FISH PASSAGE THROUGH HEADWATER STREAM ROAD CROSSINGS MONITORED BY RADIO FREQUENCY IDENTIFICATION STATIONS

By

IAN R. MACLEOD

Submitted to the Faculty of the Graduate College of Arkansas Tech University in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE IN FISHERIES AND WILDLIFE SCIENCE December 2013
FISH PASSAGE THROUGH HEADWATER STREAM ROAD CROSSINGS MONITORED BY RADIO FREQUENCY IDENTIFICATION STATIONS

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Road crossings on small streams typically alter stream hydrology and potentially fragment aquatic ecosystems. The Ouachita National Forest, Arkansas has thousands of road crossings which may hinder fish movement and contribute to genetic inbreeding or extirpation. To monitor the impacts of road crossings on fish movement I used stationary antenna arrays to detect and record radio frequency identification (RFID) tags, also known as PIT tags, in the Ouachita Mountains. In 2011-2013, I injected 12-mm, half-duplex, RFID tags in ~3,800 fish (nine species) 85 mm or greater total length. I installed remotely-powered RFID detection stations in two streams with road crossings and two reference streams without road crossings to continuously monitor fish movements. The RFID stations included two, pass-through antennas transecting the stream, with one antenna upstream of the road crossing or reference reach and the other located downstream. The two-part antenna array was designed to precisely record timing and movement direction of each fish passage. The antennas lacked rigid, in-stream structures, which may have affected fish movement. I developed a figure-eight crossover antenna design to improve tag detection efficiency. I monitored associated stream depths and velocities to characterize hydrological conditions and road crossing hydraulics. Fish passed at higher rates across reference reaches than road crossings and at higher rates across a box-culvert than a vented-ford, where fish utilized high water events to bypass high velocity and low swimming depth barriers. Stream intermittency caused extensive stream dryness and exacerbated the hydraulic obstacles at road crossings, which reduced passage rates. Fish species and length had little impact on passage rates. The RFID stations monitored fish passage more efficiently than electrofishing recapture methods
and should enhance future studies of aquatic organism passage and road crossing permeability.

Keywords: Detection efficiency, Fish passage, Hydrology, Radio frequency identification, Road crossing
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Introduction

Fragmentation of aquatic habitats threatens the biodiversity and persistence of stream fish populations in the central and southeastern United States (Sheldon 1988; Bessert and Ortí 2008; Kashiwagi and Miranda 2009; Perkin and Gido 2011). Fragmentation disrupts life history strategies of migratory fish, such as the White-spotted Char *Salvelinus leucomaenis* in Japan, decreasing fitness and lowering population viability in isolated upstream habitats (Morita et al. 2009) and extirpating populations from dammed sites (Morita and Yamamoto 2002). Fragmentation also impacts non-migratory fish and has led to increased extinction risk in rare desert fish (Fagan et al. 2002) and extirpation of Blackside Darter *Percina maculata* from impounded headwater streams in Mississippi (Kashiwagi and Miranda 2009). Although they are considered nonmigratory, the endangered Apron *Zingel asper* requires dispersal among riverine habitats to maintain its population viability (Labonne and Gaudin 2006) and the vulnerable Southern Pygmy Perch *Nannoperca australis* utilizes dispersal to connect semi-discrete populations and maintain effective population size (Cook et al. 2007).

Road crossings are widespread on forested streams in North America. For example, the boreal forest in Alberta, Canada has several thousand culverts (Park et al. 2008) and the states of Oregon and Washington are estimated to have more than 10,000 culverts on fish-bearing streams, 2,600 of which disrupt salmon migration (Gibson et al. 2005). Fish in the Yellowstone River, Montana successfully pass individual low-head diversion dams at high flow, but the cumulative effect of the river’s six dams restrict fish distributions and limit abundance (Helfrich et al. 1999). Most research regarding the impact of road crossings on fish movement has involved salmonids in the Pacific
Northwest (Belford and Gould 1989; Wofford et al. 2005; Burford et al. 2009). Despite having an abundance and diversity of road crossing types, distinct hydrology, and fish taxa unique to the southeastern US, the Ouachita National Forest, Arkansas has received limited attention (but see Standage and Gagen 2007 and Appendix A for an estimate of road crossing abundance).

Fish require sufficient water depth and suitably low velocities to pass a given reach (Blank et al. 2005; Rodríguez et al. 2006). Road crossings that severely alter natural stream flow cause more disruption to fish passage (Warren and Pardew 1998). Road crossings primarily reduce fish passage through two mechanisms: 1) *water depth*- water flowing through the crossing is too shallow to facilitate efficient swimming; 2) *velocity*- water flowing through the crossing is too rapid for fish swimming speeds (Burford et al. 2009). Road crossings with elevated outlets (or hanging culverts, as described by Park et al. 2008) reduce passage through two additional mechanisms: excessive outlet drop height and insufficient outlet pool depth, required for jumping to the level of the outlet (Burford et al. 2009).

The variable hydrology of stream systems, road crossing hydraulics, and fish characteristics all impact the passability of road crossings, which often function as semipermeable barriers (Bouska and Paukert 2009). Connolly et al. (2008) detected trout in Washington state moving disproportionately across culverts on high-flow days. Fish species inhabiting different micro-habitats were affected differently by road crossing obstacles. Fish inhabiting the water column passed upstream through culverts with elevated outlets during high flow events, while benthic fish did not (Norman et al. 2009).

Passage rates also differ based on fish size. Larger fish such as trout (Blank et al.
may experience passage challenges caused by lack of sufficient water depth in places where flow is diminished to a sheet such as over concrete aprons. Small trout (less than 100 mm FL) passed through culverts with outlet drops less frequently than did larger trout (Burford et al. 2009). Movement patterns of headwater stream fish are less well understood. Lonzarich et al. (1998) concluded that Arkansas pools were recolonized more rapidly by larger fish (greater than 100 mm, TL) and when intervening riffles had greater water depths. Conversely, Smithson and Johnston (1999) did not report size-based differences in movement patterns in Ouachita Highlands streams. Schaefer (2001) observed small cyprinids crossing artificial riffles and detected no significant reduction in movement rates when depths varied from 1 to 10 cm. Minimum depth requirements vary with species and length but Blank et al. (2005) determined 3 cm to be the minimum swimming depth permitting passage in Montana streams for several species of trout after observing adult fish passing unimpeded through 3 cm of water in riffles. However, this depth may be the absolute minimum and Rodríguez et al. (2006) concluded 40 cm to be a more conservative minimum depth for passage of Brown Trout *Salmo trutta*.

Road crossings concentrate water velocity, which fatigues fish and deters upstream movement (Belford and Gould 1989; Warren and Pardew 1998; Norman et al. 2009; Bourne et al. 2011). While studying Ouachita Mountain streams, Rajput (2003) measured lower species richness upstream of road crossings with spring baseflow velocities exceeding 0.6 m/s. I hypothesized that slower swimming species, such as Longear Sunfish *Lepomis megalotis*, would be more susceptible to velocity barriers than significantly faster species such as Creek Chub *Semotilus atromaculatus* and Highland Stoneroller *Campostoma spadiceum* (Table 1; Leavy and Bonner 2009).
Table 1.— Mean prolonged swimming speeds ± SE for fishes measured in a mobile swim tunnel. In the Ouachita Mountains, the Central Stoneroller, *Camostoma anomalum*, whose speed is given here, merited its own taxonomic distinction and was designated Highland Stoneroller by Cashner et al. (2010). (Adapted from Leavy and Bonner 2009.)

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<th>Species</th>
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<td>Creek Chub</td>
<td>44 ± 1.6</td>
</tr>
<tr>
<td>Central Stoneroller</td>
<td>63 ± 2.8</td>
</tr>
<tr>
<td>Longear Sunfish</td>
<td>28 ± 4.2</td>
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In order to reduce fragmentation, older road crossing designs may be replaced with newer designs that more closely simulate natural stream conditions and minimize hydraulic alteration (Gibson et al. 2005). Lack of regulatory oversight in the field and the high cost of road crossing replacement contribute to the persistence of impermeable road crossings (Gibson et al. 2005). For example, in Alberta’s boreal forest 50% of culverts have elevated outlets, presenting a serious challenge to upstream fish movement (Park et al. 2008). Vented-ford (also known as pipe culvert) road crossings appear to alter hydraulics and impair passage more than other road crossing designs (Belford and Gould 1989; Norman et al. 2009; Bourne et al. 2011). Vented-fords are defined as crossings whose road grade is constructed above stream bottom with pipes designed to convey water under the crossing during periods of low flow (USFS 2006). However, during high flow conditions, the pipes are overwhelmed and the majority of water flows over the crossing. Box-culverts support the road surface with boxes, whose narrow support columns generally constrict stream flow less than vented-fords. Vented-fords allow less fish passage than box-culvert and natural-ford road crossings, which permit passage comparable to reference reaches (Standage and Gagen 2007; Norman et al. 2009). In the Ouachita Mountains, less than half as many small stream fish moved across 50-m reaches with vented-fords compared to reference reaches (Standage and Gagen 2007).

Fish in headwater streams are often exposed to passage challenges in addition to
road crossings. For example, streams in the eastern Ouachita Mountains experience
drying in summer that results in discontinuous surface flow and seasonally eliminates
portions of populations including the Ouachita Madtom *Noturus lachneri*, Creek Chub,
Central Stoneroller [sic], Green Sunfish *Lepomis cyanellus*, Longear Sunfish, and
Smallmouth Bass *Micropterus dolomieu* (Gagen et al. 1998; Magoullick and Kobza 2003;
Hafs et al. 2010). In their recolonization study, Lonzarich et al. (1998) reported that fish
fully recolonized the least-isolated pools, those nearby large source pools or separated
only by short, shallow riffles, twice as fast the most-isolated pools. This further highlights
the challenges present in intermittent streams where recolonization is seasonally
dependent on rainfall to provide connectivity among pools.

I sought to evaluate the impact of road crossings on fish movement in Ouachita
Mountain streams. More specifically, I sought to elucidate trends in fish passage related
to: 1) reach characteristics such as type of road crossing; 2) variable stream hydrology
such as high water events and intermittency; and 3) fish characteristics such as species,
size, and swimming abilities. I expected to find higher passage rates: 1) across reference
reaches than road crossings; 2) across road crossings (such as box-culverts) with less
hydraulic alteration; and 3) during high water events when road crossing obstacles may
have been surmountable. I hypothesized stronger swimmers would more easily negotiate
velocity barriers while larger fish would be deterred by insufficient swimming depths.
Methods

Stream and Site Selection

I examined fish movements in four warm-water, low-order streams in the Ouachita Mountains, an ecoregion of approximately 4.8 million hectares in Arkansas and Oklahoma (The Nature Conservancy 2003). The region is located in a humid, subtropical zone with precipitation ranging from 1.1 to 1.5 m annually. Its low order streams are generally cool and clear, have medium-high gradients, have substrates of sand, gravel, cobble, or exposed bedrock, and support the region’s greatest fish species diversity (Stroud and Hanson 1981; The Nature Conservancy 2003). The area supports 24 fish families and 8 ecoregionally-endemic fish species with diversity concentrated in the minnow (Cyprinidae), perch (Percidae), sucker (Catostomidae), sunfish (Centrarchidae), and catfish (Ictaluridae) families.

I chose streams in two different regions of the Ouachita Mountains to study contrasting summer flow conditions (Figure 1). The two study streams located in southern Ouachita National Forest are perennial and supported by groundwater flow throughout the summer. Conversely, the two study streams located in northeastern Ouachita National Forest are intermittent and experience extensive drying of long reaches in summer, particularly riffle and run habitats (Gagen et al. 1998). Each pair of streams included a treatment stream intersected by multiple engineered road crossings within the study reach and a reference stream without road crossings. I chose two pairs of streams from within the same drainage to minimize confounding variables such as differing fish assemblage, geology, and climatic conditions. Similar to the work of Norman et al. (2009), the small sample size limited my ability to extrapolate conclusions.
beyond the four study streams. This descriptive study generated testable hypotheses for future research sensu Hurlbert’s (1984) comparative mensurative experiment and evaluated an important fish monitoring technique.

Figure 1.—Four study streams located within the Ouachita National Forest, Arkansas where I established RFID detection stations. Bear Creek and Crystal Prong are intermittent streams, while Long Creek and Little Missouri River are perennial. Bear Creek and Long Creek contain road crossings whereas Crystal Prong and Little Missouri River are paired reference streams, free of road crossings within the study reaches.
In Perry and Saline Counties (northeastern Ouachita Mountains) the two intermittent streams drain into the Fourche La Fave River in the Arkansas River watershed (Figure 2). Bear Creek has three road crossings within the study reach. Crystal Prong is located in the minimally-disturbed Flatside Wilderness Area and has no road crossings. I selected a vented-ford road crossing on Bear Creek as the core of the experimental reach.
Figure 2.—Map of the intermittent streams, Bear Creek and Crystal Prong, in the northeast portion of the Ouachita Mountains, Arkansas. Within the study reaches, Bear Creek contains two vented-fords and one slab-ford while Crystal Prong, the reference stream, has no road crossings. In 2011, I marked fish at three sites on each stream, the downstream (DS), middle (with RFID station), and upstream (US). The 2012-2013 electrofishing area spanned 1,000 m on either side of the middle site. Bear Creek and Crystal Prong are both tributaries of the South Fouche La Fave River. (Adapted from Schanke 2013).

