Movement patterns, habitat use, and home range of adult robust redhorse *Moxostoma robustum* released into the Oconee River, Georgia

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EXECUTIVE SUMMARY

The robust redhorse *Moxostoma robustum* is a large, long-lived riverine catastomid native to Atlantic slope drainages in the southeastern United States. Currently, natural populations inhabit the Upper Coastal Plain ecoregion of the Oconee River, Georgia, the Piedmont and Upper Coastal Plain ecoregions of the Savannah River, Georgia/South Carolina, and the Pee Dee River, North Carolina/South Carolina. In 1995, the Robust Redhorse Conservation Committee (RRCC) was established under a memorandum of understanding between state and federal resource agencies, private industry, and academic institutions with the goal of developing and managing a recovery approach for the robust redhorse. Because of concerns over low recruitment rates and population declines in the Oconee River, the RRCC initiated a plan to create refugial populations by stocking hatchery-reared individuals, propagated from Oconee River broodstock, into the Ogeechee, Broad, and Ocmulgee rivers in Georgia. Our goal for this study was to use radio telemetry to assess the movement patterns and habitat use of adult robust redhorse in the section of the Oconee River referred to as the lower Oconee, which extends from Sinclair Dam down to its confluence with the Ocmulgee River. Because of diminishing catch rates of adults and a decline in the number of fish spawning annually at the historic Avant Mine gravel bar, we used naturalized hatchery-reared robust redhorse transplanted from the Ogeechee River as surrogates for wild Oconee River fish. Our specific objectives were to: 1) document movement patterns and habitat use, and estimate home range of robust redhorse in the lower Oconee River, 2) compare movement patterns, habitat use, and home range size of stocked fish during specified periods, and 3) use radio-tagged fish as guide fish to locate previously unknown spawning aggregations or population centers. From April 2008 through June 2010, radio-

tagged robust redhorse released into the Oconee River exhibited behavior patterns that were like wild fish, including making spawning migrations, forming spawning aggregates over habitat associated with gravel substrates and fast current, and returning to preferred non-spawning habitat (woody debris over sandy substrates, deep water with current) the remainder of the year. Tagged fish were located in previously unknown spawning locations in 2009 and 2010. Morphological changes to the main channel of the lower Oconee River seem to influence the recruitment and location of gravel substrate and consequently the location of spawning robust redhorse. Since 1994, declining catch rates indicate a severe reduction in the abundance of adult robust redhorse in areas of the Oconee River typically sampled during the spring (i.e., Central Georgia Railroad Trestle (CGRT) to Dublin, GA). However, during April 2004, May 2010, and May 2011, electrofishing surveys from the top of the study reach (i.e., Sinclair Dam) down to Dublin, GA were conducted. This effort was a multi-agency collaboration to address whether historic catch rates reflected overall population decline or if the population distribution shifted into areas above the CGRT that previously received limited sampling effort. Results of the April 2004 electrofishing survey documented a continued decline in catch rate from previous years but also indicated that most of the population was located in the previously restricted sampling area above the CGRT. The absence of robust redhorse from the 2010 and 2011 electrofishing surveys suggest that the abundance of wild-spawned adult robust redhorse in the lower Oconee River has continued to decline even though telemetry results indicate that robust redhorse, if present, would be located in the reach between the Avant Mine site and the CGRT. However, sampling data for the previously restricted area above the CGRT is still limited and additional electrofishing surveys in the area would help to verify the actual abundance and fate of adult robust redhorse in the lower Oconee River, Georgia.

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INTRODUCTION

The robust redhorse *Moxostoma robustum* is a large, long-lived riverine catastomid, native to Atlantic slope drainages in the southeastern United States. The historic range included the Yadkin-Pee Dee River drainage in North Carolina/South Carolina southward to the Altamaha River basin in Georgia. The species was extirpated from much of its range and lost to science for over a century until its rediscovery in the Oconee River, Georgia, in 1991 (Evans 1994, Bryant et al. 1996; Ruetz and Jennings 2000). Currently, natural populations inhabit the Upper Coastal Plain ecoregion of the Oconee River, Georgia, the Piedmont and Upper Coastal Plain ecoregions of the Savannah River, Georgia/South Carolina, and the Pee Dee River, North Carolina/South Carolina. The imperiled robust redhorse is currently classified as Endangered by the Georgia Department of Natural Resources and is considered a Species of Special Concern by the U.S. Fish and Wildlife Service (RRCC 2010). Declines of robust redhorse have been attributed to increased sedimentation caused by deforestation and poor farming practices, which can degrade spawning sites, and to the construction of dams, which can block seasonal migrations, alter riverine flows, reduce water quality, and modify habitat (Evans 1994; Hendricks 1998; Cooke et al. 2005). Introduced species such as flathead catfish *Pylodictis olivaris*, which some believe may prey on robust redhorse (Bart et al. 1994; Hendricks 1998, 2002), are another potential cause for reduction in robust redhorse abundance.

