of individuals (regardless of movement direction) was significantly greater in below-tagged (M = 6.55 km, SE = 2.91 km) than above-tagged (M = 0.92 km, SE = 0.33 km) fish (Figure 5; Table 3). A significant interaction between location relative to the crossing and mobility type revealed greater maximum displacement of mobile individuals below the crossing (M = 16.08 km, SE = 6.40 km) than mobile individuals above (M = 3.12 km, SE = 1.50 km) the crossing (Figure 5; Table 3). The upstream/downstream direction of maximum displacement significantly differed between above-tagged (M = 0.83 km, SE = 0.35 km) and below-tagged (M = −5.27 km, SE = 3.03 km) fish (Figure 5; Table 3). Furthermore, a significant interaction between location relative to the crossing and mobility type showed different direction of maximum displacement between mobile individuals above (M = 3.12 km, SE = 1.50 km) compared to below (M = −13.28 km, SE = 7.16 km) the crossing (Figure 5).

Table 3. Results of two-way ANOVAs for effects of tagging location and mobility type on maximum displacement and directional maximum displacement of Northern Hog Suckers.

Source of variation	df	SS	MS	F	P
Maximum displacement					
Tagging location	1	2.264	2.264	9.995	0.003
Mobility type	1	11.306	11.306	49.911	<0.0001
Tagging location * Mobility type	1	1.203	1.203	5.311	0.0263
Error	41	9.287	0.227		
Total	44	24.06			
Directional maximum displacement					
Tagging location	1	14.04	14.043	10.767	0.0021
Mobility type	1	0.34	0.345	0.264	0.6099
Tagging location * Mobility type	1	7.15	7.153	5.484	0.0241
Error	41	53.48	1.304		
Total	44	75.01			

Discussion

Fish passage and streamflow

Our findings that fish passage typically occurred during periods of moderate to high flows support our hypothesis (H1) that the Cedar Grove low-water crossing is a semi-permeable barrier. However, we found passage was more common in the upstream direction than our hypothesized (H2) downstream direction. We anticipated that a velocity barrier within the culverts would be the limiting factor on upstream-directed movements past the crossing, but evidence suggests that elevated flows created a pseudo-fish ladder lateral to the main channel that was likely the mechanism for upstream passage. Higher flows that promoted passage lateral to the crossing also likely reduced barrier effects created by the extensive sediment deposition upstream of the crossing. We observed juvenile Northern Hog Suckers passing upstream in this manner, and it is likely that the tagged adults that successfully passed used a similar strategy. The single downstream passage event (Fish # 31) directly followed a high-flow event in which the river reached the maximum discharge recorded during the study, and streamflow inundated the crossing. This high flow event scoured out areas of heavy sediment deposition upstream of the crossing (personal observation) and almost certainly enhanced downstream passage.

Northern Hog Suckers also could have passed upstream and downstream of the crossing in the side channel, where culvert velocities have been documented to be lower, and upstream sediment deposition is less pronounced. Side channel use by Northern Hog Suckers has been documented during periods of elevated flow in lower sections of the Current River (Matheney and Rabeni 1995). Other fishes, such as Rainbow Trout *Oncorhynchus mykiss* and European Grayling *Thymallus thymallus*, also have been found to use side channels to avoid small barriers (Jungwirth 1996). We observed tagged (N = 2, Figure 6: A and B) and non-tagged Northern Hog Suckers moving throughout the side channel downstream of the crossing year-round and congregating in its plunge pool. However, both of the tagged fish found in the side channel moved back downstream into the main channel after reaching the plunge pool (Figure 6: A and B), and non-tagged fish were frequently observed swimming in a downstream direction within the side channel. During the study, no adult fish (tagged or non-tagged) were observed upstream of the side-channel crossing. This pattern suggests that individuals were using the side channel for upstream movements but were inhibited by the culverts and the absence of flow lateral to the crossing.