I selected a pair of perennial streams in Polk and Montgomery Counties (southern Ouachita Mountains), Long Creek and Little Missouri River, that drain to the Ouachita River watershed (Figure 3). Long Creek has nine road crossings including slab-fords, vented-fords, box-culverts, and arched-bridges within the study reach. The adjacent Little
Missouri River has no road crossings within the study reach (though some exist in the headwaters and farther downstream). These streams reach a confluence downstream near the Albert Pike Recreation Area where the Little Missouri River continues flowing into Lake Greeson and the Ouachita River. On Long Creek, I focused on a newly-constructed box-culvert to contrast with the older style vented-ford on the other treatment stream, Bear Creek.

Figure 3.—Map of the perennial streams, Long Creek and Little Missouri River, in the southern portion of the Ouachita Mountains, Arkansas. The treatment stream, Long Creek, contains nine road crossings including two slab-fords, three vented-fords, and four box-culverts within the study reach. The reference stream, Little Missouri River, has no road crossings, but contains the Little Missouri Falls. In 2011, I marked fish at three sites on each stream, the downstream (DS), middle (with RFID station), and upstream (US). The 2012-2013 electrofishing area spanned 1,000 m on either side of the middle site. Long Creek is a tributary to the Little Missouri River. (Adapted from Schanke 2013.)
To test the hypothesis that passability of road crossings varied with hydrological conditions, I measured water levels on the treatment streams and estimated the highest water level occurring during fish passage. I used recorded water levels on respective, nearby treatment streams to estimate water level fluctuations on the reference streams. To quantify stream drying on the intermittent streams, Schanke (2013) and I used a hip-chain to document dryness on the ~6-km study reaches of the two intermittent streams.

I installed two water level recorders (Vented WL-16- Global Water Instrumentation, Dallas, TX) to measure and log water levels near the vented-ford on intermittent Bear Creek and the box-culvert on perennial Long Creek. I installed the water level recorders (WLR) along the stream bank in a protective PVC pipe with its sensitive diaphragm below water level to measure hydrostatic pressure relative to the depth of overlying water. The WLR compensated for changes in barometric pressure to calibrate hypostatic pressure. I did not install WLR on the two reference streams, but I did install stream gauges and monitored water height at each visit. I monitored water level on intermittent Bear Creek from July 24, 2012 to April 14, 2013 and on perennial Long Creek from July 25, 2012 to April 13, 2013. I filled in gaps in the water level record prior to installation of the WLR by consulting USGS databases for nearby gauged streams (Appendix B). The exact water levels measured were arbitrary, based on the location of the WLR on each stream, and did not coincide with any specific benchmark.

Passages were based on two confirmed location records (detection events), one upstream and one downstream of the middle site with the RFID station. I detected fish with a variety of methods, and detection events leading to confirmed passages were sometimes separated by seconds or hours, but also spanned days or even months.
Because I could not always ascertain the exact moment of fish passage, I utilized the highest water level occurring between the two detection events. When detection events spanned days or months, I still documented the highest water level recorded during that timeframe, but fish may or may not have passed at that particular time and water level.

I characterized the hydraulic challenges for fish crossing a given reach at a diversity of water levels. In particular, I assessed the treatment reaches for barrier effects caused by high velocity and low water depth. I used an electronic flow meter (Flo-Mate, Model 2000- Marsh-McBirney, Loveland, CO) and wading rod to measure depth and velocity transects at several points on road crossings to identify the most likely route of passage available to a fish. Similar to others’ methods (Belford and Gould 1989; Rajput 2003), I measured water velocity near stream bottom since this represented the lowest velocity path for fish movement. More specifically, I recorded velocity at 3 cm above the bottom, which was the lowest depth measurable by the flow meter. To identify areas with sufficient water depth for the small-bodied target species to swim, I measured the presence (or lack of) a water column equal to or greater than 3 cm. Neither of the road crossings on the treatment streams had measurable outlet drops to cause outlet drop height or outlet pool depth barriers.

The vented-ford on intermittent Bear Creek has two pipes designed to permit water flow underneath the roadway. However, the pipes were filled with gravel and cobble, conveyed only small trickles of water, and presumably precluded fish passage. This diverted most of the water over, rather than through, the road crossing. Thus, fish passage was restricted to movement over the top of the large concrete slab or to adjacent portions of the floodplain and gravel road. The road surface was elevated above the
stream, creating a large pool upstream. At low water levels (below 0.24 m) water did not pass over the road crossing (Figure 4). Above water levels of 0.45 m, the pool upstream of the road crossing flowed over the concrete roadway and down the steep concrete slope on the downstream side of the road prism at velocities ranging from 2.3 to 2.8 m/s (Figure 5). The downstream slope supported a swim zone (with the minimum 3-cm swimming depth) when water levels reached 0.69 m, but water velocities on the slope increased to 2.5-4.5 m/s. The stream also intersects a slab-ford road crossing upstream of the vented-ford but the stream flowed over this slab-ford during low-moderate flows.

Figure 4.—Upstream photograph of the vented-ford road crossing on intermittent Bear Creek during low summer flows (water level = 0.11 m). Cobbles and gravel clogged the upstream side of the two pipes (not visible) preventing natural downstream flow. Thus, the road crossing bisected the stream and created a pool upstream and a dry concrete slab downstream that precluded fish passage during low flows. The downstream antenna of the RFID station was located just behind the camera.
Figure 5.—The vented-ford on intermittent Bear Creek during high flow (water level = 0.73 m). The clogged pipes precluded stream flow through the road crossing and forced water over the top. The water flowing over the road crossing supported a swim zone (with the minimum 3-cm swimming depth) but velocities on the downstream slope of the concrete road prism were in excess of 2.5 m/s. The upstream antenna of the RFID station was located at the top right corner of the photograph behind the white measuring tape suspended over the road crossing.

I monitored depth and velocity on perennial Long Creek near the RFID station at the box-culvert. The road crossing was 4.9 m wide and spanned 6.2 m of longitudinal stream distance (Figure 6). The box-culvert consisted of five 2.4-m-wide boxes installed below stream grade and covered in natural gravel and cobble substrate. The box-culvert always maintained the minimum swimming depth of 3-cm and velocities in the swim zone never exceeded 0.5 m/s (measured at a water level of 0.54 m).

The stream intersected eight other road crossings within the 7-km study reach of the 2011-phase of the project including three vented-fords and two slab-fords upstream. From 2004 to 2010, managers replaced four road crossings, including the box-culvert at the middle site (formerly a slab-ford) and three box-culverts downstream of the middle
site (see Appendix C for a summary of road crossing types, both historical and current). Ryles (2012) used FishXing to classify the three upstream vented-fords as likely fish barriers (due to high culvert velocities), including a vented-ford, located 200 m upstream from the box-culvert. Initially, I also installed a RFID station at this road crossing and monitored its depth and velocity profile, which posed significant hydraulic challenges to passage (Appendix D). The reference, perennial Little Missouri River, which paralleled the treatment stream, did not have any man-made road crossings within the study reach. However, the Little Missouri Falls, a series of stair-step waterfalls, appears to inhibit gene flow for Highland Stonerollers and Longear Sunfish (Schanke 2013).

Figure 6.—Downstream photograph of the box-culvert on perennial Long Creek. The bottom of the box-culvert was below stream grade, facilitating a gravel and cobble bottom. Water pooled on both sides of the road crossing even during summer low flow conditions, maintaining adequate swimming depth. The five boxes included areas of low velocity (0.07 m/s) even during high flow (water level = 0.53 m).

Fish Detection

Researchers assess the impacts of aquatic fragmentation via several methods. A
software package called FishXing (USFS 2012) models the hydraulics of culverts and estimates passability. This modeling approach is inexpensive (Bourne et al. 2011), but tends to underestimate crossing permeability (Cahoon et al. 2007; Burford et al. 2009). The software is best suited to rapid assessments when more extensive study is impossible. More detailed assessments of fish community fragmentation include: analysis of population genetics (Neraas and Spruell 2001; Wofford et al. 2005; Bessert and Ortí 2008), direct observation of individuals (Cahoon et al. 2007), and recapture of marked specimens (Belford and Gould 1989; Morita and Yamamoto 2002).

Radio frequency identification (RFID) tags, also known as PIT tags, are an increasingly popular technology for monitoring fish movement. Smithson and Johnston (1999) RFID-tagged fish to investigate movement patterns in Ouachita Mountain streams. They electrofish-recaptured tagged fish and achieved high recapture rates (18-65%) but focused efforts only within 1.1 km of a single stream and largely within the fishes’ home pool. Recapture methods also include seining, which can be successful (e.g. 11% recapture of marked fish; Bouska and Paukert 2009). However, I sought to detect fish movement in study reaches that did not always encompass pools conducive to seining and during high flows when electrofishing would be unsafe. Researchers have achieved high recapture rates by establishing autonomous RFID stations to detect tagged fish in place of electrofishing recapture. Hewitt et al. (2010) examined re-encounter probabilities of more than 8,000 tagged Lost River suckers in Oregon and found autonomous RFID antennas (deployed year-round) demonstrated superior detection compared to seasonal trammel net sampling. Salmonid researchers have used fixed RFID antennas in diverse applications to autonomously and remotely monitor fish behavior.
(Armstrong et al. 1996), assess populations (Hewitt et al. 2010), track fish movement in streams (Bond et al. 2007; Horton et al. 2007; Connolly et al. 2008), and monitor movement through road crossings (Blank et al. 2005).

Using 12-mm RFID tags, I tagged the small-bodied fish present in Ouachita Mountain streams and sought to utilize the increased efficiency of autonomous 24/7 RFID station technology over more traditional recapture methods. I developed and installed RFID detection stations to monitor fish movement and population fragmentation in four low-order streams with and without road crossings. Additionally, I recaptured tagged individuals via electrofishing to increase the spatial scale of detections, augment the passage database, and assess the efficacy of the RFID stations versus more traditional methods for fish monitoring. The RFID stations had the ability to operate continuously, but electrofishing was capable of recapturing fish throughout the entire study reach and was not limited to the discrete points fitted with the RFID antennas. In March and April 2013, with tagging completed, I coordinated electrofishing recapture efforts in the four streams. The recapture crew ran two electrofishing units simultaneously, either side-by-side or one after another depending on reach width. The crew moved quickly, collecting as many fish as possible, immediately scanned fish for an RFID tag, and returned untagged individuals.

**RFID Detection Stations**

I installed RFID detection stations (Multi-antenna Half-duplex Reader- Oregon RFID) in the middle reach of each stream to detect RFID-tagged fish (Figure 7). In the treatment streams, the middle reach spanned the target road crossings and in reference streams, I positioned the middle reach across a riffle. To detect fish passage (or lack
thereof) across the study reach, each station operated an antenna array composed of two in-stream antennas installed upstream and downstream of the road crossing or reference reach. I placed antennas ~60 m apart (ranging 55-70 m) to accommodate the large road crossings and the variability in antenna placement suitability of particular stream sections. The RFID reader recorded each fish by its unique ID, including which antenna was passed, along with a precise timestamp for the detection event. When the fish was detected by both antennas the timing of detection events indicated the direction of upstream or downstream movement.

![Diagram of RFID detection station](image)

Figure 7.—Schematic of RFID detection station to detect and log fish marked with 12-mm half-duplex RFID tags. A steel box housed the RFID reader, battery bank, and solar charge controller and nearby trees supported the photovoltaic panel(s) which supplied electricity to the system. The antenna array consisted of two antennas on either side of the ~60-m study reach, each with an antenna tuner. The station detected timing and direction of fish movements across the road crossing (on treatment streams) or natural study reach (on reference streams).
Numerous researchers have used RFID technology to monitor fish passage through fishways (Castro-Santos et al. 1996; Baumgartner et al. 2010; Thiem et al. 2011) and ocean-bound salmonid passage at hydroelectric dams of the Pacific Northwest (Hockersmith et al. 2003; Axel et al. 2005). However, few researchers have installed RFID detection stations in situ in small and remote streams like those present in the Ouachita Mountains. I sought to operate a solar-powered two-antenna array without the aid of antenna support structures such as weirs or frames, absent on the study streams. Additionally, I sought to install RFID stations with maximum fish detection efficiency, defined as the ability of the RFID system to detect a tagged fish passing its antenna array. Detection efficiency has two components: 1) path efficiency— the proportion of tags that physically pass through the antenna array (rather than around it) and 2) antenna efficiency— the proportion of tags that are detected (of those tags passing through the antenna; Zydlewski et al. 2006).