Robust redhorse are potamodromous and make seasonal migrations sometimes over long distances, to spawning grounds and then return to preferred habitat the remainder of the year (Grabowski and Isely 2006; RRCC 2010). Adults form spawning aggregates over loose gravel substrate in moderate to swift current from late April to early June when water temperatures are between 18–24°C (Hendricks 1998; Freeman and Freeman 2001). Non-spawning adults in the Coastal Plain ecoregion are generally found in the bends of meandering rivers, usually with woody debris and deep water with moderate to swift current (Grabowski and Isely 2006; Grabowski and Jennings 2009; RRCC 2010). Spawning activity has only been documented in two locations along the Oconee River; these sites are located between Milledgeville and Dublin, Georgia and consist of 1) a near-shore to mid-channel gravel bar located in a section of meander bends below Ball's Ferry Landing at river kilometer (rkm) ~ 151 (RRCC 2010). This site was apparently abandoned several years prior to initiation of the current study (Jimmy Evans, Georgia Department of Natural Resources, personal communication); and 2) a larger mid-channel gravel bar adjacent to the Avant Kaolin Mine (rkm ~ 191; Freeman and Freeman 2001). Over the past decade, there has been a dramatic decrease in the number of individuals observed spawning at the Avant Mine gravel bar site as well as a continued decline in annual catch rates during electrofishing surveys and broodstock collection between the Central Georgia Railroad Trestle (CGRT; rkm ~166) and Dublin, Georgia (rkm ~ 120; RRCC 2010). These decreases have raised questions as to whether the overall Oconee River population is in decline or if unknown spawning aggregations or population centers exist elsewhere.

In 1995, the Robust Redhorse Conservation Committee (RRCC) was established under a memorandum of understanding between state and federal resource agencies, private industry, and academic institutions with the goal of developing and managing a recovery approach for the robust redhorse. Because of concerns over low recruitment rates and population declines of robust redhorse in the Oconee River, the RRCC initiated a plan to create refugial populations by stocking hatchery-reared individuals, propagated from Oconee River broodstock, into the Ogeechee, Broad, and Ocmulgee rivers in Georgia.

Radio telemetry has been used successfully to document dispersal rates, movement patterns, and habitat use of hatchery-reared juvenile robust redhorse released in the Oconee (Hess et al. 2001) and Ocmulgee (Jennings and Shepard 2003) rivers. Radio telemetry has also been used to determine movement patterns and habitat use of wild adult robust redhorse in the Savannah (Grabowski and Isely 2006) and Pee Dee (Fisk 2010) rivers, as well as hatchery-reared adult robust redhorse in the Broad (Freeman and Straight, in preparation) and Ocmulgee (Grabowski and Jennings 2009) rivers. Accordingly, radio telemetry was determined to be a suitable tool for addressing the questions about adult robust redhorse movement patterns, habitat use, and alternate spawning locations in the Oconee River. However, recent low catch rates in the Oconee River suggest that capturing sufficient numbers of individuals to effectively conduct a telemetry study might be problematic.

Hatchery-reared robust redhorse in refugial populations exist and have been successfully used as surrogates for wild robust redhorse in recent studies (Grabowski and Jennings 2009; Freeman and Straight, in preparation). Although some studies suggest that hatchery fish may have lower fitness levels than wild fish in a natural system (Bettinger and Bettoli 2002; Araki 2008), other studies indicate that the discrepancy in fitness levels between hatchery and wild fish becomes less obvious when the hatchery fish have been exposed and acclimated to a natural environment (Brown and Day 2002; Huntingford 2004). Grabowski and Jennings (2009) transplanted hatchery-reared adult robust redhorse from naturalized refuge populations in the Ogeechee and Broad rivers into the Ocmulgee River and used radio telemetry to document that hatchery-reared individuals adopted behavioral patterns that were analogous with those previously observed for radio-tagged wild fish in the Savannah River (Grabowski and Isely 2006). The recent successes by researchers (Jennings and Shepard 2003; Grabowski and Isely 2006; Graboswki and Jennings 2009; Fisk 2010) conducting telemetry studies on both hatchery-reared and wild individuals, coupled with the perceived decline in robust redhorse abundance, has renewed interests in the use of radio telemetry to address questions about the location and movements of adult robust redhorse in the Oconee River.

