Spring 2019

A Low-water Crossing Impacts Movement Behavior of Northern Hog Suckers in an Ozark Stream

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Recommended Citation

Williams, Jeff Michael, "A Low-water Crossing Impacts Movement Behavior of Northern Hog Suckers in an Ozark Stream" (2019). *MSU Graduate Theses*. 3351.
https://bearworks.missouristate.edu/theses/3351

A LOW-WATER CROSSING IMPACTS MOVEMENT BEHAVIOR OF NORTHERN HOG SUCKERS IN AN OZARK STREAM

A Master's Thesis
Presented to
The Graduate College of
Missouri State University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science, Biology

By
Jeff Michael Williams
May 2019

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Biology

Missouri State University, May 2019

Master of Science

Jeff M. Williams

ABSTRACT

Low-water crossings are common in Ozark streams and can restrict longitudinal movement in fishes. I evaluated the impact of the Cedar Grove low-water crossing on Northern Hog Sucker *Hypentelium nigricans* movement behavior in Missouri's Current River. Radio-tagged fish upstream (henceforth 'above'; N = 24) and downstream (henceforth 'below'; N = 26) of the crossing were followed monthly for a year to assess 1) frequency of fish passage, 2) direction of passage, and 3) maximum displacement of mobile (displacement > 1 km) fish. I then looked at diel movement behavior of stationary (displacement < 1 km) fish near the crossing to assess 1) total displacement and linear home range, 2) direction of diel displacement, and 3) habitat use. Passage was limited to four below-tagged fish and was more likely to occur in the upstream direction and during high flow. The direction of maximum displacement in mobile fish was primarily away from the crossing, and below-tagged fish exhibited over seven times greater displacement than above-tagged fish. Diel displacement and linear home range were greater in above-tagged fish, likely due to degraded upstream habitat that increased the distance between day and night habitats. My results suggest the crossing is a semi-permeable barrier that also affects local-scale movement behavior of Northern Hog Suckers. Alternatives to the low-water crossings at Cedar Grove, such as modifying the side channel into a fish bypass, should be considered to promote natural longitudinal movement of fishes in the upper Current River.

KEYWORDS: Northern Hog Sucker, movement, low-water crossing, longitudinal connectivity, stream fragmentation, Ozark, Missouri, mobile and stationary behavior, radio telemetry

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ACKNOWLEDGEMENTS

I would like to thank my graduate committee for their support and advice during my research. I thank the Heartland Inventory and Monitoring Network (HTLN) of the National Park Service for providing sampling and tracking equipment as well as Jen Haack for GPS assistance. Furthermore, I thank Victoria Grant and Mike Gossett at Ozark National Scenic Riverways for their assistance in field logistics and study design. Lastly, thanks to Payton Lackman, Mathew Matheney, Trenton Jones, J. Tyler Cribbs, Nathan Dorff, Ryan Langer, Ashley Williams, Stephanie Sickler, Mary Short, Pat Curtin, Libby Glaser, Kristen Sardina, Paige Schneider, Nicole Haynes, and Brad Thornton for their assistance with field sampling. This research was primarily funded through the Missouri Cooperative Fish and Wildlife Research Unit of the US Geological Survey and HTLN. Additional funds were provided through thesis research support from the Missouri State University Graduate College and Biology Department.

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OVERVIEW

Streams are complex, dynamic systems that are vulnerable to environmental alterations in their watersheds. This vulnerability is due in large part to the four dimensions of connectivity (vertical, lateral, longitudinal, and time) associated with the transfer of resources and organisms in streams (Allen and Castillo 2007; McKay et al. 2013). Vertical exchange between surface and subsurface waters enhances primary and secondary production (Boulton 2007). Lateral exchange between the stream and floodplain influences riparian vegetation establishment, channel morphology, allochthonous material input, and provides essential habitat for the rearing of fishes (Copp 1989; Burgess et al. 2012). Longitudinal connectivity provides material resources from upstream to downstream (Ensign and Doyle 2006; McIntyre et al. 2008) and provides a migration corridor for fish to essential habitat (Ward 1989; Matheney and Rabini 1995; Ward and Stanford 1995; Poff et al. 1997). All three of these spatial dimensions interact with time, such as seasonal and diel changes and response following disturbances (Ward 1989). Any barrier that disrupts these dimensions can threaten natural biological communities and ecological processes.

Stream fragmentation by anthropogenic barriers such as dams, weirs, and low-water crossings negatively impact connectivity of streams worldwide (Ward and Stanford 1995). Within the United States, there are an estimated 82,000 dams over 2 m in height and approximately 2,000,000 smaller structures that disrupt longitudinal connectivity of streams (Baker et al. 2011). The majority of biological research on stream fragmentation has focused on the migrations of economically important salmonids around large dams (Gowans et al. 1999; Scruton et al. 2007; Davis and Davis 2011); however, current research is beginning to look at the movement behavior of less economically important fishes around smaller stream barriers (Benton et al. 2008; Helms et al. 2011; Mueller et al. 2011). Further research on the impacts of low-water crossings on a variety of fishes is warranted and can help provide important information on the effects of these barriers on the longitudinal distribution of understudied, common stream fishes and associated ecosystem processes.

In my thesis research, I evaluated the impacts of the Cedar Grove low-water crossing in Missouri's Current River on the longitudinal movement behavior of a common stream fish, the Northern Hog Sucker *Hypentelium nigricans*. The crossing is unique in that it spans both the main channel and a side channel of the upper Current River and is the only anthropogenic source of fragmentation it its 296 km length. The structure is composed of corrugated pipe culverts (main channel = 10, side channel = 4), which have been found to have a strong negative impact on fish passage (Bouska and Paukert 2010; Eisenhour and Floyd 2013).

I assessed the impacts of the crossing on Northern Hog Sucker movement behavior at contrasting temporal (annual vs. diel) scales and fish movement behaviors (mobile vs. stationary fish). My first chapter emphasizes the longer temporal scale. I radio-tagged Northern Hog Suckers upstream (N = 24) and downstream (N = 26) of the Cedar Grove low-water crossing and followed their monthly movements over a year to assess 1) frequency of fish passage, 2) direction of fish passage, and 3) maximum displacement and direction of displacement in mobile fish (displacement > 1 km). This chapter is currently in-prep to be submitted to *Transactions of the American Fisheries Society*. My second chapter emphasizes the shorter temporal scale. I followed the diel movements of stationary (displacement < 1 km) Northern Hog Suckers that remained near (< 2 km) the Cedar Grove low-water crossing to assess 1) total diel displacement and linear home range, 2) direction of diel displacement, and 3) habitat use. I plan to publish the data from chapter 2 in collaboration with Mathew Matheney, an ecologist with the Missouri Department of Conservation who has studied diel Northern Hog Sucker movements in the Current River. This project was approved by the National Park Service Institutional Animal Care and Use Committee (IACUC: MWR_OZAR_Williams_Fish_2017.A3), Ozark National Scenic Riverways (Permit: OZAR_2017_SCI_0004), and Missouri Department of Conservation (Permit: 17419).

A LOW-WATER CROSSING IMPACTS NORTHERN HOG SUCKER *HYPENTELIUM NIGRICANS* MOVEMENT IN AN OZARK STREAM

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 upstream and downstream movement to feeding, spawning, and seasonal habitats that are often distantly distributed within stream networks (Calles and Greenberg 2009; Armstrong and Schindler 2013; Ettinger et al. 2016; Wells et al 2016). For example, Armstrong and Schindler (2013) found that juvenile Coho Salmon *Oncorhynchus kisutch* take advantage of the spatial heterogeneity in water temperature daily 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 commersonii*, 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 in lotic systems worldwide is the construction of barriers, including dams, weirs, and road crossings. The United States alone has over 82,000 dams over 2 m in height and approximately 2,000,000 smaller structures (Baker et al. 2011). These barriers can prevent fish from reaching feeding and spawning grounds, eliminate refuge from predators, and can result in genetic isolation among populations (Helms et al. 2011). For example, 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 higher 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 connectivity in their life histories and the economic importance of these taxa (Gowans et al. 1999; Scruton et al. 2007; Davis and Davis 2011).

Recent research has examined the impacts of smaller barriers (weirs and road crossings) on less economically important stream fishes such as *Campostoma* spp., *Cyprinella* spp., and *Cottus* spp. (Benton et al. 2008; Helms et al. 2011; Mueller et al. 2011). The majority of small barriers are considered semi-permeable, with fish primarily capable of passing upstream/downstream of the structure during certain events, such as high flow, which may allow successful passage through or around the barrier (Perkin and Gido 2012). Semi-permeability is often the case with low-water crossings that have perched culverts at the outflow. For example, Norman and Hagler (2009) found that fish passage through perched culverts was limited to periods of storm runoff when the water column reconnected with the culverts.

Low-water crossings are common in small, low-order streams and range in size and complexity. Crossings containing pipe culverts have been shown to have the greatest negative impact on fish movement when compared to box culverts, clear span bridges, and natural reaches (Warren and Pardew 1998; Benton et al. 2008). Pipe culverts primarily inhibit fish movement by creating a jump barrier, where the culvert is perched above the downstream channel, a velocity barrier, where fish lack sufficient energy to move upstream against the current, or a depth barrier, in which there is inadequate water depth for fish to physically move through the culvert (Benton et al. 2008; Hansen and Reeves 2008; Bouska and Paukert 2010; Eisenhour and Floyd 2013). Further research on the impacts of low-water crossings on a variety of fishes is warranted and will contribute to understanding the effects of smaller barriers on 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 classified as benthic, as it spends much of its time resting and foraging for invertebrates on the streambed. Northern Hog Suckers are abundant and a popular game fish in the Missouri Ozarks (Turner 2014) and can be commonly found in loosely organized schools of conspecifics and heterospecifics (e.g. *Moxostoma* spp.). Spawning in Missouri occurs during early spring (April/May) when fish move into the tails and heads of pool habitat (Matheney and Rabeni 1995). Northern Hog Suckers frequently dislodge primary consumers into the drift (Pflieger 1997) and are commonly preyed upon by larger fish, wading birds, and mammals (Cooke et al. 2005); therefore, these fish can be an ecologically important link in stream food webs.