RFID systems for fish detection include newer half-duplex (HDX) and more traditional full-duplex (FDX) transmission technologies. Half-duplex tags receive and transmit data from the antenna sequentially while FDX tags receive and transmit simultaneously (Bond et al. 2007). Systems based on HDX equipment are considerably less expensive than the FDX equivalent (Burnett et al. 2013). Small antenna movements are less critical to proper tuning of HDX systems, which allows direct in-stream placement of antennas, which may be submerged in water without a watertight insulating frame. Alternatively, FDX antennas require rigid frames or spacers to separate and stabilize parallel loops of antenna wire in rigid support structures such as fishways, weirs, or small in-stream constructions (Bond et al. 2007). The simpler HDX antenna designs
cause minimal alteration to the stream environment and little hydraulic disruption, vital for establishing reference RFID stations on natural reaches.

Hence, to study the small-bodied fish present in Ouachita Mountain headwater streams, I was limited to HDX systems and the smallest commercially-available tags (12 mm), which have only been available in HDX formats since 2007 (Bond et al. 2007). While HDX systems benefit from more flexible antenna designs, they have weaker antenna efficiency than comparably sized FDX designs. Additionally, the compact 12-mm tag has a small read range, caused by the greater need for electromagnetic energy to energize the small internal antenna coil (Zydlewski et al. 2006). For instance, research on varying sizes of HDX RFID tags resulted in detection of only 56% of fish carrying a 12-mm tag, compared to 91% and 97% of fish carrying 23-mm and 32-mm RFID tags, respectively (Burnett et al. 2013). Aymes and Rives (2009) detected 97% of fish tagged, but used the more easily read 23-mm tags and modified the natural environment to enhance fish detection; channeling fish through a PVC pipe equipped with antennas spanning only 30 cm in diameter.

RFID antennas can be designed as pass-through antennas arranged vertically in the stream or pass-over antennas installed along the stream bottom. RFID antennas operate most efficiently, and have the best read range, when tags are oriented perpendicular to the antenna plane. Pass-over designs and flat-plate designs suffer reduced antenna efficiency, especially during high flows, since tags travel parallel to the antenna plane, (Armstrong et al. 1996; Zydlewski et al. 2006). Connolly et al. (2008) reported a high level of detection efficiency (96-100%) monitoring salmonids in remote unaltered streams. They utilized an innovative hybrid design combining pass-over and
pass-through elements that withstood the assaults of high flows and stream debris while still attaining high detection efficiency during low flow periods. However, this approach had several design limitations and when practical, Connolly et al. (2008) recommended a pass-through antenna capable of spanning the entire stream width to maximize efficiency.

Considering the read range limitations of 12-mm HDX RFID tags, I designed pass-through antennas to maximize detection efficiency throughout the water column. I maximized path efficiency by designing pass-through antennas spanning as much of the bankfull width and height as possible. I constructed antennas with a single loop of wire encompassing a cross-section of stream. The bottom strand of the loop ran along the stream bed and the top strand was suspended above bankfull.

While large pass-through HDX antennas maximized path efficiency, I was forced to shrink the size of the antennas to mitigate unacceptable antenna efficiency (the ability of the antenna to correctly identify a tag within its boundaries) as noted by Zydlewski et al. (2006). However, despite these efforts and experimentation with various materials and settings, the antenna efficiency remained low. Bond et al. (2007) designed a successful RFID detection station to detect movements of juvenile Steelhead Salmon *Oncorhynchus mykiss*, but the single-antenna was only 2.8 m wide and tag detection performance suffered when the antenna was installed more than 60 cm from the reader. However, this study required an antenna array of two large antennas each located more than 30 m from the shared RFID reader.

Designs must be optimized to reach maximum antenna efficiency on a site by site basis and in August and September 2012, I developed a crossover antenna design that dramatically improved antenna efficiency and read range (Figure 8). I divided the
antenna loop into smaller cells in a crossover figure-eight pattern, which benefited read range by canceling electrical noise. I formed the antenna cells by crossing the top and bottom strand of wire in opposing directions through a column made of either 1/2” (1.27 cm) black plastic poly tubing or PVC pipe. I constructed crossover columns every 1.5-3 m. Taller than antennas with more cross-sectional area required more crossovers. The antenna widths ranged between 5 and 10 m to accommodate bankfull width. I constructed antennas of 10 or 12 AWG stranded electrical wire (2.59 mm and 2.05 mm in diameter, respectively). In some cases, I used high-tensile 5-mm static rock climbing rope (BlueWater Ropes, Carrollton, GA) to suspend the top strand above the stream.

Figure 8.—Schematic of the in-stream pass-through RFID antenna design. Each station operated an antenna array composed of two antennas (second antenna not shown in figure) composed of 10-12 gauge stranded electrical wire. Antennas were attached to natural structures and each encompassed the bankfull width of the stream to ensure maximum cross-sectional coverage and path efficiency. The cross-over columns forced the antenna wire into a figure-eight pattern and improved antenna efficiency by dividing the antenna plane into smaller cells.
The RFID reader sent electric current through the antenna array, which transmitted encoded radio waves that interrogated any RFID tags within read range (see Appendix E for further design details). The passively-powered RFID tags contained no batteries, but received electrical energy from the antenna array and re-emitted radio waves via a small internal antenna. Thus, the tags transmitted unique serial numbers to the antenna array and the reader. The reader interrogated tags at 10 scans/s, and divided the scan rate within the antenna array, effectively lowering the rate of each antenna to 5 scans/s. The RFID reader electronically logged up to 10 million tag detection events in nonvolatile memory. Each stored event included a tag serial number, time of detection, and detection duration. I used a wireless Bluetooth-enabled personal digital assistant (MEZ1000 Rugged Digital Assistant- Aceeeca, Christchurch, New Zealand) to upload the data from the reader and transfer the data to Microsoft Excel.

The characteristics of each antenna, such as the wire gauge, shape, size, and number of coils, determined its inductance, a property of its electromagnetic field. I used a dedicated antenna tuner (Oregon RFID) to adjust inductance (to within 20-50 µHenries) so the antennas could effectively transmit and receive radio communication with RFID tags. The tuner consisted of a small waterproof plastic box containing electrical equipment that interfaced between a reader and an antenna. The antenna tuner also served as a junction point between the 18 ga. (1.02 mm) Triax wires connecting it to the reader and the 10 or 12 ga. stranded electrical wires of the antenna. I used an inductance meter (Passive Component LCR Meter 380193- Extech, Nashua, NH) to inform the initial antenna tuning level and verify proper antenna construction. I placed the tuner in an electrical combiner box (available at hardware stores, Main Lug 125 Amp- Murray
Electrical Products, Norcross, Georgia), which I mounted to a tree adjacent to its antenna and padlocked, to provide protection from weather and vandalism and reduce strain on the connected wires.

A solar power system provided electric power to each RFID station enabling it to operate continuously 24 h/d and 365 d/y to maximize fish detection opportunities (Appendix E). Each RFID detection station required 12 volts and ~1 amp of direct current electricity, supplied by the battery bank. A 12-volt, 205-watt photovoltaic solar panel charged four, 6-volt, deep-cycle batteries (216 amp-hour, heavy-duty, deep-cycle battery- Interstate Batteries, Dallas, TX). I wired the batteries in series and parallel to produce 12 volts and store up to 432 amp hours, designed to provide enough electricity storage for four sunless days. Despite attempts to predict power generation and consumption, battery banks often became depleted during initial operation. Thus, I modified the photovoltaic systems at all sites to mitigate low winter solar azimuth, low solar radiation in winter and during inclement weather, and shading from trees. To repel inclement weather and vandalism, I placed the RFID reader, battery bank, and other components in a steel storage chest (dimensions 79 cm L x 46 cm W x 39 cm H; JoBox model 651990- Delta Consolidated Industries Inc., Jonesboro, AR), which I bolted to a concrete apron.

Between August and December 2011 I researched RFID technology, purchased equipment, prepared field sites, and tested equipment in the lab. I installed the RFID detection stations between January and April 2012 and began operating the first functional two-antenna RFID detection stations in February 2012 (Table 2). I continually improved the design of the RFID stations and antennas by experimenting with different
antenna materials and designs, upgrading electrical power supply and collection systems, and modifying RFID equipment and antenna placement.

Table 2.—The four RFID detection stations in Ouachita Mountain streams each operated for more than 350 days in 2012-2013. During this time the stations detected fish but also experienced equipment failure leading to reduced operating time.

<table>
<thead>
<tr>
<th>Stream</th>
<th>RFID station operation</th>
<th>Fish detected</th>
<th>Total operating time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beginning</td>
<td>End</td>
<td>First</td>
</tr>
<tr>
<td>Vented-ford, intermittent</td>
<td>18-Feb-12</td>
<td>14-Apr-13</td>
<td>23-Feb-12</td>
</tr>
<tr>
<td>Reference, intermittent</td>
<td>18-Apr-12</td>
<td>12-Apr-13</td>
<td>18-Apr-12</td>
</tr>
<tr>
<td>Box-culvert, perennial</td>
<td>28-Apr-12</td>
<td>13-Apr-13</td>
<td>30-Apr-12</td>
</tr>
<tr>
<td>Reference, perennial</td>
<td>21-Apr-12</td>
<td>13-Apr-13</td>
<td>21-Apr-12</td>
</tr>
</tbody>
</table>

I sought to maximize the operating time of the RFID detection stations (Figure 9). Damage from high stream flows, technical challenges, and equipment failure periodically contributed to failure of one or both antennas (Appendix E). I successfully operated the RFID stations on the treatment streams for more time than their counterparts on the reference streams, which were more difficult to access and maintain. The RFID stations on the reference, intermittent stream and box-culvert, perennial stream operated only a single antenna for a considerable time period (78 and 67 days, respectively) as I dealt with noise and electrical issues affecting the RFID readers.
Figure 9.—The RFID detection stations mostly operated two antennas (dark bars) but sometimes operated only one antenna at a time (light bars), or failed to operate entirely.

Poor antenna design, overly large antenna size, antenna damage, electrical noise interference, and excessive distance from the RFID reader deteriorated antenna efficiency and increased the probability of missed detections. To accurately measure antenna efficiency, I experimented with tagged drones such as oranges and neutrally buoyant bottles, as suggested by Zydlewski et al. (2006), but these suffered from improper tag orientation. I also tested rectangular wooden blocks, which maintained proper tag orientation, but poorly resembled passing fish both in shallow riffles (where they bumped the bottom) and low velocity pools (where they failed to pass through the antenna plane). Hence, I tested antenna efficiency by manually manipulating an RFID tag (taped to the end of a stick) perpendicularly through the antenna plane at ~1 m/s.

When an antenna was working well and demonstrating the best possible efficiency, it detected all tags within the boundaries of the pass-through antenna wires, up to 10 cm away from the wire within the antenna plane, and up to 5 cm upstream or downstream of the antenna plane. I classified antenna efficiency into four categories:
- Excellent- more than 95% detection within pass-through area of antenna plane. Usually accompanied by detection outside boundaries of antenna wire and outside antenna plane.
- Good- more than 75% detection within antenna. Contained detection holes within antenna and had mediocre detection outside antenna wire or antenna plane.
- Fair- more than 25% detection within antenna. Contained many sizable detection holes within antenna and had minimal detection outside antenna wire and antenna plane.
- Poor- less than 25% detection within antenna. In extreme cases, antenna only detected tags within 2 cm of antenna wire.

The antennas required frequent maintenance to sustain proper tuning and acceptable efficiency. High water events, such as occurred on January 9, 2013, dismantled the antennas by snapping wires and suspension ropes, ripping hardware out of trees, and tearing through plastic polytube and PVC pipe. High water events caused by smaller storms decreased antenna efficiency by dislodging debris, principally leaves and sticks, that collected on antenna wires and pulled the antennas out of shape (and hence out of tune). Low efficiency and downtime (when an antenna was off) led to missed detections. The RFID stations on the two treatment streams enjoyed more than 190 days when both antennas operated at good or excellent efficiency (Figure 10). The RFID stations on the two reference streams experienced more than 149 days when both antennas were off or operated with poor efficiency.
Figure 10.—The efficiency, or tag detection ability of the antenna, fluctuated for the upstream antennas (dark bars) and downstream antennas (light bars) at each RFID detection station. Figures represent the number of days the RFID stations operated antennas at various classes of efficiency.

**Fish Collection and Marking**

In the initial phase of fieldwork in 2011, I established three 400-m reaches on each stream where I backpack-electrofished and implanted RFID tags. The middle reaches (MR) contained the road crossings (on the treatment streams) and the upstream (UR) and downstream (DR) reaches were located ~3-4.5 km from the MR (see Appendix
F for location details). The study reaches avoided order-changing confluences but contained additional road crossings. I established similar length study reaches on the two reference streams and subdivided the 400-m reaches into eight 50-m fish sampling sections to facilitate detection of small-scale movement. Section length varied ±10 m to accommodate natural breaks in stream habitats, such as riffles, and to avoid splitting pools between sections. I used a hip-chain to establish each 50-m section, recorded GPS coordinates, and photographed each section.