Our goal for this study was to use radio telemetry to assess the movement patterns and habitat use of adult robust redhorse stocked in the Oconee River, Georgia. Our specific objectives were to: 1) document movement patterns and habitat use, and estimate home range of robust redhorse in the Oconee River, 2) compare movement patterns, habitat use, and home range size of stocked fish during specified periods, and 3) use radio-tagged fish as guide fish to locate previously unknown spawning aggregations or population centers.

METHODS

Study Area

The Oconee River Basin drains approximately 13,800 km^2 and is located in the Piedmont and Coastal Plain of central Georgia (GAEPD 1998). The Oconee River is about 360 km long and converges with the Ocmulgee River to form the Altamaha River (Figure 1). Our study focused on the section of river referred to as the lower Oconee, which originates below Sinclair Dam and extends approximately 230 river kilometers (rkm) to the confluence with the Ocmulgee River. Sinclair Dam is a main-stem, Georgia Power Company hydroelectric facility that creates an impassable upstream barrier to fish.

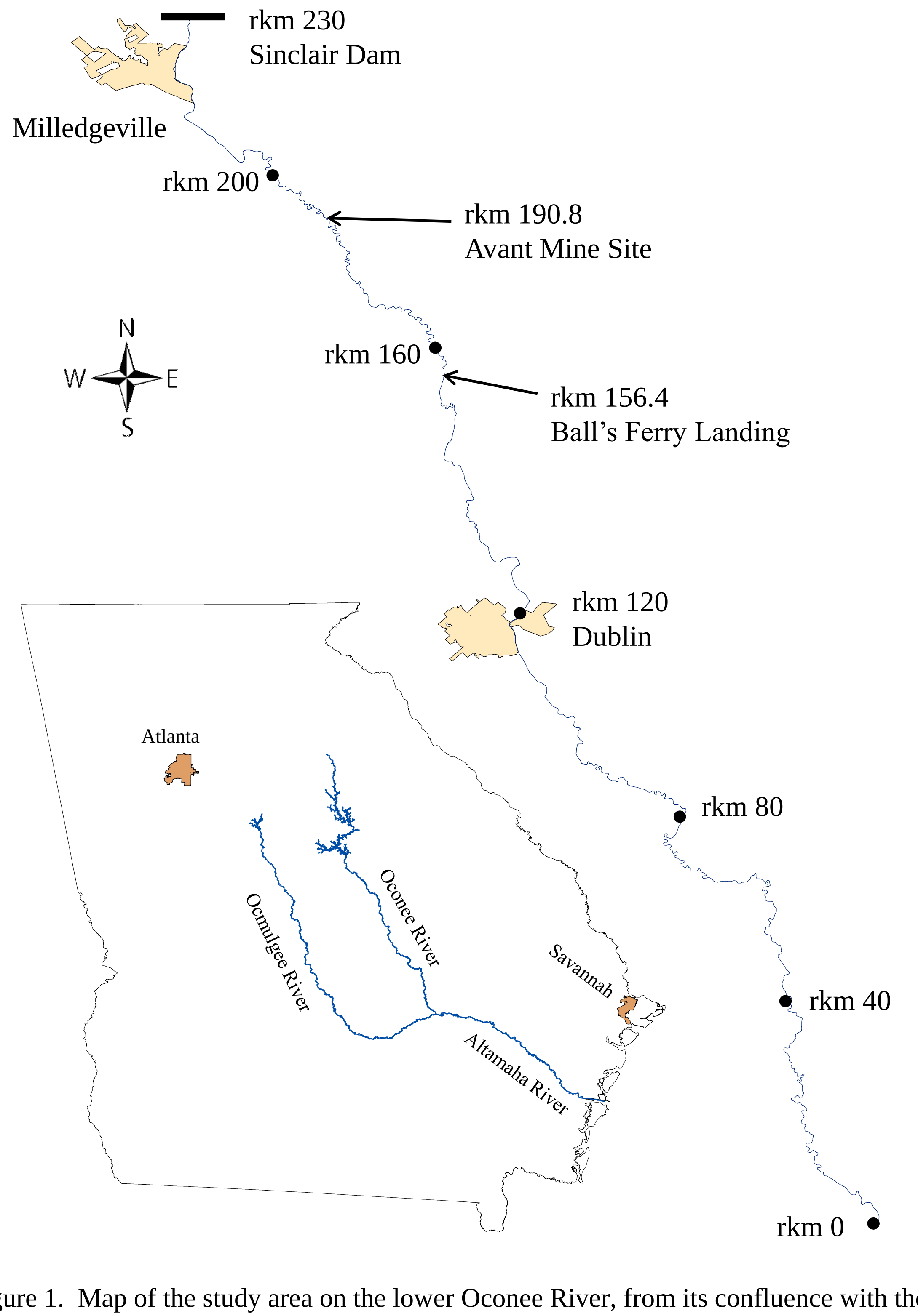


Figure 1. Map of the study area on the lower Oconee River, from its confluence with the Ocmulgee River at river kilometer (rkm) 0 to Sinclair Dam at rkm 230. The inset shows the location of the Altamaha River system in the state of Georgia.

Mean daily discharge from Sinclair Dam ranged from 6 m^3/s to 1280 m^3/s; mean daily water temperatures that occurred at robust redhorse relocations in the lower Oconee River during this study ranged from 7°C to 32°C (Figure 2).