Northern Hog Suckers are strong swimmers capable of exhibiting mean daily movements of at least 425 m; however, this species will avoid high flow velocities by retreating to edge habitats (Matheney and Rabeni 1995). Velocity barriers, such as those commonly associated with pipe culverts, likely impact Northern Hog Sucker movement differently depending upon swimming capabilities and life stages. A method for assessing velocity barriers in fishes is with the FV50 (velocity in which 50% of fish fail to maintain their position in a 30-minute period; Ivasauskas 2017). Juvenile Northern Hog Suckers (25 mm total length, henceforth ‘TL’) have been documented maintaining a FV50 of 0.142 m/s with adults (330 mm TL) projected to have a FV50 of 1.485 m/s (Ivasauskas 2017).

Fishes commonly exhibit stationary and mobile behaviors within a population (Matheney 1993; Matheney and Rabeni 1995; Radinger and Wolter 2014; Wells et al. 2016). The majority of fish remain within a resident area (defined by the swimming ability of the species) while a small number of individuals migrate or disperse out of the resident area. Radinger and Wolter (2014) classified the threshold between stationary and mobile movement behavior of members of the Catostomidae family as approximately 1 km. Matheney and Rabeni (1995) reported similar home range size (936 m) in Northern Hog Suckers in Missouri's Current River. Movements necessary for Northern Hog Suckers to reach suitable habitats during different life stages (juveniles vs. spawning adults), seasons (summer vs. overwintering habitat), or mobility types (mobile vs. stationary) makes this species vulnerable to high velocity barriers that restrict longitudinal movement.

I investigated potential differences in movement behavior of Northern Hog Suckers around a large, pipe-culvert lined low-water crossing in a third-order Ozark river. I radio-tagged and monitored individuals upstream (henceforth 'above') and downstream (henceforth 'below') of the crossing to test three hypotheses: H1) The crossing acts as a semi-permeable barrier that limits fish passage to periods of high flow where fish can bypass the crossing. H2) Velocity barriers caused by the pipe culverts will restrict upstream directed passage. H3) The direction of maximum displacement in mobile fish (which are more likely to interact with the crossing) is upstream-directed in above-tagged fish and downstream-directed in below-tagged fish.

Methods

Study site. The Current River is located within the Ozark Plateau of Southeastern Missouri, and much of its length is within the National Park Service's Ozark National Scenic

Riverways (OZAR, Dodd 2009). 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 majority of the river's baseflow is spring-fed, but the flow regime is strongly influenced by rainfall events with highest flows typically occurring during spring (Leasure et al. 2016). OZAR encompasses 5% of the river's watershed and helps protect over 100 species of fish (Dodd 2013). The river is free flowing over its 296 km length, with the exception of a single low-water crossing at Cedar Grove, 17 km downstream of the river's headwaters at Montauk Spring (Wilkerson 2003; Figure 1).

The Cedar Grove low-water crossing (henceforth 'the crossing') consists of two structures spanning the main channel and a side channel of the river forcing water to pass through 10 and 4 corrugated pipe culverts, respectively, during periods of baseflow (Figures 1, 2; Table 1). The culverts are non-perched year round, due in part to stable baseflow from groundwater sources. Both crossings create upstream impoundments (main channel: length = ca. 400 m, mean depth = ca. 1.5 m, mean width = ca. 33 m; side channel: length = ca. 100 m, mean depth = ca. 0.6 m, mean width = ca. 9 m) with moderate to heavy sediment deposition (main channel: sand - cobble; side channel: sand). A scoured plunge pool (main and side channel: length = ca. 10 m), followed immediately by natural habitat (riffle-pool sequence) is representative of the downstream habitat.

Study design. In July 2017, Northern Hog Suckers were collected using boat electrofishing procedures outlined by Peterson et al. (2008). I anesthetized fish using a solution of river water and 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), such that tags were less than 2% of the body weight (Matheney and Rabeni 1995). I tagged 24 fish upstream and 26 fish downstream of the crossing and allowed fish two hours to recover before releasing them centrally within the sample reaches, approximately 600 m upstream and downstream of the crossing. High initial mortality (N = 17) likely associated with tagging stress, warm water temperatures, and predation resulted in a second tagging event upstream (N = 8) and downstream (N = 9) of the crossing in November 2017 in order to bring the total tagged individuals back to 50.

I conducted 14 surveys between July 2017 and June 2018. A 40 km stretch of the Current River, between Baptist Access and Pulltite Campground was surveyed during each tracking event (Figure 1). 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). I conducted surveys monthly during periods of low flow (summer: June - August, fall: September - November, winter: December - February) and increased the frequency of surveys during periods of higher flow and spawning season (spring: March - May, Figure 3). I assessed fish position by first floating the study area with a receiver (Lotek Wireless, Biotrack Receiver, 3-element Yagi Antenna) until I was within close proximity of a tagged fish. I then determined individual fish locations with triangulation from the 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, I deployed a series of iButton temperature loggers (2-hr intervals, Maxim Integrated) vertically placed at four levels in both the main and side channels: 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 the floodplain lateral to the channel (air temperature control). Air temperature fluctuates more rapidly than water temperature due to water's higher heat capacity (Perlman 2018). Therefore, I was able to determine if the water column reached these vertical stages by evaluating temperature differences between the two mid-level sensors (culverts and top of crossing) and the controls (water temperature and air temperature loggers) throughout the study period. As such, I could ask whether fish passage events were associated with high flow events at the crossing, and I could approximate stream discharge during these events, as recorded by a USGS gauge station (07064533, Akers Ferry) approximately 13 km downstream of the crossing (Figure 3). For the purpose of this study, I classified flow magnitude in the following categories: low flow (< 17-year annual mean discharge (AMD) at gauge = approx. 12 m^3/s, bottom of culverts), moderate flow (between AMD and top of culverts = approx. 12 m^3/s – 70 m^3/s), and high flow (> 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. Spatial 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 was located on the opposite side of the crossing from a previous survey. Passage events were then cross referenced to flow magnitude by using the temperature loggers and USGS gauge data (as mentioned above). Movements were measured by snapping fish locations to a digitized midline of the stream channel and measuring the linear stream distance between fish locations. I determined the maximum displacement value for each fish by measuring the greatest distance a fish was located from its release site during the study. I used Radinger and Wolter's (2014) classification scheme of mobile and stationary behaviors for Catostomidae. Therefore, Northern Hog Suckers which exhibited maximum displacement greater than 1 km were classified as mobile fish and those that remained within 1 km of the release site were stationary fish. I required individuals to be located at least twice following initial release to be included in further analysis (Above: N= 22, Below: N = 23).

Statistical analysis was conducted in RStudio with an alpha of 0.05. To test for differences in the proportion of mobile and stationary individuals between tagging location, I conducted a chi-square test of independence (Package: stats, Function: chisq.test). Maximum displacements were first analyzed without including the direction (upstream/downstream) of movements thus giving me an estimate of the total magnitude of maximum displacement in all fish (mobile and stationary) above vs. below the crossing. I conducted the same analysis in which I included the directional component of maximum displacement in all fish. Maximum displacement data were non-normally distributed (Package: e1071, Function: skewness and kurtosis), so I transformed data (^ 1/3) to meet the assumptions required for parametric statistical analysis. To test for differences in the 1) total maximum displacement and 2) direction of maximum displacement between above-tagged vs. below-tagged and mobile vs. stationary fish, I conducted two separate two-way ANOVAs with tagging location and mobility type as factors and tested for interactions between factors (Program: stats, Function: aov). ANOVAs were followed by Tukey post-hoc analysis (Program: stats, Function: tukeyHSD) for pairwise comparisons and p-value adjustments.

Results

I located 45 of the 50 tagged fish at least twice following release and collected a total of 316 fish locations (Table 2). There was no difference in the total length (t (44) = 2.015, *P* = 0.4538) or weight (t (44) = 2.015, *P* = 0.8069) between above-tagged (mean = 341 mm, 406 g; SE = 7.41 mm, 32.49 g) and below-tagged (mean = 332 mm, 395 g; SE = 9.21 mm, 34.15 g) fish (Table 2). During the fall and winter, discharge typically remained below AMD with the exception of one event (24-25 February 2018; Figure 3) where the crossing was inundated. Early summer was also below AMD while late summer (August) and spring typically had moderate flows (Figure 3). During moderate flows, I observed a predictable formation of lateral overflow at the main channel crossing (Figure 4). I regularly observed juvenile Northern Hog Suckers use this overflow to pass the crossing in the upstream direction.

Fish passage and flow. Four below-tagged fish successfully passed the crossings resulting in a total of six passage events. Five of these passage events were upstream-directed and one downstream (Figure 3). In August 2017, two individuals (fish # 37 and 41) passed upstream of the crossing during a period of low to moderate flow (Figure 3; Table 2). The third individual (fish # 31) passed upstream of the crossing shortly after its release in November 2017 during low flow conditions (Figure 3; Table 2). The same individual (fish # 31) passed back downstream in the early spring 2018 , following the highest flow event in which the crossing was inundated, and again upstream in late spring during moderate to high flows (Figure 3; Table 2). The fourth individual (fish # 43) passed upstream during late spring 2018 after several moderate flow events (Figure 3; Table 2).

Movement behavior and maximum displacement. The majority of tagged Northern Hog Suckers (N = 45) at Cedar Grove exhibited stationary (71%) over mobile behavior (29%;

Table 2). Mobility type was not significantly different between tagging location (above vs. below; χ^2 (1, N = 45) = 1.491, $P = 0.2221$; Table 2). The interaction between location and mobility type was significant for total maximum displacement (Table 3; Figure 5). Mobile fish below the crossing exhibited significantly greater maximum displacement than the following groups: mobile-above ($P = 0.0454$), stationary-above ($P < 0.0001$), and stationary-below ($P < 0.0001$; Figure 5). In addition, the interaction between location and mobility type was significantly different for directional maximum displacement (Figure 5). The downstream-directed maximum displacement exhibited by mobile fish below the crossing was significantly different than the upstream-directed displacement in mobile ($P = 0.0048$) and stationary ($P = 0.0140$) fish above the crossing (Figure 5).