I focused RFID tag deployment closer to the RFID stations in 2012 (Appendix F). Specifically, I tagged fish exclusively in the middle reach (MR) and did not tag any additional fish in the downstream or upstream reaches. However, I extended the size of the MR 800 m in each direction for a total of 2,000 m, subdivided into forty 50-m fish sampling sections. The center points of the MR deviated up to 100 m from the 2011 locations to accommodate placement of the RFID detection stations. The more extensive sampling regime of the 2011 pilot phase allowed detection of fish movements as long as 4.5 km, but was not designed to efficiently detect shorter movements. Warmwater stream fish rarely move more than 1,000 m and typically move less than 300 m (Smithson and Johnston 1999; Skalski and Gilliam 2000; Albanese et al. 2003; Albanese et al. 2004; Hafs et al. 2010). The 2012 sampling regime concentrated tag intensity around the RFID stations to detect more probable (less than 1,000 m) fish movements rather than capturing long-distance outliers. The 2,000-m study reach also reduced the need for distance-weighted correction of bias towards short distance movements found in some studies that sample short distances more frequently than long-distances (Albanese et al. 2003).

In July-December 2011, I captured and RFID-tagged ~700 fish in the four
I tagged ~800 fish per stream from May 2012 to February 2013 within the 2-km reaches centered on the RFID detection stations (Figure 11). I collected fish via single pass, backpack electrofishing (Smith-Root LR 20- Smith-Root, Vancouver, Washington) and dip-nets, beginning in the farthest downstream section and proceeding upstream in 50-m sections. I electrofished without block nets in continuous sweeps and temporarily stored captured fish in screen-bottom buckets or mesh laundry baskets within respective 50-m sections to await tagging and documentation. On subsequent visits, I electrofished multiple passes to capture additional fish, where needed, to meet the tagging quota.

Figure 11.—Fish tagging centered on the RFID detection station of each stream during the main phase of fish tagging in 2012-2013. Tagging ranged from a site 1,000 m downstream (D1000) to a site 1,000 m upstream (U1000) of the station. I aimed to tag 200 fish within each 500-m segment of the study reach.

I used a plastic syringe-style implanter (MK7 Implanter- Biomark, Boise, Idaho) to inject a 12.0 mm x 2.15 mm HDX RFID tag (Oregon RFID, Portland, Oregon) in all fish 85 mm total length (TL) or longer on. I documented species and used a PVC measuring board to record length. I injected RFID tags at a shallow angle just below the skin on the left side of the body, below the dorsal fin and above the lateral line. Prior to injection, I sterilized the syringe needles and RFID tags in ethanol. I injected the tag 5 mm or deeper into the incision to reduce chances of tag loss and clipped the caudal fin of all fish receiving a RFID tag to assist in identification of tagged fish during electrofishing recapture. To indicate tagging location, I marked fish that were tagged in upstream sections by removing the upper lobe of their caudal fin and vice versa for those tagged in
downstream sections. Each RFID tag had a unique serial number to individually identify each fish. I used a handheld RFID reader (APR 350- Agrident, Barsinghausen, Germany) to record serial numbers during tagging. During repeat electrofishing visits, I used the handheld RFID reader to scan fish and identify previously tagged fish. Additionally, I tested the ability of the handheld RFID reader and its handheld antenna probe to detect free-swimming fish but found it to be ineffective (Appendix G).

I focused tagging efforts on commonly encountered species to maximize recapture opportunities and movement sample sizes. Target species, in alphabetical order, included: Creek Chub, Creek Chubsucker *Erimyzon oblongus*, Green Sunfish, Highland Stoneroller, Longear Sunfish, Northern Hogsucker *Hypentelium nigricans*, Smallmouth Bass, Striped Shiner *Luxilus chrysocephalus*, and Yellow Bullhead *Ameiurus natalis*.

During the pilot phase of fish tagging in 2011, I operated more conservatively and only tagged fish 100 mm TL or longer. Individuals of several freshwater fish species less than 85 mm TL have successfully survived and retained 12-mm RFID tags (Baras et al. 2000; Zydlewski et al. 2006; Acolas et al. 2007; Keeler et al. 2007). I studied potential mortality near the vented-ford on intermittent Bear Creek to assess short-term tag retention rates and handling stress associated with capture and tag injection (Appendix H). I concluded that it was appropriate to tag smaller fish, and in the interest of efficiency, decreased the minimum length limit to 85 mm for the main phase of fish tagging in 2012-2013.

*Data Analyses*

I used multiple data sources, including the RFID detection stations and locations of tagging, incidental recapture, and intentional recapture to detect fish passage. The
streams contained slightly different fish communities; thus, to minimize bias, I frequently restricted analyses to only a subset of species. When analyzing all four streams, I restricted tests to the three species commonly tagged across all four streams: Creek Chub, Highland Stoneroller, and Longear Sunfish. Alternatively, I tested the pairs of intermittent and perennial streams separately, permitting comparisons of groups of five species (rather than just three) common to the intermittent and perennial streams, respectively. In addition to the three species common to all streams, the intermittent stream analyses included Creek Chubsuckers and Green Sunfish and the perennial stream analyses included Striped Shiners and Yellow Bullhead. Because the number of fish tagged varied by stream and species, rather than analyzing passages, I generated and tested passage rates normalized to the number of fish tagged (displayed as a percentage value). Additionally, I tested each of the three common species individually, for differences in passage rates to compensate for unequal tagging rates among the four streams. I only tagged considerable samples of Northern Hogsucker and Smallmouth Bass on one stream, the box-culvert, perennial, and hence excluded these species from many analyses.

I used ANOVA along with the Tukey-Kramer multiple comparisons tests to analyze continuous variables such as length and movement distances. To compare passage rates and proportions among streams, water levels, and species I ran chi-squared tests. To compare passage rates among species and either hydrologic regime (intermittent versus perennial) or crossing type (treatment versus reference) I used loglinear modeling. I reported means with one standard error (mean ± SE) and reported statistical significance at $\alpha = 0.05$. 
Results

Tagging

I tagged 3,795 fish comprising nine species in the four streams between July 21, 2011 and February 3, 2013 (Table 3). During the pilot phase of fish tagging in July-December 2011, I tagged 719 fish in the downstream, middle, and upstream reaches within the 6 to 9-km study reach of each stream. I tagged an additional 3,076 fish between May 2012 and February 2013, focusing only on the middle tagging reaches of each stream, which were extended to 2,000 m. The most and least abundant tagged fishes were the Creek Chub and the Northern Hogsucker, making up 37.8% of the total (1,439 individuals) and 1.4% (54 individuals) respectively. The mean lengths of tagged fish ranged from 106 to 118 mm among the four streams and from 101 to 202 mm among the nine species.

Table 3.—I electrofished and implanted RFID tags in nine fish species in four Ouachita Mountain streams in 2011-2013. Tags were implanted both upstream and downstream of RFID detection stations located on each stream.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Location relative to RFID station</th>
<th>Upstream</th>
<th>Downstream</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vented-ford, intermittent</td>
<td></td>
<td>349</td>
<td>504</td>
<td>853</td>
</tr>
<tr>
<td>Reference, intermittent</td>
<td></td>
<td>433</td>
<td>490</td>
<td>923</td>
</tr>
<tr>
<td>Box-culvert, perennial</td>
<td></td>
<td>574</td>
<td>455</td>
<td>1029</td>
</tr>
<tr>
<td>Reference, perennial</td>
<td></td>
<td>488</td>
<td>502</td>
<td>990</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1,844</td>
<td>1,951</td>
<td>3,795</td>
</tr>
</tbody>
</table>

Fish communities differed between the pairs of intermittent and perennial streams (Figure 12). The intermittent streams had abundant Creek Chub, Creek Chubsucker, Green Sunfish, Highland Stoneroller, and Longear Sunfish. The perennial streams had abundant Creek Chub, Highland Stoneroller, Longear Sunfish, Striped Shiner, and Yellow Bullhead. Among the three species common to all streams, I tagged 2,630
individuals and tagged 592-727 in each stream (mean, 657.5; SE, 29.8).

Figure 12.—I captured and tagged nine species of fish in four Ouachita Mountain streams. Bar height indicates the total number of fish tagged. The number above the bar is the proportion that species represented of the total. The patterns within the bars indicate the stream in which the fish were tagged.

I electrofished more passes on the intermittent streams as taggable fish (of suitable length and species) were more scarce (Figure 13). This led to a lower catch per unit effort, i.e. number of fish tags deployed per electrofishing pass. During the electrofishing efforts in the summer and fall seasons, the perennial streams supported more abundant communities of taggable fish and I met the tagging quotas after only two passes of electrofishing.
Figure 13.—The average number of fish tagged per electrofishing pass in each 50-m segment on the four streams. Numbers above bars indicate average numbers of electrofishing passes needed to reach tagging quotas.

Movement and Passage

The nine species passed study reaches 352 times and many individuals passed more than once (Figure 14). Due to the inherent bias caused by the inconsistent fish communities among streams, I did not test these data statistically but present them for illustrative purposes.
Figure 14.—Total passages detected across the study reaches (entire bar) and the number of RFID-tagged fish passing those reaches (light portion of bar), by species. Many individuals passed study reaches more than once.

Of the three species common to all streams, 130 individuals conducted 264 passages across the study reaches. The proportion of passages per fish tagged varied significantly from 2% to 21% among the four streams ($\chi^2 = 112$, df = 3, $P < 0.01$; Figure 15). The low passage rates across the vented-ford, intermittent reach and the high passage rates across the reference, perennial reach contributed the most to the significant difference ($\chi^2 = 40.4$ and 68.3, respectively). When I analyzed the passage rates among the four streams for each species individually, it became apparent that Creek Chub were the main driver of differences while Highland Stonerollers and Longear Sunfish passed at similar rates among the four streams (Table 4).
Figure 15.—The proportion of passages to RFID-tagged fish (three species common to all streams), by stream, across the study reaches monitored by RFID stations.

Table 4.—The proportion of passages to RFID-tagged fish, tested separately for each of the three species common to all streams. Bold text indicates statistical significance.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Creek Chub</th>
<th>Highland Stoneroller</th>
<th>Longear Sunfish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vented-ford, intermittent</td>
<td>3%</td>
<td>0%</td>
<td>3%</td>
</tr>
<tr>
<td>Reference, intermittent</td>
<td>8%</td>
<td>11%</td>
<td>3%</td>
</tr>
<tr>
<td>Box-culvert, perennial</td>
<td>5%</td>
<td>12%</td>
<td>8%</td>
</tr>
<tr>
<td>Reference, perennial</td>
<td>31%</td>
<td>15%</td>
<td>7%</td>
</tr>
<tr>
<td>Mean</td>
<td>11%</td>
<td>11%</td>
<td>7%</td>
</tr>
<tr>
<td>SE</td>
<td>7%</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>143</td>
<td>6.4</td>
<td>3.5</td>
</tr>
<tr>
<td>$P$</td>
<td>&lt;0.01</td>
<td>0.09</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Mean passage rates for the five species common to intermittent streams were 2% (SE, 1%) across the vented-ford and 8% (SE, 3%) across the reference reach and were significantly different ($\chi^2 = 28.3$, df = 1, $P < 0.01$; Figure 16A). Mean passage rates for the five species common to perennial streams were 8% (SE, 2%) across the box-culvert and 17% (SE, 5%) across the reference reach, but were statistically similar ($\chi^2 = 25.2$, df = 1, $P < 0.01$; Figure 16B).
Figure 16.—The proportion of passages to RFID-tagged fish, by stream, across the study reaches monitored by RFID stations. The figures represent passage rates among (A) the five species common to the two intermittent streams and (B) the five species common to the two perennial streams.

The three species common to all streams passed at an average of 10% of tagged individuals (SE, 2%) and differences among species were not significant ($\chi^2 = 4.24$, df = 2, $P = 0.12$; Figure 17A). Passage rates for the five species common to the intermittent streams ranged from 3-9% for tagged individuals (mean, 5%; SE, 1%), but differences among species were not significant ($\chi^2 = 4.54$, df = 4, $P = 0.34$; Figure 17B). I tested passage rates across the vented-ford separately to test the hypothesis that the road crossing hydraulics precluded passage by weaker swimmers. Passage rates among the five species varied from 0 to 3% (mean, 1%; SE, 0.6%) and Creek Chubsuckers and Highland Stonerollers did not pass the vented-ford. However, sample sizes were low and differences were not statistically significant among species ($\chi^2 = 2.86$, df = 4, $P = 0.58$).