Located directly below Sinclair Dam (rkm 230) is a small Piedmont reach that extends approximately 6 to 7 kilometers to Highway 22/24 (rkm ~ 223) in Milledgeville, Georgia. This section of river is primarily straight and cover generally consists of rocky shoals and boulders with occasional woody debris (i.e., fallen logs, branches, and stumps) and sediment types mostly consist of rocky substrates (i.e., bedrock, gravel, and cobble). The remaining portion of the Oconee River to the confluence primarily falls within the Upper Coastal Plain ecoregion and consists of meander sections with cover that generally includes woody debris, separated by long, straight reaches, and a few rocky shoals and boulders. Sediment types include sand, mud, and rocky substrates.

A mid-channel gravel bar located adjacent to the Avant Kaolin Mine is the last known spawning site of robust redhorse in the Oconee River, Georgia (Figure 3). In past observations, spawning aggregations at the Avant Mine site generally consisted of 30–50 adults, but recently the number of individuals has decreased substantially (RRCC 2010). The cause(s) for the decline in individuals at the spawning site is unclear, although morphological changes to the river channel may have negatively affected the suitability of the gravel bar as a spawning site. Over a decade ago, the creation of a new oxbow changed the course of the main river channel and moved it away from a gravel-embedded bluff located just upstream of the Avant Mine spawning site. Because the hydraulics of the river have changed (Figure 3), flows that previously eroded the bluff and transported new gravel downstream to the spawning site occur much less often than before the oxbow was created. As a result, the lack of new gravel input could have negatively affected the suitability of the Avant Mine gravel bar as a spawning site and caused the fish to seek