Discussion

Fish passage and flow. My findings supported hypothesis H1 that the Cedar Grove low-water crossing is a semi-permeable barrier to Northern Hog Suckers. Just 8% of tagged fish passed, and most of the passage events were associated with elevated flow (moderate to high). The single passage event documented during low flow (Fish # 31) occurred within two weeks of release and was likely influenced by tagging stress. Matheney (1993) reported extreme movements in two Northern Hog Suckers (15 km downstream and 17 km upstream) shortly after release from surgical tagging procedures. This behavior seems to be common across fish taxa; for example, European Grayling *Thymallus thymallus* released in an experimental stream moved up to 400 m within the first 12 minutes of release (Carlstein and Eriksson 1996).

I predicted (H2) that upstream passage would be limited due to velocity barriers associated with the pipe culverts that frequently exceed the FV50 of adult Northern Hog Suckers.

However, passage was only observed in below-tagged fish and typically occurred in the upstream direction. The higher frequency of upstream passage can likely be attributed to habitat degradation and alternative pathways associated with the crossing. Mobile fish below the crossing probably came into more frequent contact with the crossing due to the relatively short length of degraded habitat downstream of the crossing compared to upstream. The combination of heavy sediment deposition immediately upstream of the crossing and large impoundment pools likely reduced downstream passage at Cedar Grove by deterring above-tagged fish from approaching the crossing. Sediment deposition upstream of the main channel crossing accumulates quickly and has to be excavated, typically, every two to four years. High flow events can also affect the amount of deposition. For example, the highest flow event during the study inundated the crossing and scoured out areas of heavy sediment deposition upstream of the crossing (personal observation). Hence, high flow events may temporarily reduce the sediment barrier to downstream passage, thus resulting in the single downstream passage event.

During elevated flows, the lateral overflow in the main channel creates an upstream pathway for juvenile (personal observation) and potentially adult Northern Hog Suckers to avoid the culvert velocity barriers in the main channel crossing and move around the crossing. Northern Hog Suckers may also be using the side channel to pass upstream of the crossing where culvert velocities are substantially lower (Table 1). Side channel use by Northern Hog Suckers has been previously observed during periods of elevated flow on the middle section of the Current River (Matheney and Rabeni 1995). During the current study, I observed below-tagged (N = 2) and non-tagged Northern Hog Suckers moving throughout the Cedar Grove side channel, downstream of the crossing, and congregating in its plunge pool. However, I did not document passage of the two tagged fish in the side channel, and both fish moved back downstream into the main channel after reaching the side channel plunge pool (Figure 6). Non-tagged fish were also frequently observed swimming downstream towards the main channel. During the study, no adult fish were observed in the side channel upstream of the crossing. Other fishes have been found to use side channels to avoid small barriers (Jungwirth 1996); thus Northern Hog Suckers observed congregating in the side channel's plunge pool may have been seeking an alternative pathway upstream of the large main channel crossing.

Movement behavior and maximum displacement. The crossing seemed to impact the movement behavior of mobile fish (29% of tagged fish). My prediction (H3) that the direction of maximum displacement in mobile above-tagged (100%) and below-tagged (67%) fish would be away from the crossing was supported. The only exceptions were three below-tagged fish (Fish # 31, 41, and 43) that exhibited greater upstream maximum displacement and successfully passed upstream of the crossing (Figure 5: B1). Downstream displacement in above-tagged fish appeared to be strongly limited by the presence of the crossing (Figure 5: A1, A2).

I found that Northern Hog Suckers, like other sucker species, are capable of exhibiting large (> 15 km) movements (Modde and Irving 1998; Bunt and Cooke 2001). Nearly 70% of these large 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 during the spring spawning period. Other sucker species, such as Razorback Sucker and Greater Redhorse have been documented exhibiting 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). Differences in movement patterns may be associated with the relative position of tagged fish in the watershed. For example, the Cedar Grove low-water crossing is located 17 km downstream of the Current

River's headwaters; therefore, large movements during non-spawning periods may have been attributed to fish migrating downstream to overwintering habitat (deep pools) as water levels receded. Similar to my 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 differences in terms of movement behavior may have influenced maximum displacement in Northern Hog Suckers. The fish in my study were not sexed due to the absence of identifying characteristics (gametes and tubercles) during the non-spawning period of initial capture; however, male-biased dispersal is common in fishes and has been well documented. For example, Hutchings and Gerber (2002) observed male Brook Trout *Salvelinus fontinalis* dispersing two and a half times greater distances than females, and Croft et al. (2003) found that Guppy *Poecilia reticulate* emigration from release sites was greater in males (27.3%) than females (6.9%). Timing future Catostomidae movement studies to coincide with spawning activity can help fill much needed gaps in our understanding of sex-specific sucker movements.

Management implications. On the Current River, gigging is permitted for Northern Hog Suckers downstream of the Cedar Grove low-water crossing (Turner 2014). Because the crossing limits passage, Northern Hog Suckers are restricted from reaching upstream refugia from gigging pressure. Replacing the Cedar Grove low-water crossing with a clear-span bridge or larger culverts (arch or 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 would be difficult as it would require substantial time and resources and would disrupt vehicle crossing and human recreational activities (fishing, canoeing, and swimming) that are popular in this stretch of river. Because Northern Hog Suckers and other fishes regularly use the Cedar Grove side channel, a modification focused strictly on improving connectivity through the smaller side-channel should allow fishes to bypass the main channel crossing (Jungwirth 1996; Schmutz et al. 1998; Santos et al. 2005). A side-channel bypass could be both an economically and biologically beneficial alternative to replacing the entire main channel crossing.

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Table 1. Physical characteristics of the main and side channel crossing and associated culverts. Velocity range is during baseflow conditions and was taken at the culvert outflows.

	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

Table 2. Individual fish data with corresponding passage, maximum displacement, and mobility type. Asterisks indicate fish tagged during the November tagging event. Maximum displacements for fish re-located at least twice following release are provided with corresponding direction (negative = downstream).

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

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	0.0030
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			

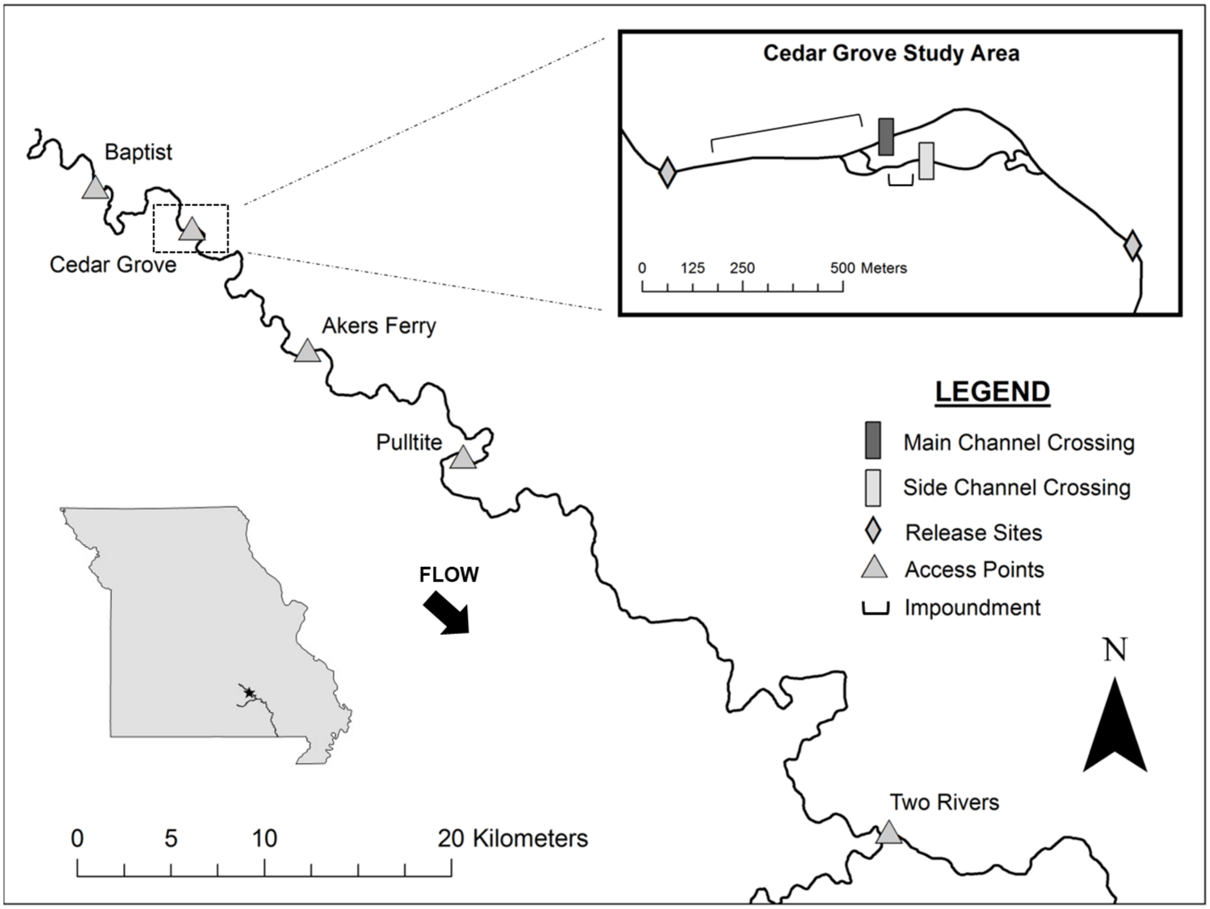

Figure 1. Map showing the headwaters of the Current River and the Cedar Grove study area. Northern Hog Sucker release sites (diamonds), low-water crossings (dark and light rectangles), commonly used access points (triangles), and impoundments (brackets) are represented. Main tracking efforts were conducted between Baptist and Akers Ferry access points with periodic extended surveys to Two Rivers.