For the five species common to the perennial streams, 6-25% of the tagged fish passed
(mean, 13%; SE, 3%), but again intra-species differences were insignificant ($\chi^2 = 6.83$, df = 4, $P = 0.15$; Figure 17C).

Figure 17.—The proportion of passages to RFID-tagged fish tagged, by species, across study reaches monitored by RFID stations in the four streams. The figures represent passage rates for (A) the three species common to all four streams, (B) the five species common to the intermittent streams, and (C) the five species common to the perennial streams.
Based on loglinear models, I identified significant three-way interactions for two tests: 1) among hydrologic regime (intermittent versus perennial), species, and passage and 2) among crossing type (treatment versus reference), species, and passage ($\chi^2 = 16.2$, df = 2, $P < 0.01$ and $\chi^2 = 41.4$, df = 2, $P < 0.01$, respectively). Among two-way interactions, hydrology interacted with passage, and passage rates were significantly higher on perennial streams than intermittent streams (means of 15% versus 5%, respectively; $\chi^2 = 89.1$, df = 1, $P < 0.01$). However, this varied among species, as evidenced by the three-way interaction. Creek Chub passed perennial reaches at rates six times higher than intermittent reaches and Longear Sunfish at rates 3.5 times higher, while Highland Stonerollers barely favored perennial streams and passed at rates 1.6 times higher. Crossing type also interacted with passage, and passage rates were significantly higher on reference reaches than treatment reaches (means of 15% versus 5%, respectively; $\chi^2 = 51.5$, df = 1, $P < 0.01$). However, there were exceptions to these patterns, as evidenced by the significant three-way interactions. Unlike the other two species, Longear Sunfish actually passed at higher rates across the treatment reaches.

Based on a three-way ANOVA, the length of tagged fish among the three species common to all streams, varied significantly among both streams and species ($F = 20.1$, df = 3, $P < 0.01$ and $F = 57.9$, df = 2, $P < 0.01$, respectively). However, the lengths of fish passing and not passing was similar indicating that length (on its own) was not a determining factor of passage (mean ± SE: 117 ± 30 versus 110 ± 30; with $F = 0.04$, df = 1, $P = 0.84$). However, when modeling for effects on fish length, all two-way interactions between stream, species, and passage were significant. Passing Creek Chub were longer, on average, than Creek Chub that did not pass (126 ± 2 versus 112 ± 0.5). Differences
between passing and non-passing Highland Stoneroller and Longear Sunfish were less than 3 mm. Fish passing the reference reach on perennial Little Missouri River were longer, on average, than non-passing fish (127 ± 2 versus 113 ± 0.7). Differences between passing and non-passing fish on the other three streams were less than 4 mm.

The RFID stations did not always operate both antennas continuously. To account for possible missed fish detections and underestimation of fish passage among streams, I scaled fish passage per year based on RFID operating time (Figure 18). The passages/y varied from 17 to 253 among streams and differences were highly significant ($\chi^2 = 163$, df = 3, $P < 0.01$). Fish passed upstream and downstream at rates that were not statistically different (based on binomial proportions tests for each stream).

![Figure 18](image)

Figure 18.—All of the RFID detection stations experienced periods of downtime, leading to missed detections. Here, the number of upstream passages (dark bars) and downstream passages (light bars) by the three species common to all streams have been scaled to the time that each RFID station successfully operated two antennas. Additionally, the passages have been projected for a full year of RFID station operation.

I detected very few passages by any of the 226 fish tagged in the middle reaches in 2011. I did not detect any passages by the 439 fish originating in the upper and lower
reaches which were located 3-4.5 km from the four RFID detection stations. However, fish (tagged in 2012-2013) moved as far as 950 m from their original capture locations to pass study reaches. Among the three species common to all streams, the mean travel distance was 250 m (SE, 21; median, 150) and the majority of passing fish originated near the middle site (Figure 19). It appeared that passing fish traveled farther on the reference streams, but mean travel distances among the four streams were not statistically different \((F = 0.11, \text{df} = 3, P = 0.95)\). I examined streams and species simultaneously, but their two-way interaction did not significantly alter the comparison of travel distances \((F = 0.36, \text{df} = 6, P = 0.90)\). Likewise, travel distances were not significantly different between the treatment and reference stream when I analyzed the two intermittent streams (and their five common species) or the two perennial streams (and their five common species) separately.

Figure 19.—The average distance that RFID-tagged fish traveled from their original tagging location to pass study reaches on the four streams. Analysis only includes the three species common to all streams.

Among all nine species, Creek Chub and Highland Stoneroller moved the greatest distances to pass study reaches, 950 m; whereas, only one Northern Hogsucker
successfully completed a passage and moved 50 m (Figure 20A). Among the three species common to all streams, mean travel distances of 130 m ± 52 (mean ± SE) appeared shorter for the Longear Sunfish than for Creek Chub or Highland Stonerollers (280 m ± 27 and 260 m ± 40, respectively; Figure 20B). However, when tested in a two-way ANOVA alongside stream, the differences were statistically similar ($F = 2.4$, df = 2, $P = 0.09$).
Figure 20.—In 2012, fish were captured and tagged in a sampling zone 1,000 m upstream and downstream of the MIDDLE site, with the RFID detection station. Fish that successfully passed the study reaches are shown here, grouped by their original tagging location e.g. U700 (700 m upstream) of the RFID station. Passing fish are displayed for (A) all nine species and (B) the three species common to all streams.
Among the three species common to all streams, relatively few fish passed across the vented-ford on intermittent Bear Creek and no fish traveled more than 500 m to do so (Figure 21A). In contrast, fish moved 950 m to pass the reference reach on intermittent Crystal Prong (Figure 21B). On perennial Long Creek, fish traveled from as far as 600 m downstream to cross the box-culvert and five fish traveled more than 200 m to pass (Figure 21C). However, no fish moved from more than 200 m upstream to pass the RFID station, which would have required downstream passage through a vented-ford. Furthermore, many fish passed downstream through the RFID station from the 200-m stretch abutting the downstream outlet of the nearby vented-ford. The patterns of movement across the reference reach on perennial Little Missouri River were similar to those of the other reference stream and fish passed from as far as 800 m (Figure 21D).
Figure 21.—In 2012 fish were captured and tagged in a fish sampling zone 1,000 m upstream and downstream of the MIDDLE site, with the RFID detection station. Fish that successfully passed the study reaches are shown here grouped by their original tagging location e.g. U700 (700 m upstream) of the RFID station. The data include passages by the three species common to all streams.
Hydrology and Passage

Water levels near the vented-ford on intermittent Bear Creek fluctuated from a low of 0.07 m on August 13, 2012 to a high of 1.35 m on January 12, 2013 (Figure 22A). Water levels fluctuated most commonly between 0.4-0.5 m (mean, 0.47 m; SE, 0.002; Figure 23A). The first three weeks of the hydrograph show the low-flow conditions characteristic of the intermittent stream in summer. Summer drying caused a decrease in pool depth and a complete lack of surface water on 62% of Bear Creek and 61% of Crystal Prong in June 2012 (Schanke 2013) when water levels were generally less than 0.3 m. Discharge increased beginning in mid-August to 0.4-0.5 m, more characteristic of baseflow outside of the summer dry season. Water levels near the box-culvert on perennial Long Creek fluctuated from a low of 0.08 m on July 29, 2012 to a high of 1.01 m on January 12, 2013 (Figure 22B). Water levels fluctuated most commonly between 0.1-0.2 m (mean, 0.18 m; SE, 0.001; Figure 23B). Perennial Long Creek did not demonstrate a measurable seasonal change in baseflow.
Figure 22.—Hydrographs generated by the water level recorders (WLR) installed near (A) the vented-ford on intermittent Bear Creek (located in northeastern Ouachita Mountains) and (B) the box-culvert on perennial Long Creek (southern Ouachita Mountains). The WLR continuously monitored the treatment streams July 2012-April 2013. Note: the actual water levels are based on an arbitrary scale and differ between the intermittent and perennial streams.
Figure 23.—The water level recorders installed on the treatment streams recorded the frequency of a given water level near (A) the vented-ford on intermittent Bear Creek (located in eastern Ouachita Mountains) and (B) the box-culvert on perennial Long Creek (southern Ouachita Mountains). The WLR continuously monitored the treatment streams July 2012-April 2013. Note: the actual water levels are based on an arbitrary scale and differ between intermittent and perennial streams.
Fish passing the vented-ford on intermittent Bear Creek passed most often when maximum water levels were 1.3-1.4 m, far from the most frequent water level (Figure 24A). Fish conducted 9 (of 19 total) passages across the vented-ford when water levels were above 1.0 m. Alternatively, on the nearby reference, Crystal Prong, fish passed most frequently when maximum water levels were 0.4-0.6 m, which coincided with the most frequent water levels at the Bear Creek WLR (Figure 24B). The two perennial streams appeared similar and the majority of fish passed when maximum water levels were 0.1-0.3 m, coinciding with the most frequent water levels at the Long Creek WLR (Figure 24C and D). Surprisingly, two Creek Chub, 86 and 88 mm in length, seemingly passed upstream through the vented-ford on intermittent Bear Creek when water levels were less than 0.2 m and water did not flow over the road crossing. Passage under these conditions seemed implausible and I cannot explain this occurrence.
Figure 24.—Fish passages for the three species common to all streams, categorized by the maximum water level occurring during upstream passage (dark bars) or downstream passage (light bars). Maximum water level was the highest measured in between the two detection events used to confirm fish passage across the study reach.
The five species common to the intermittent streams passed study reaches when water levels were both low and high (Table 5). I measured 0.7 m as the approximate water level at which the vented-ford at intermittent Bear Creek presented sufficient swimming depth for passage; below 0.7 m the depth was insufficient. Therefore, I assigned passages conducted when water levels were less than 0.7 m to the “low” category and greater than 0.7 m to the “high” category. The number of passages during low and high water levels were significantly different between the two intermittent streams ($\chi^2 = 9.20$, df =1, $P = 0.002$) and fish passed significantly more often across the vented-ford when water levels were high; whereas, fish passed the reference reach at higher rates when water levels were low. Creek Chub conducted the majority of passages across the vented-ford and they were the only species to pass during low water levels. Conversely, at low water levels on the reference reach, Green Sunfish and Highland Stoneroller passed more frequently than Creek Chub.
Table 5.—The number of fish passages by the five species common to the intermittent streams through a road crossing and a reference reach. Fish passed when water levels (logged by the water level recorder) were low (less than 0.7 m) and high (more than 0.7 m). The vented-ford did not permit a hydraulically-favorable “swim zone” at low water levels.

<table>
<thead>
<tr>
<th>Species</th>
<th>Low water levels</th>
<th>High water levels</th>
<th>Percent of low water passages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vented-ford (Bear Creek)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Creek Chub</td>
<td>9</td>
<td>8</td>
<td>53%</td>
</tr>
<tr>
<td>Creek Chubsucker</td>
<td>0</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Green Sunfish</td>
<td>0</td>
<td>1</td>
<td>0% a</td>
</tr>
<tr>
<td>Highland Stoneroller</td>
<td>0</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Longear Sunfish</td>
<td>0</td>
<td>1</td>
<td>0% a</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>9</td>
<td>10</td>
<td>47%</td>
</tr>
<tr>
<td><strong>Reference (Crystal Prong)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Creek Chub</td>
<td>17</td>
<td>7</td>
<td>71%</td>
</tr>
<tr>
<td>Creek Chubsucker</td>
<td>2</td>
<td>5</td>
<td>29%</td>
</tr>
<tr>
<td>Green Sunfish</td>
<td>18</td>
<td>1</td>
<td>95%</td>
</tr>
<tr>
<td>Highland Stoneroller</td>
<td>21</td>
<td>1</td>
<td>95%</td>
</tr>
<tr>
<td>Longear Sunfish</td>
<td>3</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>61</td>
<td>14</td>
<td>81%</td>
</tr>
</tbody>
</table>

* The percentages of low water passages for Green Sunfish and Longear Sunfish are zero due to the lack of passages at low water levels. These species did pass during high water levels. The Creek Chubsucker’s percentage is zero due to a complete lack of detected passages at any water level.

The five species common to the perennial streams passed the two perennial streams at low and high water levels in similar proportions ($\chi^2 = 0.02$, df =1, $P = 0.88$; Table 6). The perennial streams did not have a clear hydraulic cut-off for low and high water levels since both study reaches supported a swim zone at all measured conditions. Therefore, I arbitrarily divided water levels at 0.6 m, or approximately half of maximum level recorded. This mimicked the division on the intermittent streams and separated common baseflow levels from rare high water events.
Table 6.—The number of fish passages by the five species common to the perennial streams through a road crossing and a reference reach. Fish passed when water levels (logged by the water level recorder) were low (less than 0.6 m) and high (more than 0.6 m). Both streams supported a hydraulically-favorable swim zone at all water levels measured.