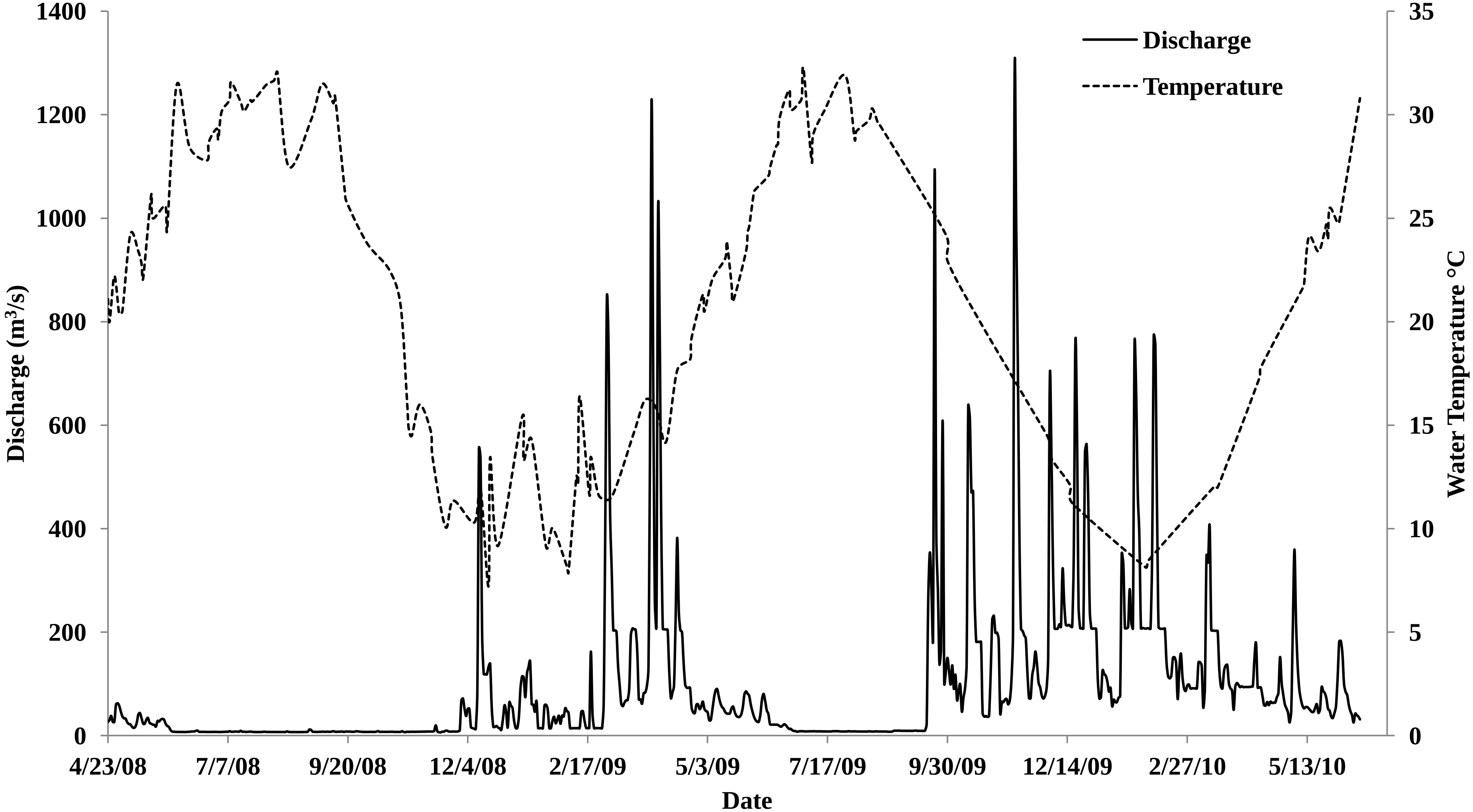


Figure 2. Mean daily water temperatures (dashed line) taken from radio-tagged robust redhorse relocations throughout the lower Oconee River and mean daily discharge (solid line) below Sinclair Dam (U.S. Geological Survey gauging station 0223000 on the Oconee River at Milledgeville, Georgia) between April 2008 and June 2010.

Figure 3. Satellite image from 2009 of the lower Oconee River, Georgia, at the Avant Mine site. The historic gravel bar (rkm 190.8), old river channel, and flow direction are marked and labeled with white arrows. The old river channel was confirmed from satellite imagery taken in 1993.

alternate spawning locations. Gravel substrates similar to those at the Avant Mine site have been documented in other locations in the Oconee River (Jimmy Evans, Georgia Department of Natural Resources, personal communication; EA 1994), and undiscovered spawning sites may exist elsewhere in the system.

Fish Sampling

Boat-mounted electrofishing was used to collect 33 adult robust redhorse (448−576 mm TL, 1270−2980 g) from a naturalized population of robust redhorse in the Ogeechee River, Georgia. These fish were hatchery-produced progeny of Oconee River broodstock that had been stocked into the Ogeechee River as fingerlings over multiple years from 1997 to 2004. Following collection on 23 April (n=17) and 24 April (n=10) 2008, a total of 27 study fish were placed in oxygenated hauling tanks and transported to Ball's Ferry Landing on the Oconee River for surgery and release the day of capture. To assess capture-related handling mortality, six other individuals were collected and transported to the University of Georgia's Whitehall Fisheries Laboratory on 18 April (n=4) and 24 April (n=2) 2008 and held in an aerated 500-L fiberglass tank for 4 to 10 days prior to transmitter implantation. Following surgery on 28 April 2008, tagged fish were held for an additional four days to monitor recovery before being transported to Ball's Ferry Landing where they were released into the river on 02 May 2008.