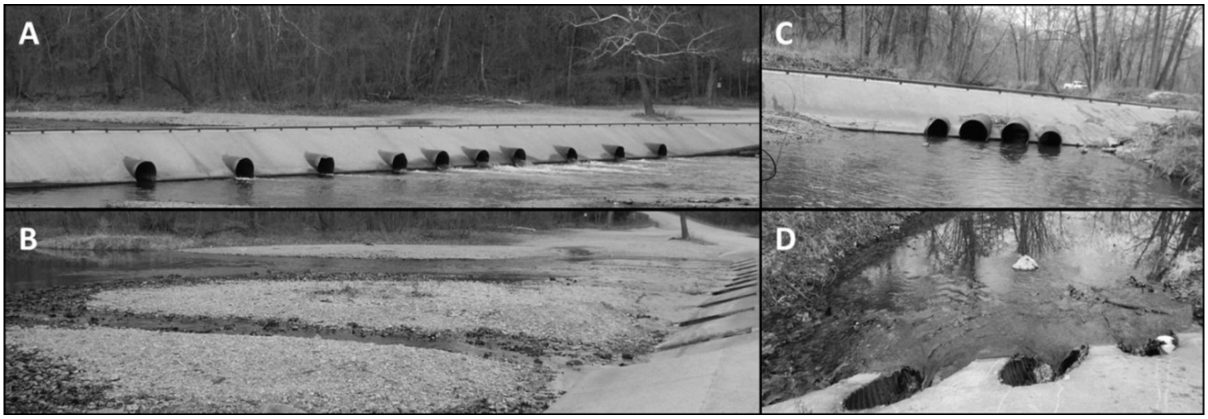

Figure 2. (A) Downstream view of the main channel crossing at Cedar Grove. (B) Upstream view of the main channel crossing showing extensive sediment deposition. (C) Downstream view of the side channel crossing at Cedar Grove. (D) Upstream view of the side channel crossing showing lighter sediment deposition. Photos were taken 9 February 2018. Discharge at the Cedar Grove low-water crossing was 2.33 m^3/s.

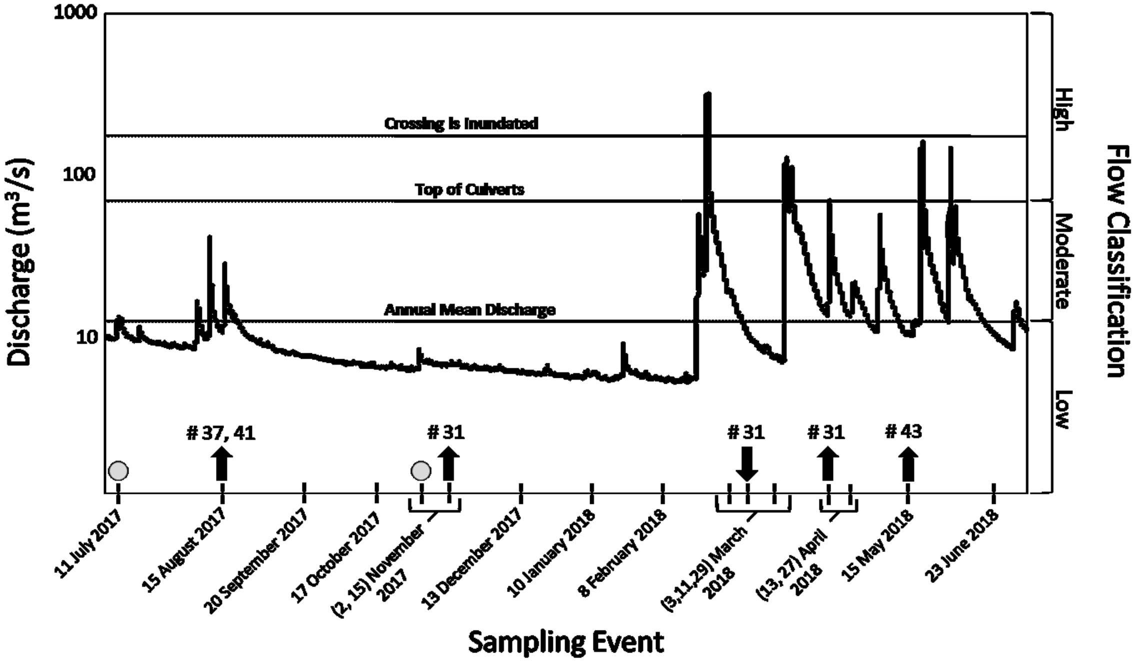

Figure 3. Stream discharge at USGS gauge station 07064533 during the study period. The gauge is approximately 13 km downstream of the crossing near Akers, MO. The 17-year annual mean discharge (12 m^3/s), discharge at which water level reached the top of the culverts (70 m^3/s), and discharge that inundated the crossing (300 m^3/s) are plotted. Flow classifications used in the study are represented on the right side of the y-axis. Sampling events are represented on the x-axis (hashmark and date) with the two tagging events indicated by circles. Arrows indicate when a fish passage was detected and the direction of passage (upstream/downstream). Numbers above each arrow represent the ID of each fish that passed (Table 2).

Figure 4. Image of the lateral overflow formed along the edge of the main channel crossing during moderate flows. The discharge at Akers Ferry was approximately 28 m^3/s during this photo. Photo taken 17 August 2017.

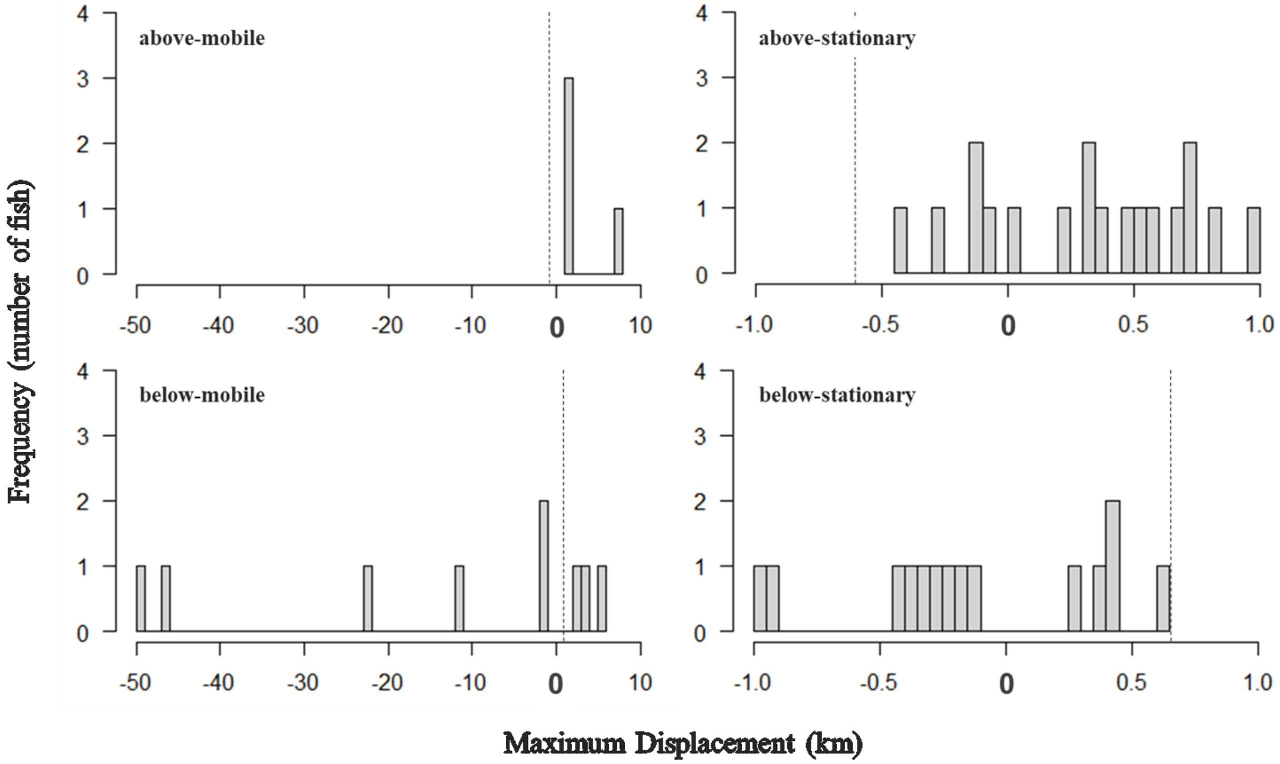

Figure 5. Frequency distribution representing directional maximum displacement of Northern Hog Suckers above and below the Cedar Grove low-water crossing. Mobile fish above and below the crossing are represented on the two left panels while stationary fish above and below the crossing are represented 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.

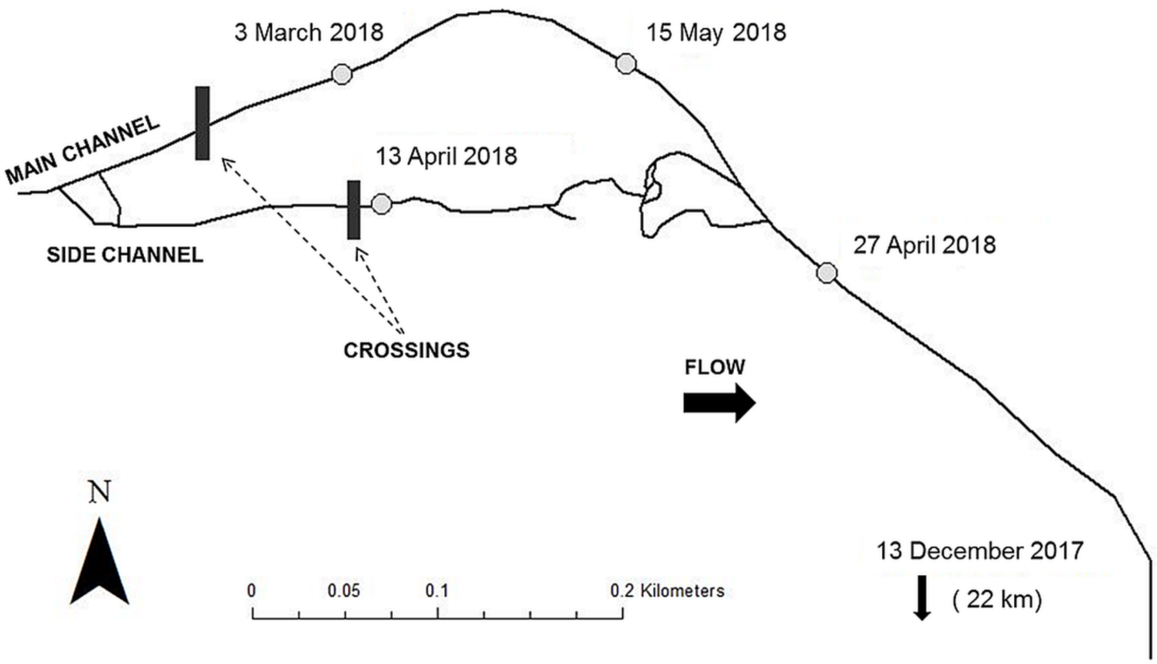

Figure 6. Map showing the movements exhibited by a fish (Fish #44, Table 2) from the main channel crossing to the side channel crossing.