<table>
<thead>
<tr>
<th>Species</th>
<th>Low water levels</th>
<th>High water levels</th>
<th>Percent of low water passages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Box-culvert (Long Creek)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Creek Chub</td>
<td>4</td>
<td>2</td>
<td>67%</td>
</tr>
<tr>
<td>Highland Stoneroller</td>
<td>21</td>
<td>3</td>
<td>88%</td>
</tr>
<tr>
<td>Longear Sunfish</td>
<td>19</td>
<td>4</td>
<td>83%</td>
</tr>
<tr>
<td>Striped Shiner</td>
<td>15</td>
<td>3</td>
<td>83%</td>
</tr>
<tr>
<td>Yellow Bullhead</td>
<td>3</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>62</td>
<td>12</td>
<td>84%</td>
</tr>
</tbody>
</table>

| **Reference (Little Missouri River)** |                  |                   |                               |
| Creek Chub               | 99               | 10                | 91%                           |
| Highland Stoneroller     | 23               | 1                 | 96%                           |
| Longear Sunfish          | 8                | 3                 | 73%                           |
| Striped Shiner           | 6                | 0                 | 100%                          |
| Yellow Bullhead          | 9                | 9                 | 50%                           |
| **Total**                | 145              | 23                | 86%                           |

**RFID Detection Efficiency**

The RFID stations, exclusive of electrofishing location data, recorded more than 300,000 individual detection events, defined as instances when the reader interrogated and logged an RFID tag (Table 7). All nine species, 427 individuals, reached the antennas and were detected by the RFID stations, but may or may not have passed the study reach. Electrofishing recapture and the RFID stations combined to detect similar numbers of fish on the four streams. However, the RFID station on the reference reach of perennial Little Missouri River detected more fish than the other stations despite having the fewest operating days. The proportion of fish detected to fish tagged varied from 8-15% among streams and the RFID stations encountered and identified an average of 11% (SE, 14%) of the fish tagged (Figure 25). The RFID stations detected a mean of 47.4 (SE, 15.2)
individuals among the nine species and the proportion of detections to fish tagged, ranged from 4% for Northern Hogsucker to 14% for Smallmouth Bass (Figure 26).
Table 7.—The RFID station and electrofishing recapture contributed to detections of 882 tagged fish (all nine species). The RFID stations detected individuals multiple times leading to thousands of time-stamped detection events.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Detections</th>
<th>Fish detected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RFID stations (thousands)</td>
<td>Recapture</td>
</tr>
<tr>
<td>Vented-ford, intermittent</td>
<td>57</td>
<td>206</td>
</tr>
<tr>
<td>Reference, intermittent</td>
<td>58</td>
<td>148</td>
</tr>
<tr>
<td>Box-culvert, perennial</td>
<td>44</td>
<td>204</td>
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<tr>
<td>Reference, perennial</td>
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<td>134</td>
</tr>
<tr>
<td>Total</td>
<td>322</td>
<td>692</td>
</tr>
<tr>
<td>Mean</td>
<td>81</td>
<td>173</td>
</tr>
<tr>
<td>SE</td>
<td>28</td>
<td>18</td>
</tr>
</tbody>
</table>
Figure 25.—The RFID stations (exclusive of electrofishing location data) on the four streams detected 427 tagged fish (all nine species). Bar height indicates the proportion of fish detected to fish tagged, by stream. Numbers above bars indicate the number of individuals detected. These fish contacted at least one antenna, but may or may not have passed the study reach.

Figure 26.—The RFID stations (exclusive of electrofishing location data) detected all nine species of fish. Bar height indicates the proportion of fish detected to fish tagged, by species. Numbers above bars indicate the number of individuals detected. These fish contacted at least one antenna, but may or may not have passed the study reach.
I concluded that a fish had passed when I could confirm its location at least once on both the upstream and downstream side of the study reach. I used all available data sources to infer fish locations including detections by the RFID station and locations of tagging, incidental recapture, and intentional recapture. Passages (composed of two detection records) were derived from five possible combinations of detection events: 1) the RFID station detected a fish at both antennas; 2) original tagging location and one antenna; 3) incidental recapture location and one antenna; 4) intentional recapture and one antenna; or 5) electrofishing-only without the help of the RFID station. The RFID station, exclusively or augmented by the original tagging location, identified the majority of confirmed fish passages on all four streams (Figure 27) by all nine species (Figure 28). By contrast, the intentional recapture efforts of March and April 2013, contributed to only seven confirmed passages and electrofishing-only detections led to no more than five confirmed passages on any given stream.
Figure 27.—The percentage of passages (all nine species) contributed by each detection type, organized by stream. I used multiple sources of location data to infer fish passages including: RFID detection station data (utilizing both antennas), tagging location and one antenna, incidental recapture location and one antenna, intentional recapture location and one antenna, and electrofishing-only (including both tagging and recapture locations).
Figure 28.—The percentage of passages (all nine species) contributed by each detection type, organized by species. I used multiple sources of location data to infer fish passages including: RFID detection station data (utilizing both antennas), tagging location and one antenna, incidental recapture location and one antenna, intentional recapture location and one antenna, and electrofishing-only (including both tagging and recapture locations).

While the RFID stations detected more passages than any other method, exclusive use of RFID detection station data (two antennas) would have missed approximately one third (mean, 31%; SE, 6%) of total passages on the four streams (Figure 29). These missed passages were detected by electrofishing location data after fish had passed RFID antennas undetected due to station downtime and poor detection efficiency.
Figure 29.—Exclusive use of RFID detection stations would have resulted in missed passages that were alternatively confirmed by electrofishing location data. Bars represent the percentage of undetected passages (RFID station only) to total passages recorded.

The intentional recapture efforts in March and April 2013 yielded 1,128 fish (mean, 282; SE, 126) in the four streams, 59 of which carried RFID tags (mean, 15; SE, 4.0; Figure 30). The recapture proportion varied from 1-13% among the four streams (mean, 8%; SE, 3%) and contributed location records leading to seven confirmed passage events.

Figure 30.—The 2013 electrofishing recapture efforts collected tagged fish and generated location records to supplement detected passages. Captured fish consisted of untagged fish (light bars) and tagged fish (dark bars) yielding recapture proportions from 1-13% (numbers above bars).
Discussion

Fish Passage

Fish of the three species common to all streams passed reference reaches at higher rates than road crossings, even when accounting for differences in numbers of fish tagged and RFID station operating time, consistent with other non-salmonid road crossing studies (Benton et al. 2008; Bouska and Paukert 2009). Passage rates were lower at the vented-ford on intermittent Bear Creek than the box-culvert or reference reaches, similar to the conclusions of Warren and Pardew (1998) and Standage and Gagen (2007). However, the pipes in this vented-ford were clogged, decreasing its permeability beyond that of a functioning vented-ford. The impassability of the road crossing was exacerbated by stream intermittency and discontinuous surface flow that frequently lacked sufficient discharge to flow over the crossing. When water did flow over the crossing at moderate water levels, the steep downstream slope of the structure produced a sheet of water with high velocity and insufficient depth for upstream movement of most fish species. Thus, it seems that fish opportunistically crossed this barrier during hydrologically favorable times, when water rose near or above bankfull and flowed over and around the road crossing creating lower velocity swim zones, consistent with the conclusions of Helfrich et al. (1999) and Norman et al. (2009).

Fish passed the box-culvert on perennial Long Creek at lower rates than its paired reference, Little Missouri River. However, passage rates were higher than rates for either of the two intermittent streams, including the reference, contributing to a shared conclusion that box-culverts are generally more conducive to passage than other crossing types (Standage and Gagen 2007; Norman et al. 2009). At the full range of water levels,
the box-culvert sustained hydraulic conditions favorable for fish passage, which was corroborated by FishXing passability screening software (Ryles 2012). The road crossing had a natural substrate bottom, sufficient swimming depth, low velocities, and lacked major cross-section constrictions or jumps.

Fish traveling on the treatment streams encountered not only the road crossing of interest, with the RFID station, but additional road crossings, which may have compounded the difficulties of passage. For instance, quantifying long-distance passability on perennial Long Creek was complicated by the presence of eight additional road crossings. The vented-ford, upstream of the RFID station on Long Creek, seemed to impair both upstream and downstream passages. Disproportionately large numbers of fish passing down through the box-culvert originated from within the 200-m reach abutting the outlet of this vented-ford. These fish likely headed downstream after encountering the upstream velocity barrier presented by the channelized pipe culvert and steep concrete slab of the vented-ford. Results indicate that the benefit of any given “fish-friendly” road crossing is likely diminished by the compounding effect of other barriers in the stream, which is a common conclusion (Helfrich et al. 1999; Zydlewski et al. 2006; Cote et al. 2009; Kashiwagi and Miranda 2009). Thus, conclusions about long-distance movement and passage at a particular crossing must be considered in the context of the overall stream system.

Passage rates were higher on the perennial streams, which I attribute to the hydrologic discontinuities of the intermittent streams, most pronounced during the dry summer months. Stream dryness created isolated pools precluding long-distance fish movement and passage across the study reaches. Stream intermittency appeared to reduce
the passage rates of Creek Chub strongly, Longear Sunfish moderately, and barely impacted Highland Stonerollers. This may indicate differing behavioral responses to stream drying, which I consider a finding that merits further study.

Size and swimming ability impact the ability of fish to pass barriers and are largely species-specific (Bourne et al. 2011). I hypothesized that species recognized in the literature as more powerful swimmers, such as Creek Chub and Highland Stoneroller (Leavy and Bonner 2009; Ryles 2012), would pass upstream through/over high-velocity road crossings more frequently than slower swimmers such as Longear Sunfish (Scott and Magoullick 2008, Burford et al. 2009). However, I found few differences in passage rates among species, even for the hydraulically challenging vented-ford on Bear Creek. Surprisingly, Longear Sunfish passed at higher rates across treatment reaches. Passing Creek Chub were longer than Creek Chub that did not pass and fish passing the reference reach on perennial Little Missouri River were longer than other tagged fish in that stream. It seems likely that the small range of fish sizes in this study (compared to many salmonid studies) contributed to the observed insignificant species-effect on passage, similar to the conclusions of Smithson and Johnston (1999).

Fish moved upstream and downstream at similar rates and distances, consistent with the findings of Albanese et al. (2003). Creek Chub, Highland Stoneroller, and Longear Sunfish, on average, passed the study reach two or more times relative to each fish that successfully passed. Rather than migratory in nature, these round-trip movements may be exploratory trips within a range that extends beyond a fish’s home pool. Smithson and Johnston (1999) arrived at a similar conclusion following observations of Creek Chub and Longear Sunfish in the Ouachita Highlands. The
electrofishing recapture efforts (both incidental and intentional) underrepresented the larger sampling and tagging areas established in 2011 and likely led to an under sampling bias for long-distance movement outside of the 2,000-m electrofishing area (Albanese et al. 2003). That being said, all fish species generally moved less than 250 m to pass a study reach and I did not detect any passages by the fish tagged in the distant upper and lower reaches established in 2011. While differences were statistically similar (by a narrow margin), Longear Sunfish appeared to travel less far for passages than Creek Chub or Highland Stoneroller. Thus, Longear Sunfish may be less inclined to longer movements, which is similar to early hypotheses that sunfish are relatively sedentary (Funk 1957) and have small home ranges (Gunning and Shoop 1963).

**RFID Detection Stations**

The RFID stations were an effective tool for monitoring fish movement and detected more fish passages than electrofishing methods (including tagging locations, intentional recapture, and incidental recapture). The mobile nature of electrofishing crews generated fish detections at a larger geographic scale within the stream and complemented the continuous yet immobile monitoring style of the RFID detection station. Fish location data generated during tagging efforts (both original capture location and incidental recaptures) contributed the second highest number of fish detections contributing to confirmed passages and required no additional electrofishing effort. The intentional recapture data proved the least helpful, but I electrofished only 25%-50% as many passes during intentional recapture compared to original tagging expeditions.

The RFID station continuously monitored a fixed study reach, but presented numerous challenges. The stations were costly, involved a complex installation, required
frequent maintenance, and were susceptible to damage and electrical problems. The technical challenges of the RFID systems delayed their successful operation and may have lowered chances for detecting fish tagged in 2011. The fish tagged during 2012-2013, provided a better return on investment (RFID detections to tagging efforts) than fish tagged in 2011. I hypothesize that many of the 2011 cohort died, emigrated from the study area, or ejected their RFID tags during the extended time interval between tagging in July-December 2011 and the beginning of successful RFID station operation in February-April 2012.