The single passage event documented during low flow (Fish # 31) occurred within two weeks of initial release and was likely influenced by tagging stress. Matheney (1993)
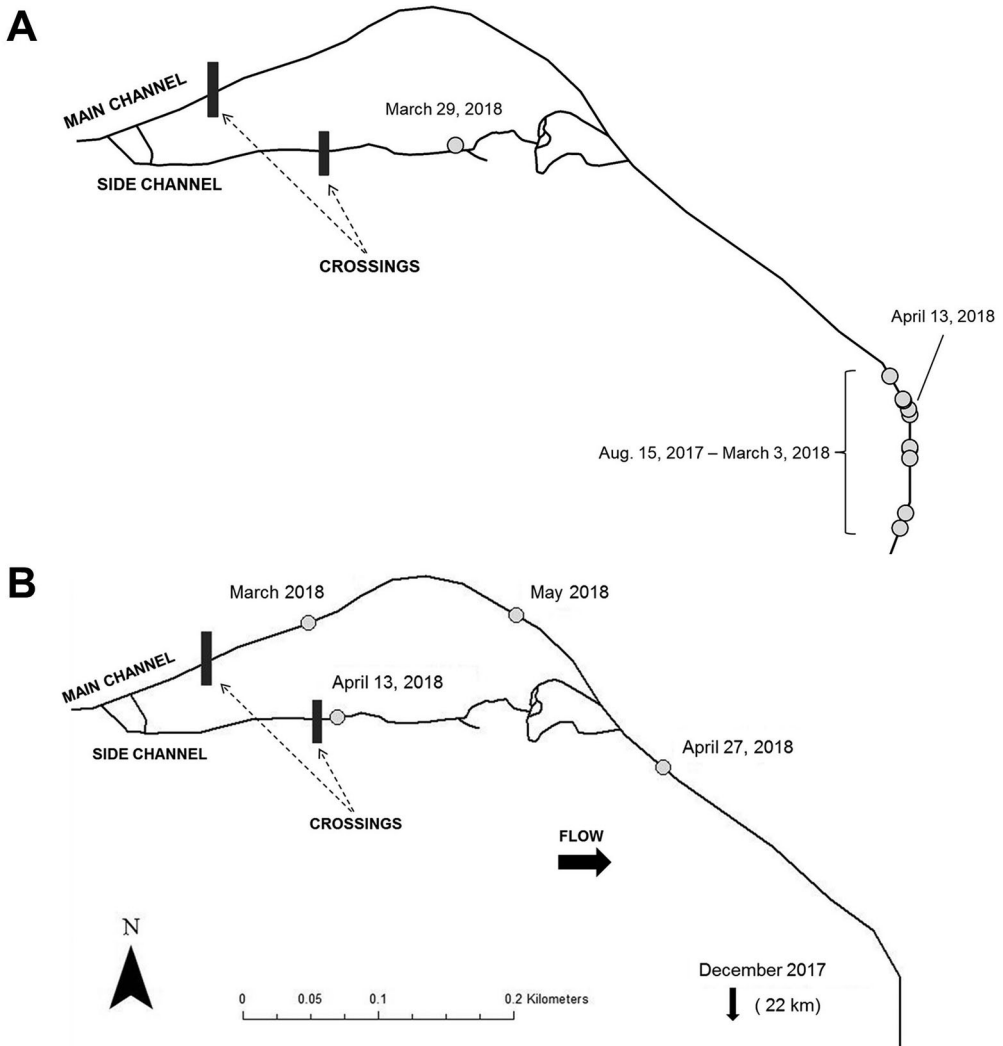
Figure 6. (A) Map showing the upstream movement of an individual (Fish # 40, Appendix) into the side channel during a period of high flow before returning downstream. (B) Map showing the movements exhibited by an individual (Fish #44, Appendix) from the main channel crossing to the side channel crossing after completing a long upstream migration.

reported extreme movements in two Northern Hog Suckers (15 km downstream and 17 km upstream) shortly after release from surgical tagging procedures. This behavior is common across fish taxa. For example, European Grayling released in an experimental stream moved up to 400 m within the first 12 minutes of release (Carlstein and Eriksson 1996). We suspect that this low flow passage event occurred through the side channel crossing due to the combination of shallower water and greater deposition upstream of the main channel crossing.