DIEL MOVEMENT PATTERNS AND HABITAT USE OF NORTHERN HOG SUCKERS NEAR A LARGE LOW-WATER CROSSING

Introduction

Diel studies provide an opportunity to observe animal behavior throughout a 24-hour period and are frequently used to investigate questions regarding fine-scale movement patterns and habitat use (Moe et al. 2007; Roberts et al. 2017; Van Cleave et al. 2018). Diel studies are popular in fisheries research and have been conducted across a wide range of aquatic systems (e.g. estuary, marine, and reservoirs; Lin and Shao 1999; Cartamil and Lowe 2004; Prado and Pompeu 2016). In lotic environments, diel studies are often designed to follow fish movement in relatively natural habitat or locations in which movement is presumably unimpeded (Matheney and Rabeni 1995; Bunnell et al. 2011; Ettinger-Dietzel et al. 2015). Anthropogenic barriers (dams, weirs, and low-water crossings) are commonly found throughout lotic systems. Diel studies in the vicinity of anthropogenic barriers focus almost exclusively on salmonid migrations, due to their clear economic importance (Long 1968; Brege and Absolon 1996; Beeman and Maule 2001; Li et al. 2015). However, recent research has begun to look at the impacts of these barriers, particularly low-water crossings, on non-salmonid fishes (Bouska and Paukert 2010; Briggs and Galarowicz 2013).

Smaller barriers such as low-water crossing and weirs are common worldwide in low-order streams, including over 2,000,000 such structures in the United States alone (Baker et al. 2011). These barriers are often considered semi-permeable, with fish primarily capable of passage during certain events, such as high flow, which allow successful passage through or around the barrier (Perkin and Gido 2012; Williams Thesis Chapter 1). Culverts are commonly associated with these barriers and come in a variety of designs dependent upon factors such as stream width, peak flow, stream gradient, and cost of installation (Briggs and Galarowicz 2013). Pipe culverts have been found to have the greatest negative impact on fish movement due to the jump, velocity, and depth barriers commonly associated with their design (Bouska and Paukert 2010; Eisenhour and Floyd 2013).

Low-water crossings are common throughout the Missouri Ozarks. In addition to impacting the longitudinal connectivity of Ozark streams, low-water crossings often impact habitat structure. Low-water crossings typically increase downstream sediment loads and turbidity due to the impervious surfaces associated with the crossing that increase storm runoff from surrounding agriculture, mining, and other land-use impacts (Bouska and Paukert 2010). Additionally, low-water crossings alter stream geomorphology upstream and downstream of the structure by interrupting the longitudinal transport of sediment and woody debris (Bouska and Paukert 2010). This alteration often results in fine sediment deposition and the formation of a large, shallow pool upstream of the crossing (henceforth ‘impoundment’) and a relatively short plunge pool with armoring (removal of finer surface sediments due to heavy upstream deposition in the impoundment), immediately downstream of the crossing (Burford et al. 2009). These degraded habitats may impact the movement behavior of common stream fishes.

The Northern Hog Sucker *Hypentelium nigricans* is widely distributed throughout the Mississippi River Basin (Phlieger 1997). It spends much of its time resting and foraging for invertebrates on the streambed in riffle, run, and pool habitats of clean gravel streams with permanent flow (Matheney and Rabeni 1995; Phlieger 1997; Williams Thesis Chapter 1). Northern Hog Suckers are abundant in Ozark streams and are a popular game fish taken traditionally by gigging or spearing (Turner 2014). In Missouri’s Current River, Northern Hog

Suckers have been documented exhibiting mobile (29%) and stationary (71%) movement behavior (Williams Thesis Chapter 1). For example, Matheney and Rabeni (1995) reported home range sizes of 936 m (winter-spring) and 838 m (summer-fall) with individuals moving up to 17 km at times. Movement patterns vary by season, and movements are likely greatest in the spawning season (Matheney and Rabeni 1995). Northern Hog Suckers spawn in early spring (April-May) when fish begin moving (up to 25 km) into pool tail (glide) and head (run) habitat (Matheney and Rabeni 1995; Williams Thesis Chapter 1).

In March 2018 prior to spawning season, I investigated diel movement behavior of Northern Hog Suckers within close proximity (< 2 km) of a large low-water crossing lined with pipe culverts. I tracked radio-tagged Northern Hog Suckers throughout a 24-hour period in populations upstream (henceforth 'above') and downstream (henceforth 'below') of the crossing and tested three hypotheses. H1) Total diel displacement and linear home range are greater in fish above the crossing due to more extensive degraded habitat upstream of the crossing that may force fish to move greater distances to access different habitat types. H2) The direction of diel displacement is upstream-directed in fish above the crossing and downstream-directed in fish below the crossing because the crossing strongly limits passage. H3) Habitat use of all tagged fish (above and below) is similar, with fish primarily associated with spawning habitat (runs and glides) due to the timing of the study. Additionally, I make comparisons between my results and results of another study (Matheney and Rabeni 1995) in a non-fragmented reach of the same stream.

Methods

Study site. I studied Northern Hog Sucker movement behavior in a third-order reach of the Current River in Southeastern Missouri (Figure 7). The Current River is located within the Ozark Plateau which consists of karst topography and 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). The river's baseflow is primarily spring-fed with an average channel gradient of 0.74 m/km (Ettinger-Dietzel et al. 2015). Over its 296 km length, the river is free flowing, with the exception of a single low-water crossing at Cedar Grove, 17 km downstream of the river's headwaters at Montauk Spring (Wilkerson 2003; Figure 7).

The Cedar Grove low-water crossing (henceforth 'the crossing') consists of two structures that span the main channel (width = 59.5 m) and a side channel (width = 24.3 m) forcing water to pass through 10 and 4 corrugated pipe culverts, respectively, during periods of baseflow (Figures 2, 7). The stable baseflow from groundwater sources allows the culverts to remain non-perched year round. Further details associated with the culvert characteristics can be found in Chapter 1 of this thesis (Table 1). Both crossings create an upstream impoundment pool with moderate to heavy sediment deposition and armored plunge pools downstream (Table 4). Natural habitat structure (riffle-pool sequence) is quickly reestablished immediately downstream of each crossing's plunge pool. Flow at the crossing was approximately 61 m^3/s during the diel study.

Sampling design. I followed the diel movements of 13 Northern Hog Suckers (above: N = 5, below: N = 8) within close proximity (< 2 km) of the crossing during a single 24-hour period spanning 10-11 March 2018. These fish were previously equipped with radio transmitters with a trailing whip antenna (F1580, 3.6 g, Advanced Telemetry Systems) as part of a concurrent study (Williams Thesis Chapter 1). Beginning at 10:00 am, two field crews simultaneously located fish above and below the crossing once every two hours, for a total of 11 movement observations per individual. Fish locations were determined with radio telemetry equipment (Biotrack Reciever, 3-element Yagi Antenna, Lotek Wireless) and triangulation from river's edge, as to not disturb the initial position of the fish. A crew member then entered the water to record the initial position of each fish using a Trimble Geo7x GPS unit with sub-meter accuracy. Habitat type (run, riffle, pool, glide) was recorded in conjunction with individual fish positions.

Data analyses. Spatial data were uploaded with GPS Pathfinder Office (Version 5.85) and imported into ArcMap 10.3 for analysis. I determined linear home range by measuring the distance between the furthest upstream and downstream location for each fish along a digitized midline of the stream channel. I calculated diel displacement by measuring the cumulative distance between consecutive locations for each fish. Diel displacement was analyzed without including the direction (upstream/downstream) of individual movements thus giving me the total magnitude of displacement in above-tagged vs. below-tagged fish. I then conducted similar analysis for diel displacement in which I included the directional component of individual movements. Directional displacement was measured by taking the sum of downstream movements and the sum of upstream movements for each individual. To assess habitat use, I calculated the proportions of fish in the two populations (above- and below-tagged) that were associated with the four major habitat types (riffle, run, pool, glide) during each 2 hour period.

Statistical analysis was conducted in RStudio with an alpha of 0.05. The majority of raw data were non-normally distributed (Package: e1071, Function: skewness and kurtosis), so I transformed data as such: diel displacement (Log_{10}), linear home range (Log_{10}), and direction-specific diel displacement (^ 1/3) for parametric statistical analysis. Proportional data associated with habitat use was also transformed (arsin(sqrt)) for parametric analysis. I tested for differences in both the total diel displacement and direction of diel displacement between tagging location (above vs. below), time of day (2-hr time slot), and interactions between these two factors by using two separate two-way repeated measures ANOVAs (Program: stats, Function: aov). Following each ANOVA, pairwise comparisons were made and p-values adjusted (Program: stats, Function: pairwise.t.test; Bonferroni adjustment). I tested for differences in linear home range between tagging location by conducting a Welch two-sample t-test (Package: stats, Function: t.test). I tested for differences in habitat use between tagging location by conducting a Welch two-sample t-test for each of the four habitat types (riffle, run, pool, glide; Package: stats, Function: t.test).