The RFID detection stations improved re-encounter probabilities of tagged fish over traditional methods such as electrofishing recapture. I was unable to accurately calculate detection (or missed detection) rates for the RFID stations as is possible in research conducted in controlled environments such as fishways (Axel et al. 2005; Aymes and Rives 2009). However, by consulting additional data sources such as electrofishing location records, I estimate that the RFID stations missed an average of about one-third of the total passages observed and hence the reported counts of fish passage are most likely biased low. I designed the RFID stations for uniform and efficient fish detection, but both intra-station and inter-station efficiency likely varied based on fish swimming speed, fish behavior, environmental conditions, and equipment downtime (Aymes and Rives 2009). The RFID station on the reference, intermittent stream apparently missed the highest proportion of passages, but this was not indicative of poor performance of this station. Rather, to meet tagging quotas, I electrofished more passes on this stream than any other. This led to high rates of incidental recapture and bolstered the passage observations generated by electrofishing.
I explored the current limits of the RFID detection equipment by building two large, \textit{in situ} antennas without the aid of rigid, in-stream structures and at substantial distances from the reader. The design of the antennas influenced efficiency, already limited by the small read range of 12-mm HDX RFID tags, and played a crucial role in fish detection. Antenna efficiency declined when I added additional antennas to the multiplex reader and as each antenna increased in size and distance from the reader. Although the station detected tags outside of the boundaries of the antenna loop and at other orientations, antenna efficiency was highest when the RFID tag was presented perpendicular to the antenna plane, as noted by (Bond et al. 2007; Aymes and Rives 2009; Burnett et al. 2013). Thus, I settled on pass-through antennas that encompassed as much of the stream cross-section as possible (maximizing path efficiency) and oriented the antenna plane perpendicular to stream flow and tag direction (maximizing antenna efficiency). To address the disappointing antenna efficiency of early designs, I developed the figure-eight crossover design, which produced multi-fold improvements in efficiency, eliminating tag detection gaps within the antenna plane. However, the crossover design, with its vertical columns, was more complex to build and repair and was more prone to damage during high flow events. By crossing over the antenna wires and creating independent cells, the electrical polarity was reversed and electrical noise was canceled out, thereby improving antenna efficiency (personal communication-Warren Leach, Oregon RFID).

I encountered a trade-off between path efficiency and antenna efficiency for large and small antenna designs. Large antennas extended farther onto the floodplain and had a taller top strand in hopes of maximizing path efficiency and detecting fish during high
flow events. While I began designing larger antennas, I later settled on more modest designs to achieve consistently higher antenna efficiency. Smaller antennas, while incapable of detecting fish passing more than ~3 cm above bankfull, more efficiently detected tags during average flow conditions and were less vulnerable to high flow damage.

I installed antennas in pools, runs, and riffles; each with advantages and disadvantages for fish detection and antenna survival. Antennas in pools increased chances of detecting a fish because fish often resided in the pool for extended periods. This contributed to a high number of detection opportunities in case the antenna did not detect the fish initially. However, antennas in pools had to accommodate the pool height and the tall antenna designs strained antenna efficiency. In runs and riffles, I was able to build squat antennas, resulting in excellent antenna efficiency. However, antenna efficiency declined when tags traveled through the antenna plane at high velocities. Fish traveling at high speeds (like those found in runs and riffles) may have escaped detection (Aymes and Rives 2009). Runs and riffles were more prone to large volumes of water and stream debris moving at high speeds, a source of antenna damage, but these antennas were generally shorter and less wide, which increased structural stability.

I designed antennas to withstand abuse, but they were susceptible to damage from high flows. I attempted to strengthen antennas with tubing and rope but the stranded copper of the wire itself proved most resistant to breakage. The RFID stations did not operate continuously as planned, but experienced downtime when one or both antennas did not operate. More frequent maintenance led to shorter gaps in operating time as I repaired and retuned damaged antennas, addressed electrical and equipment failures, and
monitored electricity supply, which changed seasonally with solar availability. Once proficient, a team of two could rebuild and tune an antenna in 2-3 hours. Station downtime led to missed detections and fewer observed passages. Often, rather than disabling the entire system, I was able to operate a single antenna which, in combination with electrofishing detection, still generated passage observations. The two RFID stations located at road crossings experienced less downtime and operated with greater antenna efficiency. These sites were easier to access and without intentionally doing so, I devoted more maintenance time to these sites.

Roads are here to stay. This presents a challenge to managers who wish to maintain access to remote areas while enabling fish movement and passage. The recent trends in road crossing construction and replacement appear beneficial to aquatic organism passage. Future work is needed to identify and improve aging road crossings with passage-inhibitory designs such as vented-fords. It is clear that road crossings impair fish passage, particularly older designs that cause more hydraulic disturbance, (Warren and Pardew 1998; Bouska and Paukert 2009). However, the biological effects of stream fragmentation and the amount of passage and road crossing permeability necessary to maintain genetic diversity of nonmigratory fish populations over time is unknown (Park et al. 2008; Bouska and Paukert 2009). In this study, I studied the mechanism driving road crossing barriers as they impacted individual fish over a relatively short time span. I was unable to determine why fish assemblages varied among streams or if road crossings had altered them from historical patterns. Researching alongside my study, Schanke (2013) analyzed DNA microsatellites to study the long-term impact of road crossings in the same stream systems. He concluded that significantly distinct genetic populations
were separated by road crossings, but he also found disruptions in gene flow across
natural barriers, such as the Little Missouri Falls and along reaches of intermittent
streams. A combination of research methods, including genetic analysis at the population
level, hydraulic evaluation of road crossings, and observation of fish movements may
help answer Bouska and Paukert’s (2009) question of how much passage is enough.

Realizing the limitations of their six week study, Norman et al. in (2009) called
for longer-term studies to evaluate the impact of hydrologic variability (e.g. stream
discharge) on fish passage at semi-permeable road crossings. I propose that RFID
detection stations can make valuable contributions to understanding this question, given
longer study periods and more consistent operation. One pitfall of this study was the
frequent downtime of the RFID detection stations. Improvements to RFID technology
will yield smaller tags, improved antenna read range and efficiency, more resilient
antenna designs, and more stable electrical operating systems. In the future, pass-over
antenna designs, like those designed by Connolly et al. (2008), may offer the same level
of detection performance as more vulnerable pass-through designs. One objective of this
study was to measure the water level at the moment of fish passage to investigate
passability at various hydrologic conditions. Conclusions were limited by the long spans
of time between detection events, which were likely exacerbated by equipment
downtime. By placing multiple antennas on each stream (e.g. more than just one
upstream and one downstream of the target reach) the spatial accuracy of fish movement
could be improved and missed detections could be minimized (Connolly et al. 2008).
Finally, the study could have benefited from more study streams to increase replication.


Appendices

Appendix A. Ouachita Mountain Road Crossings

I used GIS to analyze road networks in the Ouachita National Forest and Ouachita Mountain Ecoregion whose shared 937,687 ha contain approximately 10,855 km of paved and unpaved roads. An intersection of the road network and a stream network yielded 1,392 possible road crossings and a density of 1.4 road crossings/1,000 ha. Because the road network used in the analysis included both maintained and unmaintained roads, the actual number of constructed road crossings (as opposed to primitive natural fords) is fewer, but nonetheless impressive.

Figure A.31.—The Ouachita National Forest and the Ouachita Mountain Ecoregion intersect to form an area 937,687 ha with 10,855 km of roads. The road network intersects streams to form 1,392 possible road crossings. Vented-ford, intermittent = Bear Creek; reference, intermittent = Crystal Prong; box-culvert, perennial = Long Creek; reference, perennial = Little Missouri River.
Appendix B. Supplemental Water Level Data

I began electrofishing and generating fish location records in August 2011, prior to installation of the water level recorders on the two treatment streams in June 2012. This led to a gap in water level data needed to analyze the hydrological conditions present during fish passage. I filled this gap by estimating water level on the study streams based on US Geological Survey (USGS) water level data on nearby gauged streams. I supplemented the water level record records of intermittent Bear Creek with USGS data from Bringle Creek, draining 22.5 km² near Martindale, AR and perennial Long Creek with data from the Little Missouri River draining 176.1 km² near Langley, AR. I initially chose gauging stations closer to the study streams and with more similar drainage areas but incomplete records precluded those data sets.

I ran a linear regression between the entire ~263-day water level data sets of the study streams and overlapping water level data from the respective USGS gauged streams. The Bear Creek regression matched up reasonably well with its USGS reference stream (Figure A.32). I generated more accurate regressions for Long Creek by dividing its USGS reference stream into water levels above and below five feet (Figure A.33). Using these scatterplots and linear regressions, I estimated water levels on the study streams for a given date based on the water level of the respective USGS stream. This enabled me to estimate the hydrologic conditions at the study streams for fish detections occurring prior to installation of the water level recorders in late June 2012.
Figure A.32.—Water levels generated by the water level recorder near the vented-ford on intermittent Bear Creek and a nearby USGS gauging station on Bringle Creek. I used the relationship between the two streams to estimate water levels prior to installation of the water level recorder on Bear Creek.
Figure A.33.—Water levels generated by the water level recorder near the box-culvert on perennial Long Creek and a nearby USGS gauging station on Little Missouri River. To improve the linear regression between the two streams I split the USGS water level record into levels (A) less than 5.0 feet and (B) more than 5.0 feet. The gauging station was located downstream of the study reach on Little Missouri River. I used the relationship between the two streams to estimate water levels prior to installation of the water level recorder on Long Creek.
Appendix C. *Long Creek Road Crossing Modifications*

Table A.8.—The Ouachita National Forest has replaced four road crossings within the study reach on perennial Long Creek since 2004. The RFID station was installed at the box-culvert (numbered RC-4) that was updated in 2004. The vented-ford (numbered RC-5) intersected Long Creek 200 m upstream from the RFID station.

<table>
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<th>Road crossing, numbered from downstream</th>
<th>Crossing type in 2003</th>
<th>Crossing type in 2011-2013</th>
<th>Year of crossing replacement</th>
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<tr>
<td>RC-1</td>
<td>Box-culvert</td>
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<tr>
<td>RC-2</td>
<td>Vented-ford</td>
<td>Box-culvert</td>
<td>2009</td>
</tr>
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<td>RC-3</td>
<td>Vented-ford</td>
<td>Bottomless-box</td>
<td>2010</td>
</tr>
<tr>
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<td>Slab-ford</td>
<td>Box-culvert</td>
<td>2004</td>
</tr>
<tr>
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</tr>
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<td>Vented-ford</td>
<td>NA</td>
</tr>
<tr>
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<td>Vented-ford</td>
<td>NA</td>
</tr>
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<td>Slab-ford</td>
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</tr>
<tr>
<td>RC-9</td>
<td>Slab-ford</td>
<td>Slab-ford</td>
<td>NA</td>
</tr>
</tbody>
</table>
Appendix D. *Vented-ford on Perennial Long Creek*

Perennial Long Creek intersects a vented-ford 200 m upstream from the RFID station that was centered on the box-culvert. The vented-ford had an 11.2-m long pipe that conveyed water under the 5.1-m wide road. I measured depth and velocity at this vented-ford to compare with the other road crossings. The pipe always supported the minimum swimming depth of 3 cm, but produced high velocities. At a water level of 0.13 m, the minimum water velocity at the pipe outlet was 1.0 m/s (Figure A.34). Velocities increased to 2.0 m/s when water levels reached 0.20 m. Water flowed over the road crossing at 0.53 m (Figure A.35). However, the road prism had downstream slopes in excess of 25° and did not create a swim zone with a sufficient 3-cm water depth (Figure A.36).

![Figure A.34.—Measuring depth and velocity at the outlet of the vented-ford 200 m upstream of the RFID detection station on perennial Long Creek. During typical flows (water level = 0.13 m) water passed through the pipe, yet minimum velocities exceeded 1 m/s.](image-url)
Figure A.35.—Measuring depth and velocity at the outlet of the vented-ford 200 m upstream of the RFID detection station on perennial Long Creek. At high water levels (0.53 m), water flowed over the road crossing and created a swim zone on top of the road prism. However, velocities in the pipe and on the steep downstream slopes of the road crossing prism were high.

Figure A.36.—A schematic upstream view of the vented-ford road crossing on perennial Long Creek. This road crossing was located 200 m upstream of the box-culvert. (Adapted from Schanke 2013).
Appendix E. Technical RFID Report

I housed the RFID reader, battery bank, and solar charge controller in a padlocked steel storage chest and secured the chest to a concrete apron, embedded with steel bolts and poured on-site (Figure A.37). The bolts were completely enclosed within the steel frame of the chest to minimize the opportunity for vandalism. I placed the chest above bankfull height and the concrete foundation further decreased the chance of losing the equipment in the case of a flood event. The RFID reader was powered by a photovoltaic electrical system (Figure A.38) protected by fuses and a lightning arrestor (Figure A.39).

Figure A.37.—The RFID reader, center, flanked by the four deep cycle batteries. The solar charge controller was mounted on a piece of plywood behind the reader. A steel storage chest contained all components.
Figure A.38.—Wiring diagram detailing the electrical wiring of the RFID detection station. A steel chest contained most of the equipment including the RFID reader, the solar charge controller, the battery bank of four deep-cycle, 6-V batteries, and the lightning arrester. The charge controller acted as the electrical hub and mediated power between the solar panel, batteries, and the electrical load (reader). *Italics* indicate wire type. Yellow circles indicate fuses. The four batteries were wired in both series and parallel to supply sufficient amperage at 12-volts.
Figure A.39.—Diagram detailing the proper wiring of the lightning arrestor. The lightning arrestor (gray cylinder) was a sacrificial device designed to reroute damaging high-voltage surges away from the load (RFID reader).