Fish passage was exhibited only by individuals tagged and released below the crossing. It is unclear why these were the only fish passing throughout the year. This pattern could be explained by the greater stream length of degraded habitat upstream (impoundment pool and extensive sediment deposition; main channel = 420 m, side channel = 92 m) of the crossing compared to downstream (plunge pool; main and side channel = 10 m)

which would have allowed below-tagged fish to come in more frequent contact with the crossing. However, we only documented 3 tagged fish (above: N = 1, below: N = 2) within 30 m of the crossing during the study, and fish frequently inhabited the entire length of the main channel impoundment pool (N = 8). Other possible explanations include the higher proportion of mobile individuals tagged downstream of the crossing and the greater access to the alternative pathways (pseudo-fish ladder and side channel), previously mentioned.

Movement behavior and maximum displacement

Mobile behavior was more common in below-tagged fish, a pattern that is likely associated with the greater length of river habitat available downstream of the crossing (279 km) vs. upstream (17 km). Mobile individuals (N = 13) were more likely to come into contact with the crossing than stationary individuals (N = 32); therefore, it is not surprising that we saw the greatest impacts on movement behavior in those fish. The larger maximum displacements observed in mobile fish below the crossing lead us to reject our hypothesis (H3) that above and below-tagged fish would move similar distances. However, our hypothesis (H4) that movement by both above (100%) and below-tagged (67%) fish would be greatest in the direction away from the crossing was supported. The exceptions were three of the four below-tagged fish (Fish # 31, 41, and 43) that successfully passed upstream of the crossing (Figure 5). Downstream displacement in above-tagged fish appeared to be strongly limited by the presence of the crossing (Figure 5).

Current understanding of Northern Hog Sucker movement is minimal. In small Indiana creeks, Gerking (1953) reported Northern Hog Suckers exhibiting relatively little annual movement, with home ranges as small as 300 m. In our larger study stream, Matheney and Rabeni (1995) reported home ranges of 936 m within a single season. A variety of environmental factors such as stream size and habitat complexity may explain differences in observed movement behavior across studies. In our study, we found similarities between the magnitude of movement exhibited by stationary individuals to that of Gerking (1953) and mobile individuals to that of Matheney and Rabeni (1995). Therefore, populations of this species probably maintain a balance between mobile and stationary individuals, and conclusions likely vary depending on study stream and timing.

We found that Northern Hog Suckers, like other sucker species, are capable of large seasonal movements (Modde and Irving 1998; Bunt and Cooke 2001). Nearly 70% of these movements occurred in the downstream direction, during low flow conditions in late fall and early winter (October–December 2017), and during non-spawning periods. However, large upstream movements (30%) did occur in spring during spawning periods. Other sucker species, such as Razorback Sucker and Greater Redhorse, have exhibited large downstream movements (50 km and 15 km respectively) during periods of high flow and following spawning activity (Modde and Irving 1998; Bunt and Cooke 2001). These differences may have been associated with the relative position of tagged fish within the watershed. In our study, the focal crossing is located 17 km downstream of the Current River's headwaters; therefore, these extreme movements may have been attributed to fish migrating downstream to overwintering habitat (deep pools) during low flow conditions. Similar to our study, large upstream movements during spawning and high flow periods have been reported in Black Redhorse, which frequently school together with Northern Hog Suckers in the Current River (Bowman 1970; Bunt and Cooke 2001). It is also possible that sex-specific behavioral differences could be influencing movement behavior. The fish in our study were not sexed due to the absence of identifying characteristics (gametes

and tubercles) during the non-spawning period of initial capture; however, sex-biased dispersal is common in fishes and has been well documented (Hutchings and Gerber 2002; Croft et al. 2003).

Summary

Differences in maximum displacements and other movement behaviors exhibited within and across taxa are likely attributed to many factors, such as resource availability, environmental conditions, competition, intraspecific differences in mobility, and physical capabilities (Albanese et al. 2004; Jackson et al. 2001). These complex factors can make studying movement behavior difficult and lead to conflicting results across similar taxa. Continued species-specific movement studies with large sample sizes are necessary in both fragmented and non-fragmented streams to better understand the variety of movement behaviors displayed within species and movement behavior in its entirety. The results of our intensive, year-long study of Northern Hog Sucker movement behavior in the Current River has strong management implications. On the Current River, gigging (Turner 2014) is permitted for Northern Hog Suckers downstream of the Cedar Grove low-water crossing. Because the crossing limits passage, Northern Hog Suckers are restricted from reaching upstream refugia. Replacing the Cedar Grove low-water crossing with a clear-span bridge or larger culverts (arch and open box culverts) that maintain the natural stream substrate and flow regime would help re-establish connectivity and promote longitudinal movements of Northern Hog Suckers and other fishes (Benton et al. 2008; Bouska and Paukert 2010). However, the implementation of a large management project such as this would be difficult. It would require substantial time and resources and disrupt both vehicle crossing of the river and human recreational activities (fishing, canoeing, and swimming) that are popular in this stretch of river. Because fishes regularly use side channels, including a couple of our tagged fish, another approach may be to only modify the smaller crossing at Cedar Grove and allow the side channel to act as a fish bypass system (Jungwirth 1996; Schmutz et al. 1998; Santos et al. 2005). This fish bypass could be both an economically and biologically beneficial alternative to replacing the entire main channel crossing.