Results

I collected a total of 143 fish locations over the 24-hour period. According to the size data at initial tagging (Williams Thesis Chapter 1), there was no difference in the total length (t (11) = 0.6230, *P* = 0.5460) or weight (t (11) = 0.0581, *P* = 0.9547) of above-tagged (mean = 348 mm, 430 g; SE = 21 mm, 16 g) and below-tagged (mean = 332 mm, 423 g; SE = 104 mm, 70 g) fish (Table 5). There were no fish passage events through the culverts, and fish in both groups remained within 1.5 km of the crossing for the duration of the study. The interaction between tagging location and time of day approached significance for total diel displacement; however, p-value adjustments from post-hoc analysis resulted in no significant differences in total diel displacement between tagging location and time of day (Figure 8; Table 6). The greatest individual movements (>150 m, N = 2) occurred between 04:00 and 06:00 hours in both groups (above = 247 m, below = 169 m; Figure 8). Linear home range was significantly greater in above-tagged fish (mean = 181 m, SE = 81 m) compared to below-tagged fish (mean = 103 m, SE = 36 m; t (11) = 2.39, *P* = 0.0361; Figure 9; Table 5). Direction of diel displacement was not significantly different between tagging location, time of day, or the interaction between the two main factors (Table 6; Figure 10).

Northern Hog Suckers were associated with all four habitat types during the study period (Table 5). I found a greater association with pool habitat in above-tagged fish (t (14) = 5.68, *P* = < 0.0001) and run habitat in below-tagged fish (t (18) = -4.61, *P* = 0.0002; Figure 11; Table 5). During the day, fish above the crossing equally used pool and run habitat (40%) while at night the majority of fish (ca. 60%) moved into pool habitat (Figure 11: above). During the day, fish below the crossing primarily used run habitat (≥ 75%) and were not found using pool habitat. However, fish began using pools during the night (≤ 40%) even though runs continued to be most-used at night (≥ 40%, Figure 11: below).

Differences in habitat use between day and night were more pronounced in above-tagged fish compared to below-tagged fish (Figure 12). Furthermore, above-tagged fish did not have intersecting home ranges (Figure 12: above). Three of these fish each inhabited separate riffle-pool complexes while two fish inhabited the degraded impoundment and area of heavy sediment deposition immediately upstream of the crossing (Figure 12: above). Below-tagged fish also inhabited a single riffle-pool sequence; however, multiple fish typically co-occurred within the same sequence (Figure 12: below).

Discussion

I observed differences in the diel movement patterns of Northern Hog Suckers upstream and downstream of the Cedar Grove low-water crossing that suggest this species is capable of adjusting to habitat alterations commonly associated with stream barriers. This adjustment is likely due to the strong swimming ability (up to 0.8 km/day, Williams Thesis Chapter 1) of this species that allows individuals to freely move between large areas of fragmented habitats. Fish above the crossing were primarily found inhabiting pool habitat, which was the most abundant habitat type (ca. 76% of stream reach) due to the damming effect of the crossing. Below-tagged fish were primarily found inhabiting the higher velocity habitats that were more abundant (ca. 82% of stream reach) downstream of the crossing. Therefore, observed habitat use and movement activity may be associated with habitat availability near the crossing, which I did not measure in detail during the study. Matheney and Rabeni (1995) found that Northern Hog Suckers lower on the Current River used higher velocity run habitat in proportion to its availability. Habitat use may also be attributed to energetic costs associated with the greater distance above-tagged fish had to move in order to reach different habitat types compared to below-tagged fish. For example, fish above the crossing may have spent more time resting in pool habitat to offset the high energy demands needed to disperse to higher velocity foraging habitats (e.g. riffle, run, glides; Garrels 1979) upstream of the crossing's impoundment. Alternatively, the heterogeneity in habitat downstream of the crossing's plunge pool potentially allowed fish below the crossing to inhabit smaller areas and remain near these valuable habitats (Matthews 1990; Laurel et al. 2004).

Each tagged fish typically inhabited a single riffle-pool complex. Fish above the crossing used separate riffle-pool complexes with non-intersecting home ranges while fish below the crossing frequently co-inhabited the same riffle-pool complex. Habitat degradation can cause increased competition for limited resources, such as spawning and foraging habitat (Bostrom-Einarsson et al. 2014). Competition may help explain the observed differences in spatial use between fish above and below the crossing. The timing of my study was too early to observe movement behavior associated with spawning activity on the Current River; however, foraging activity was likely observed during the day when fish above (approx. 60%) and below (nearly 100%) the crossing moved into higher velocity habitat with larger substrate size (higher benthic invertebrate biomass, Matheney and Rabeni 1995; Duan et al. 2008). The greater availability of foraging habitat below the crossing likely made prey readily available for Northern Hog Suckers, potentially reducing competition among individuals. Conversely, the non-overlapping home ranges of fish above the crossing could be a product of increased competition due to the greater amounts of degraded habitat.

I also observed Northern Hog Sucker movement patterns in the vicinity of the Cedar Grove low-water crossing similar to natural movement behavior reported in non-fragmented reaches of the Current River. For example, crepuscular peaks in movement of Northern Hog Suckers between day (high velocity) and night (low velocity) habitats had been previously observed by Matheney and Rabeni (1995). During the same time period as my study (mid-March), Matheney and Rabeni (1995) reported total diel movements (290 m) which were comparable to my study (above: 380 m, below: 209 m). It is important to note that I only captured a single 24-hour period while Matheney and Rabeni (1995) captured six 24-hour periods between February and March.

The results from this study suggest that the strong swimming ability of Northern Hog Suckers likely allows them to inhabit areas of degraded habitat near stream barriers as long as important day and night habitats are nearby. However, the degraded upstream habitat likely limits resources such that increased intraspecific competition results in strong spatial separation. Further diel movement studies around anthropogenic barriers are needed on non-game, weaker swimming species, such as minnows, sculpins, and darters to understand how stream fragmentation impacts movement patterns and habitat use of these less mobile, understudied species.

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Table 4. 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

Table 5. Individual fish data with corresponding total diel displacement, linear home range, and habitat use. Total displacements shown represent the magnitude of displacement without direction of displacement.

Fish	Total Length (mm)	Weight (g)	Total Displacement (m)	Linear Home Range (m)	Habitat Use (%)			
					Riffle	Run	Pool	Glide
			ABOVE (N=5)					
1	352	324	295.16	133.04	0	0	100	0
2	304	236	231.44	115.43	25	8	50	17
3	370	504	266.8	164.88	17	25	42	16
4	414	805	416.36	165.32	0	42	50	8
5	301	281	693.57	327.56	0	67	0	33
			BELOW (N=8)					
6	266	212	279.82	135.92	33	67	0	0
7	357	575	250.17	130.02	0	100	0	0
8	300	271	117.2	47.44	0	92	8	0
9	320	296	117.77	62.03	0	50	50	0
10	295	304	234.83	81.78	25	25	50	0
11	400	768	429.25	278.07	8	67	17	8
12	385	597	103.14	43.96	0	100	0	0
13	330	361	143.5	45.99	8	50	17	25

Table 6. Results of Two-way Repeated Measures ANOVAs for effects of tagging location and time of day on total displacement and directional total displacement of Northern Hog Suckers. The interaction between tagging location and time of day for total displacement (*P* = 0.026) was not significant at alpha = 0.05 following the Bonferroni correction.

Source of Variation	df	SS	MS	F	P
Total Displacement					
Tagging location	1	0.563	0.563	3.317	0.072
Time of Day	10	1.559	0.156	0.919	0.519
Tagging location * Time of Day	10	3.687	0.369	2.173	0.026
Error	99	16.799	0.170		
Total	120	22.608			
Total Displacement with Direction					
Tagging location	1	0.3	0.284	0.038	0.845
Time of Day	10	46.3	4.633	0.625	0.789
Tagging location * Time of Day	10	78.1	7.814	1.054	0.405
Error	99	734.1	7.415		
Total	120	858.8			

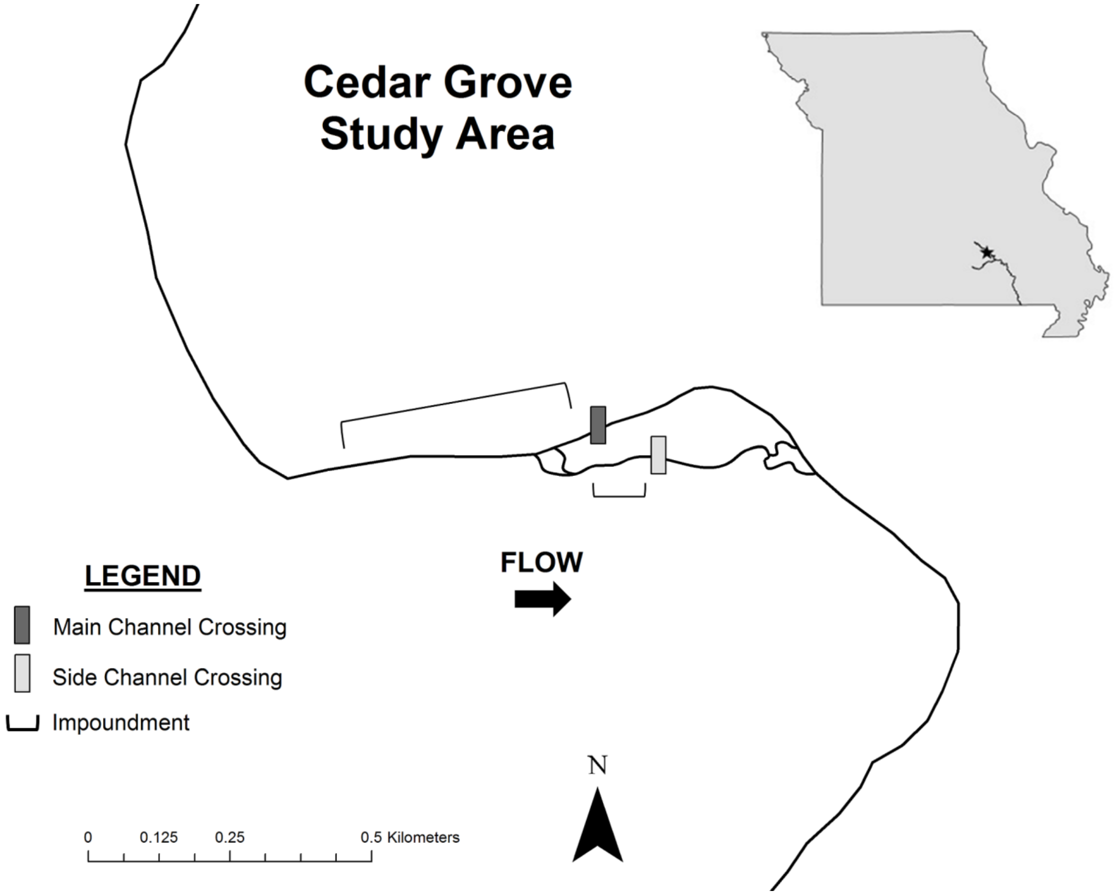

Figure 7. Map showing the Cedar Grove study area. The impoundments upstream of each crossing are represented.