Electrical cables are expensive and some shortcuts can be made from the design used in this study. The heavy-duty Triax cable which ran from the reader to the antenna tuner offered excellent durability but could be replaced with cheaper lamp wire or speaker wire. To connect the solar panel to the solar charge controller I used MC4 cables, designed for long-term solar installations and rigorous electrical code regulations. For short-lived field installations, this expensive cable could be replaced with two lines of 10 gauge electrical wire. Most solar panels come with MC4 connectors but these can be cut and the 10 gauge wire can be spliced in. I discovered that wrapping antenna wire around its anchoring tree two or more times before stapling increased antenna survival. This placed most of the strain on the tree and minimized instances of hardware failure, wire stripping, or wire breakage. Electrical staples buffered with a plastic housing were the most efficient hardware, quick to install or remove and unlikely to cut through the wire.

The RFID reader was subject to noise interference from electrical devices. The
charge controller, a MorningStar PS-30M, featured a pulse width modulation (PWM) charging mode designed to maximize battery charging efficiency. The PWM mode, when active, produced a high-frequency noise that interfered with radio transmission and severely reduced antenna efficiency. Apart from an audible buzz originating from the charge controller, there was no sign of electrical noise interference by the reader and antenna amperages remained high. I followed the instructions of MorningStar Corporation by installing a high-frequency noise filter in between the charge controller and the load and twisting the load wires around each other. This lessened the effect of the PWM noise interference but it did not eliminate it entirely. Hence, I had to disable PWM charging by opening the charge controller and severing the circuit that controlled PWM charging. This reduced battery charging efficiency but was necessary to maintain adequate antenna efficiency. This problem may have resulted in missed detections prior to the correction.

RFID systems are complex and vulnerable to environmental and electrical interference. Initially, I installed five RFID detection stations, two of which were located 200 m apart on perennial Long Creek. I installed the fifth station at the vented-ford to compare passage rates with the nearby box-culvert. However, the RFID station at this vented-ford experienced electrical noise that prevented the station from operating both antennas simultaneously. I was unable to determine the cause and in November 2012 I abandoned the installation and repurposed its reader to the reference reach on intermittent Crystal Prong, which was experiencing interference between its two antennas. I also had difficulty with the station at the box-culvert on perennial Long Creek, which operated only one antenna for several months because the multiple-antenna array caused electrical
noise and was unable to read tags.

RFID systems are also subject to more subtle deteriorations of antenna efficiency and fluctuating antenna amperages. The multiplex RFID reader was designed to operate up to four antennas simultaneously but I found that adding additional antennas decreased the performance of the entire system. With a multiplex reader operating two antennas, the antennas influenced each other’s amperage and both suffered from lower detection efficiency. At the reference, intermittent Crystal Prong, I found unacceptable levels of antenna amperage interference between the two antennas. This was resolved by installing a second reader at Crystal Prong so that each reader operated a single antenna. This approach worked well, but antennas may interfere with each other if located close together. Additionally, the internal clocks of the two readers, even when synchronized, drifted apart from each other by approximately one second per day, challenging attempts to determine precise timing of fish movements. Electrical grounding systems, both at the location of the reader and the solar panels (50 m away) elevated antenna amperages to unacceptable levels. The large variability in antenna size (initially up to 17 m across and 60 cm deep) and their considerable distance from the RFID reader (up to 40 m away) challenged the capabilities of the equipment. This situation created inequities in antenna amperage and often overpowered antennas located closer to the RFID reader and caused the reader to overheat and shut down. To reduce antenna amperage to acceptable levels, I detuned the antennas, which had the undesirable result of reducing antenna efficiency.

I experienced numerous other challenges such as RFID reader malfunction and failure. I returned malfunctioning readers to the manufacture twice for repair. The RFID detection station at the reference reach on perennial Little Missouri River suffered from a
phenomenon called “cross talk” in which its two antennas communicated with each other and erroneously detected the same tag simultaneously at both antennas. In addition to logging legitimate fish detections, the cross talk phenomenon caused the RFID reader to log false fish detections between November 22 and December 13, 2012. On December 13, I adjusted wiring and reader settings and unwittingly disabled the conditions causing cross talk. Warren Leach of Oregon RFID, the chief engineer and developer behind the RFID detection equipment, has observed cross talk in only two or three other installations. The phenomenon is rare and still poorly understood, but likely causes include: 1) antennas located close to each other in the same orientation; 2) parallel antenna wiring in which all of the Triax electrical wiring among interfering antennas shares the same polarity in the reader and the antenna tuners; and 3) metal structures located in between antennas.
Appendix F. *Study Locations*

Table A.9.—Locations of study reaches on the four streams during the initial phase of fieldwork in 2011. Each reach consisted of a 400-m fish sampling zone where I electrofished and implanted RFID tags. I later installed RFID detection stations in the middle reach of each stream. The downstream and upstream reaches were located 3-4.5 km downstream and upstream, respectively, from the middle reach. UTM coordinates are in zone 15S and projected in NAD83.

<table>
<thead>
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<th>Easting</th>
<th>Northing</th>
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</thead>
<tbody>
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<td>3852296</td>
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<td></td>
<td>US</td>
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<td>DS</td>
<td>417630</td>
<td>3805850</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>414100</td>
<td>3806800</td>
</tr>
<tr>
<td></td>
<td>US</td>
<td>410399</td>
<td>3808382</td>
</tr>
<tr>
<td>Reference, perennial (Little Missouri River)</td>
<td>DS</td>
<td>416127</td>
<td>3808030</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>413218</td>
<td>3810284</td>
</tr>
<tr>
<td></td>
<td>US</td>
<td>408481</td>
<td>3810897</td>
</tr>
</tbody>
</table>
Table A.10.—Locations of study reaches during the major phase of fieldwork in 2012-2013, which were centered on the RFID detection stations. The fish sampling zones extended 1,000 m downstream and upstream from the middle sites. I shifted the locations of the middle site up to 100 m from the 2011 locations in three of the streams (excluding Bear Creek) to accommodate installation of the RFID stations. UTM coordinates are in zone 15S and projected in NAD83.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Site</th>
<th>Easting</th>
<th>Northing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vented-ford, intermittent</td>
<td>DS 1000&lt;sup&gt;a&lt;/sup&gt;</td>
<td>483962</td>
<td>3850390</td>
</tr>
<tr>
<td>(Bear Creek)</td>
<td>DS 500</td>
<td>484120</td>
<td>3849954</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>484460</td>
<td>3849643</td>
</tr>
<tr>
<td></td>
<td>US 500</td>
<td>484868</td>
<td>3849451</td>
</tr>
<tr>
<td></td>
<td>US 1000</td>
<td>485324</td>
<td>3849293</td>
</tr>
<tr>
<td>Reference, intermittent</td>
<td>DS 1000</td>
<td>505696</td>
<td>3858456</td>
</tr>
<tr>
<td>(Crystal Prong)</td>
<td>DS 500</td>
<td>505961</td>
<td>3858067</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>505974</td>
<td>3857623</td>
</tr>
<tr>
<td></td>
<td>US 500</td>
<td>506358</td>
<td>3857319</td>
</tr>
<tr>
<td></td>
<td>US 1000</td>
<td>506842</td>
<td>3857295</td>
</tr>
<tr>
<td>Box-culvert, perennial</td>
<td>DS 1000</td>
<td>414361</td>
<td>3806241</td>
</tr>
<tr>
<td>(Long Creek)</td>
<td>DS 500</td>
<td>414228</td>
<td>3806593</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>414017</td>
<td>3806942</td>
</tr>
<tr>
<td></td>
<td>US 500</td>
<td>414032</td>
<td>3807415</td>
</tr>
<tr>
<td></td>
<td>US 1000</td>
<td>413695</td>
<td>3807415</td>
</tr>
<tr>
<td>Reference, perennial</td>
<td>DS 1000</td>
<td>414102</td>
<td>3809950</td>
</tr>
<tr>
<td>(Little Missouri River)</td>
<td>DS 500</td>
<td>413598</td>
<td>3809984</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>413226</td>
<td>3810290</td>
</tr>
<tr>
<td></td>
<td>US 500</td>
<td>412737</td>
<td>3810290</td>
</tr>
<tr>
<td></td>
<td>US 1000</td>
<td>412301</td>
<td>3810303</td>
</tr>
</tbody>
</table>

<sup>a</sup> DS 1000 signifies 1,000 m downstream of the middle site, and DS 500 signifies 500 m downstream, etc.
Table A.11.—In 2011, I RFID-tagged 719 fish from three 400-m reaches on four streams in the Ouachita Mountains, Arkansas. The RFID stations were installed at the middle reach and the upper and lower reaches were located 3-4.5 km upstream and downstream, respectively.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Upstream of RFID station</th>
<th>Downstream of RFID station</th>
<th>Lower</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vented-ford, intermittent</td>
<td>22</td>
<td>15</td>
<td>17</td>
<td>83</td>
</tr>
<tr>
<td>Reference, intermittent</td>
<td>9</td>
<td>40</td>
<td>36</td>
<td>56</td>
</tr>
<tr>
<td>Box-culvert, perennial</td>
<td>90</td>
<td>32</td>
<td>24</td>
<td>81</td>
</tr>
<tr>
<td>Reference, perennial</td>
<td>72</td>
<td>30</td>
<td>32</td>
<td>80</td>
</tr>
<tr>
<td>Total</td>
<td>193</td>
<td>117</td>
<td>109</td>
<td>300</td>
</tr>
</tbody>
</table>

Table A.12.—In 2012-2013, I RFID-tagged 3,076 fish in 2,000-m reaches centered around the RFID station on four streams in the Ouachita Mountains, Arkansas.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Upstream of RFID station</th>
<th>Downstream of RFID station</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vented-ford, intermittent</td>
<td>312</td>
<td>404</td>
<td>716</td>
</tr>
<tr>
<td>Reference, intermittent</td>
<td>384</td>
<td>398</td>
<td>782</td>
</tr>
<tr>
<td>Box-culvert, perennial</td>
<td>452</td>
<td>350</td>
<td>802</td>
</tr>
<tr>
<td>Reference, perennial</td>
<td>386</td>
<td>390</td>
<td>776</td>
</tr>
<tr>
<td>Total</td>
<td>1,534</td>
<td>1,542</td>
<td>3,076</td>
</tr>
</tbody>
</table>
Appendix G. Handheld RFID Antenna

As an alternative to electrofishing, I piloted another approach to detect free-swimming tagged fish by using the handheld RFID reader in conjunction with a handheld antenna probe. Researchers used a similar approach and a prototype of a portable detector capable of detecting tags 17-36 cm away to detect more than 70% of marked Brown Trout and Slimy Sculpin *Cottus cognatus* in streams (Cucherousset et al. 2005; Keeler et al. 2007). The handheld RFID reader used in this study was highly portable but had a maximum read range of 4 cm and was ineffective for detecting fish. However, I did use it effectively to search for tags which had been ejected from their host fish. Larger backpack mounted portable RFID readers are better suited to fish detection. However, currently available backpack units have very limited read ranges when detecting 12-mm RFID tags (Burnett et al. 2013).
Appendix H. Tagging Mortality Study

At the beginning of the study in 2011, I only tagged fish greater than 100 mm total length. This conservative lower length limit led to low returns on tagging effort in the intermittent streams, which had fewer taggable fish. I lowered the minimum length limit to increase the likelihood of encountering and tagging suitable fish. The literature documents minimal effect upon fish growth and acceptable RFID tag injection mortality and retention rates in small individuals of several species: juvenile European Perch *Perca fluviatilis* (Baras et al. 2000), juvenile Brown Trout (Acolas et al. 2007), Slimy Sculpin (Keeler et al. 2007), and several salmonid species (Baras et al. 2000; Zydlewski et al. 2006; Acolas et al. 2007; Keeler et al. 2007). Additionally, Johnston and Smithson (1999) tagged Creek Chub and Green and Longear sunfish as small as 70 mm and 65 mm, respectively, with no mortality. However, my study involved multiple species, some potentially less robust, such as the narrow-bodied Highland Stoneroller. Therefore, prior to lowering the length limit, I conducted two mortality studies by collecting and tagging ~twenty fish 80 mm TL or longer near the vented-ford on intermittent Bear Creek. I contained the fish in a mesh collection basket submerged in the stream for ~24 h. I assessed the condition of the tagged individuals; some of which showed inflammation at the injection site but had all retained their tags. I compared the survival and tag retention rates among fish size classes and concluded that 12-mm RFID tag injection was appropriate for individuals as small as 85 mm TL.