Acknowledgments

Disclosure statement

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Notes on contributors

Jeffrey M. Williams is a Research Specialist in the Biology Department at Missouri State University. He assists the Heartland Inventory and Monitoring Network of the National Park Service with long-term monitoring of fish and aquatic macroinvertebrate communities in streams throughout the Midwest.

Hope R. Dodd is the Fisheries Biologist for the Heartland Inventory and Monitoring Network of the National Park Service. Her work focuses on long-term monitoring of aquatic communities in streams and springs throughout the Midwest. Her research interests include assessment of anthropocentric disturbances and remediation practices in stream systems.

Debra S. Finn is an Assistant Professor in the Biology Department at Missouri State University. Her research emphasizes ecological connectivity in longitudinal, lateral, and vertical dimensions in stream ecosystems.

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Appendix: Individual fish data with corresponding passage, maximum displacement, and mobility type.

Fish	Total length (mm)	Weight (g)	Fish passage (N)	Maximum displacement (km)	Mobility type	Total observations
			ABOVE (N = 22)			
1	368	467	No	0.47	Stationary	3
2	307	361	No	7.58	Mobile	3
3	372	520	No	0.3	Stationary	5
4	324	322	No	0.67	Stationary	8
5*	415	748	No	1.3	Mobile	9
6	313	297	No	0.59	Stationary	4
7	310	309	No	−0.26	Stationary	3
8	352	324	No	0.34	Stationary	14
9	329	321	No	0.52	Stationary	5
10	357	403	No	0.24	Stationary	3
11	312	293	No	0.71	Stationary	4
12	361	482	No	0.71	Stationary	13
13	307	322	No	−0.11	Stationary	3
14*	304	236	No	−0.44	Stationary	10
15	370	504	No	1.98	Mobile	10
16*	342	414	No	0.39	Stationary	4
17	301	281	No	0.83	Stationary	10
18*	330	321	No	1.68	Mobile	8
19*	383	606	No	−0.13	Stationary	4
20*	414	805	No	0.03	Stationary	5
21*	310	280	No	−0.09	Stationary	3
22*	330	320	No	0.95	Stationary	8
			BELOW (N = 24)			
23*	357	349	No	−0.92	Stationary	3
24*	348	373	No	−0.35	Stationary	9
25*	330	361	No	−0.16	Stationary	11
26*	400	768	No	−0.43	Stationary	10
27*	298	241	No	−1.00	Stationary	7
28	266	212	No	0.30	Stationary	12
29	295	304	No	−0.28	Stationary	14
30	311	300	No	−1.49	Mobile	3
31*	320	296	Yes (3)	3.97	Mobile	11
32	396	563	No	0.43	Stationary	3
33	277	212	No	0.60	Stationary	2
34*	420	694	No	−1.35	Mobile	8
35	286	262	No	−0.32	Stationary	4
36	328	364	No	−46.92	Mobile	3
37	275	223	Yes (1)			1
38	300	271	No	−0.11	Stationary	14
39	300	270	No	−11.30	Mobile	3
40	357	575	No	0.40	Stationary	15
41	317	300	Yes (1)	5.90	Mobile	10
42	371	523	No	−49.01	Mobile	5
43*	385	597	Yes (1)	2.73	Mobile	8
44	396	642	No	−22.02	Mobile	10
45*	290	270	No	−0.23	Stationary	6
46	354	499	No	0.44	Stationary	6

Asterisks indicate fish tagged during the November tagging event. Maximum displacements for fish located at least twice following release are provided with corresponding direction (negative = downstream).