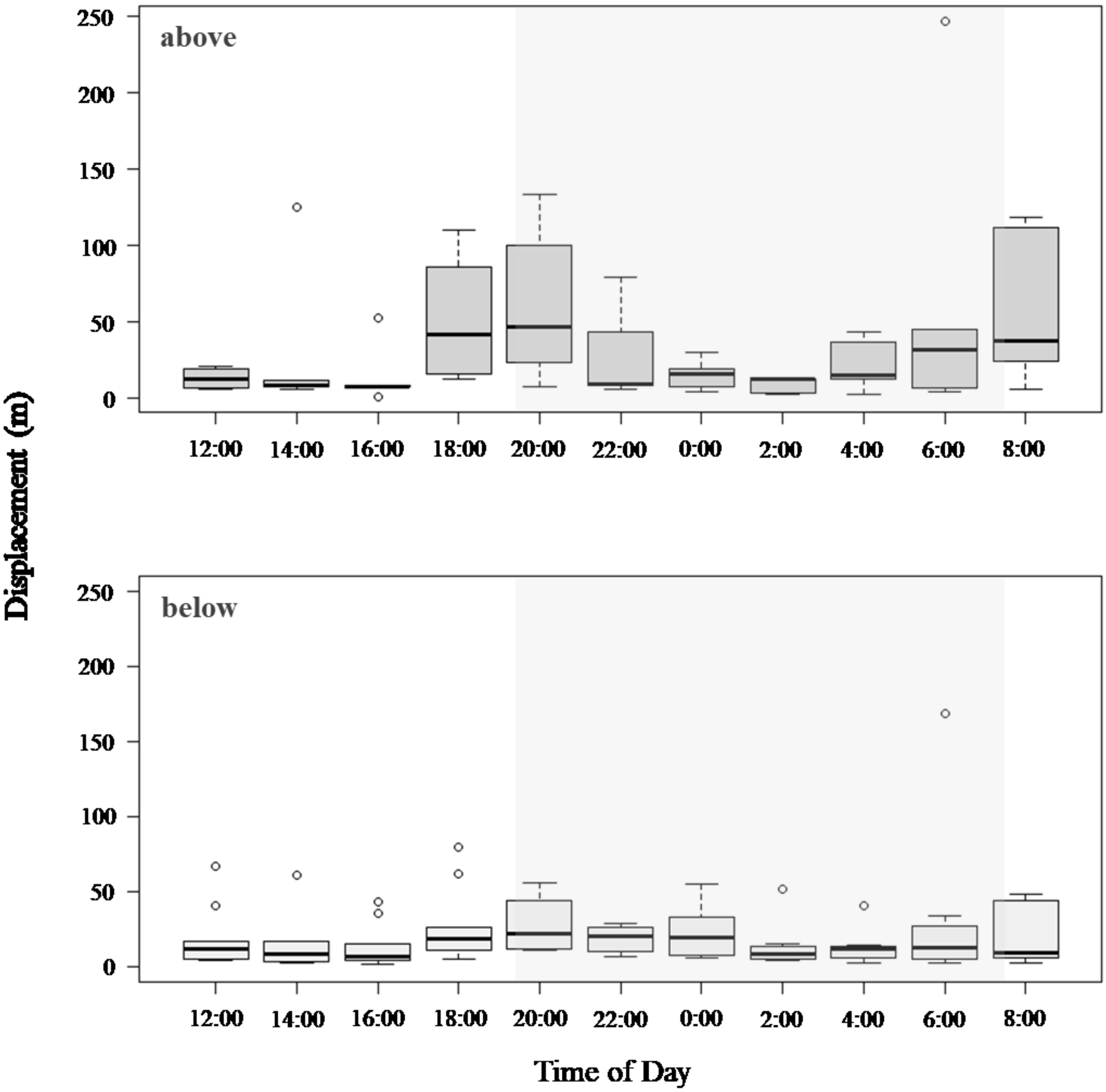

Figure 8. Total diel displacement of fish above and below the crossing. Gray-shaded area represents the period from dusk to dawn. Boxes represent the interquartile range of the data and whiskers represent the minimum and maximum of the data (excluding outliers – open circles). Horizontal lines indicate the median.

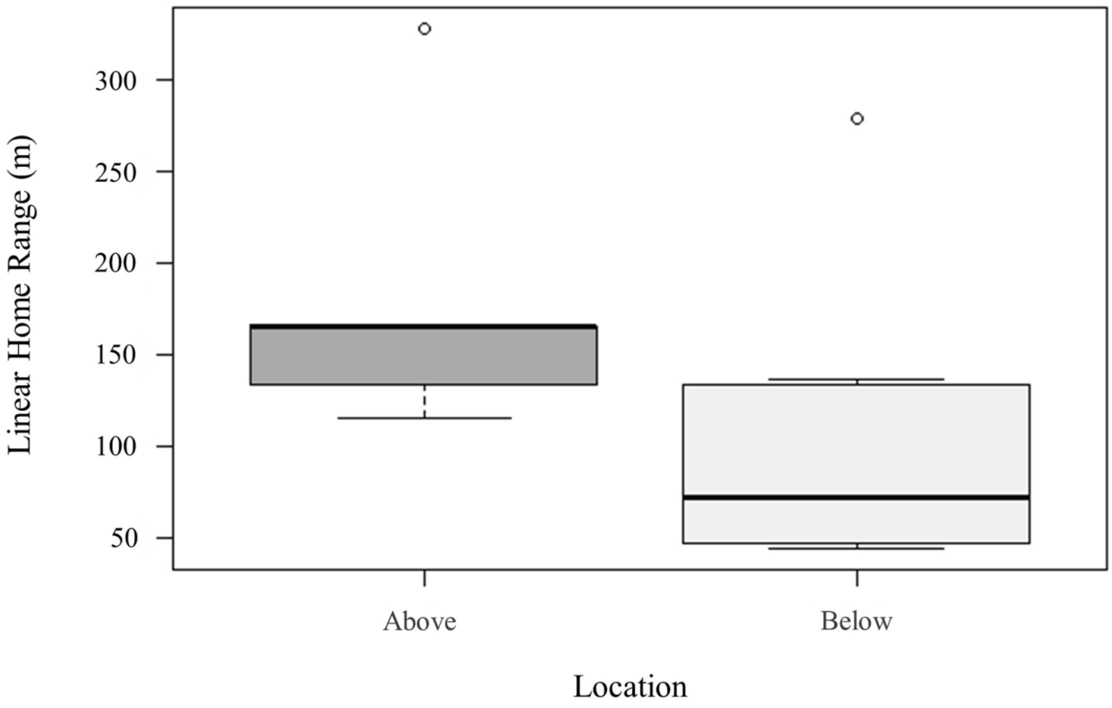

Figure 9. Linear home range observed in fish above and below the crossing during the study period. Boxes represent the interquartile range of the data and whiskers represent the minimum and maximum of the data (excluding outliers – open circles). Horizontal lines indicate the median.

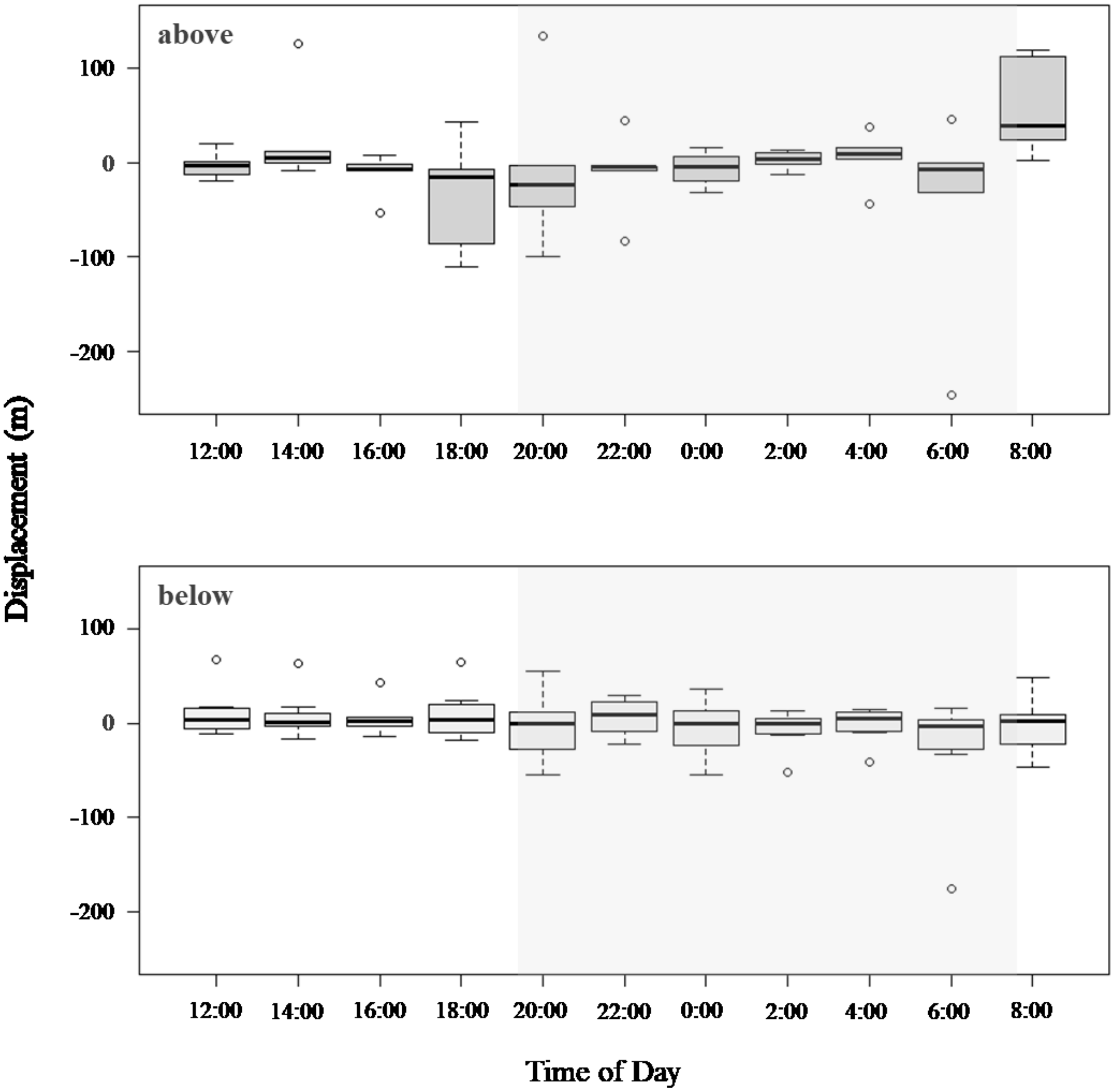

Figure 10. The direction of diel displacement in fish above and below the crossing. Positive displacement refers to upstream movements while negative displacement refers to downstream movements. Gray-shaded area represents the period from dusk to dawn. Boxes represent the interquartile range of the data and whiskers represent the minimum and maximum of the data (excluding outliers – open circles). Horizontal lines indicate the median of the data.

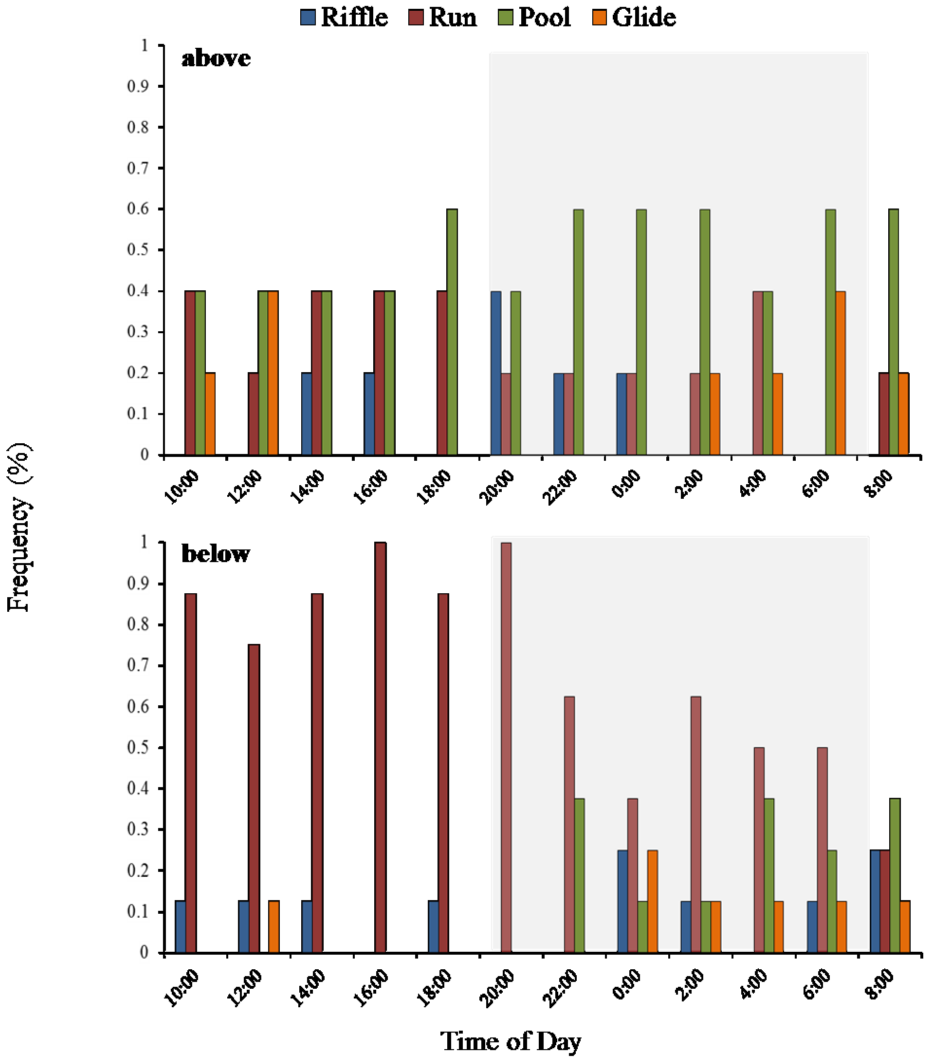

Figure 11. Diel habitat use of Northern Hog Suckers above and below the crossing. Gray-shaded area represents the period from dusk to dawn.

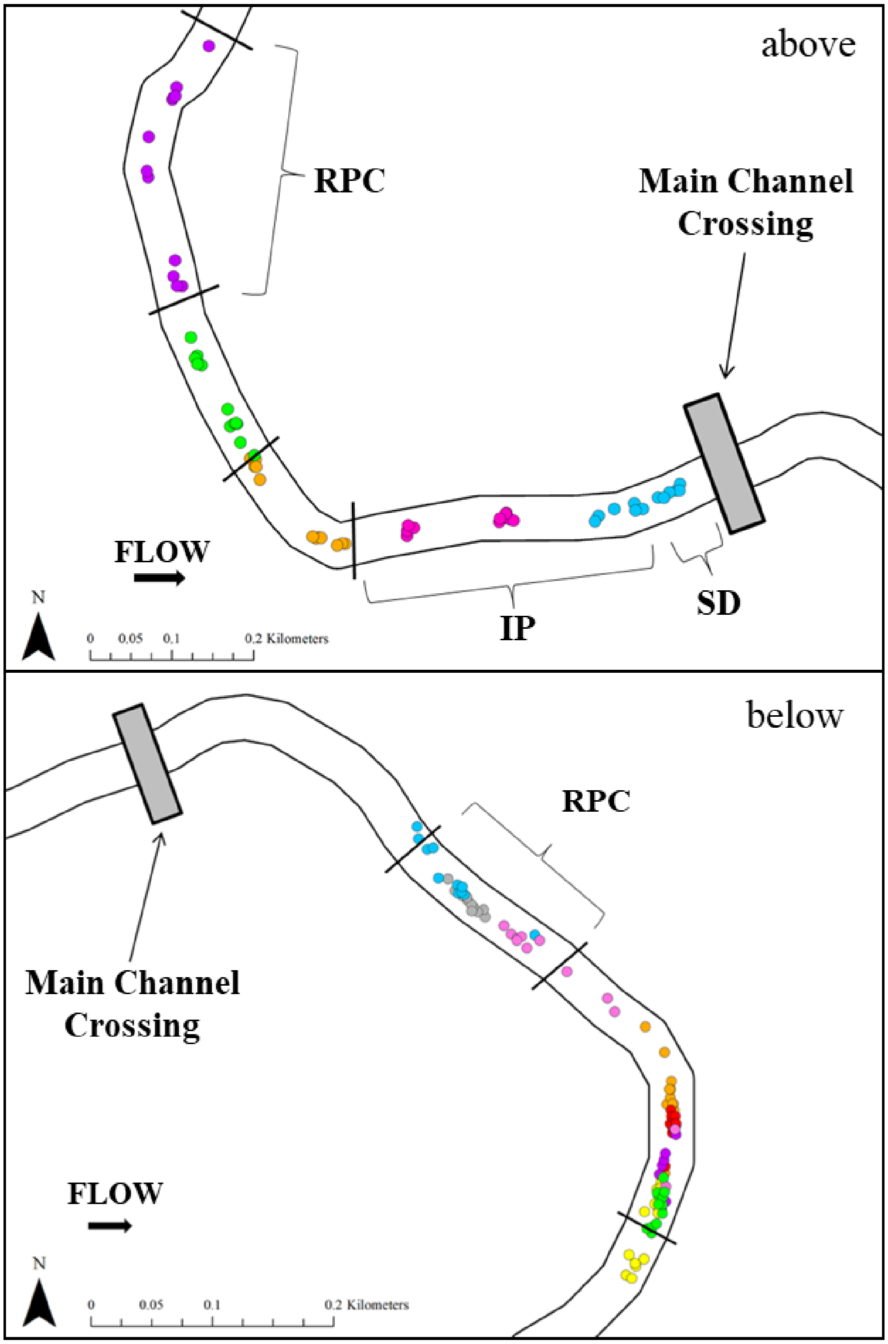

Figure 12. Diel movement patterns of Northern Hog Suckers above and below the crosing. Black lines indicate the beginning and end of a single riffle-pool complex (RPC). The impoundment pool (IP) and area of heavy sediment deposition (SD) are represented in panel A. Colors represent the positions of individual fish throughout the 24 hour period.

SUMMARY

My results suggest that the Cedar Grove low-water crossing impacts Northern Hog Sucker movement behavior at both annual and diel scales. In Chapter 1, year-long monitoring of fish movement demonstrated that passage in both directions is extremely limited even in individuals that exhibit mobile trends in movement behavior. Furthermore, the mobile fish were typically moving greater distances away from the crossing. The reduction in gene flow between upstream and downstream populations could potentially become a major issue over long durations and lead to increased proportions of interbreeding (Pritchard et al. 2007). In my second chapter, diel movement behavior of Northern Hog Suckers showed that this species is capable of adjusting to habitat degradation commonly associated with stream fragmentation. Fish above the crossing were able to move greater distances to reach different habitat types to compensate for the homogeneity of degraded pool habitat near the crossing.

The rate of small-dam removal has increased substantially over the past couple of decades (Badnarek 2001; Foley et al. 2017). Restoring the longitudinal connectivity of streams has many benefits, such as increased biotic diversity, habitat heterogeneity, and distribution of fishes (Bednarek 2001). It is ecologically important to continue researching both the impacts of stream barriers on understudied species and the effects of barrier removal. This study will help inform resource managers at Ozark National Scenic Riverways on how the Cedar Grove low-water crossing is limiting fish movement. Thus far, resource managers have shown interest in my recommendation of replacing the side channel crossing to promote longitudinal movements of fishes and restore connectivity in the upper Current River.

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