Transmitter Implantation

An internal radio transmitter (Model F1850) with a trailing whip antenna (Advanced Telemetry Systems [ATS] Inc., Isanti, Minnesota) was surgically implanted into each study fish. Each transmitter was uniquely coded by frequency, possessed a minimum battery life of 708 days, and weighed approximately 23 g in air. In an effort to decrease mortality and avoid alteration of fish behavior following implantation, all transmitters were less than 2% of the body weight of the smallest study fish, per the recommendations of Winter (1996). Prior to surgery, each fish was anesthetized in a solution of 140 mg/l sodium bicarbonate buffered tricaine methanesulfonate (MS-222). Once a fish was anesthetized, an electronic, handheld wand detector (Northwest Marine Technology Inc., Shaw Island, Washington) was used to magnetically check for the presence of a coded wire tag (CWT), and a passive integrated transponder (PIT) tag (Biomark Inc., Boise, Idaho) was implanted just below the distal end of the dorsal fin. The location (e.g., cheek, pelvic fin, pectoral fin, anal fin) of the CWT, which was used to code for year class during initial stocking in the Ogeechee River, and number of the PIT tag were recorded. The fish was then placed ventral side up into a surgery cradle fitted to the top of a 48-quart cooler containing an aerated, sedative solution (70 mg/L) of buffered MS-222, which was pumped through the fish's gills during surgery (see Jennings and Shepard 2003). A surgical scalpel (No. 11 blade) was used to make a small (≤ 3 cm) midline incision just below the pectoral fins and a radio transmitter was implanted into the peritoneal cavity of the fish. The whip antenna was allowed to exit the fish's body through a small opening created by a hollow surgical needle about 4 cm below the incision. Ethicon® 2-0 PDS II suture material with a FS-1 reverse cutting needle was used to close the incision with 3–4 interrupted sutures. The surgical procedure for each robust redhorse took about 6 minutes to complete. After surgery, tagged individuals were monitored in a separate recovery tank for 15–30 minutes prior to release.

Fish Relocation and Environmental Data Collection

Radio-tagged robust redhorse were monitored by boat weekly to bi-weekly for 16 months and then monthly for the remaining 10 months of the study except during spawning season (May), when tagged fish were relocated multiple days a week. If any of the tagged fish could not be relocated in the lower Oconee River, then tracking was extended upstream into the Ocmulgee River and along the entire length of the Altamaha River. Two separate 24-hr tracking events (15–16 April 2009, 21–22 October 2009) also were conducted; during each event, three to four individuals were relocated every 2 hours over a continuous 24-hr period. Night tracking during the October event was temporarily interrupted because of dense fog, which rendered navigation hazardous.

An ATS R2100 scanning radio receiver with a tunable loop antenna was used to relocate study fish. Once a fish had been detected, tracking continued in the direction of the strongest signal. When the signal reached its peak, the loop antenna was replaced with a less-sensitive, lower-gain, 18-cm straight antenna, then with a weaker 5-cm straight antenna until the strongest signal was observed. At this point, the antenna was removed. The specific location of a fish was determined when the boat was positioned directly over a tagged fish; this positioning allowed for the strongest, omnidirectional signal to be observed without the use of an antenna. Once a transmitter's position had been confirmed within about ± 1.5 m, a Garmin® high-sensitivity, handheld, WAAS (Wide Area Augmentation System)-enabled GPS receiver (Garmin International Inc., Olathe, Kansas) was used to record the location (latitude, longitude; accuracy ± 3 m) of the fish. Prior to data analysis, ArcGIS® 9.3.1 mapping software (Environmental Systems Research Institute, Redlands, California) was used to convert GPS positions (latitude, longitude) into river kilometers (rkm). Depth, current velocity, water temperature, dissolved oxygen (DO), turbidity, dominant cover type, and substrate composition were recorded at fish relocations[1]. Dominant cover was classified as woody debris, rocks (> 256 mm), or none (i.e., no cover). Substrate composition was classified as muddy (< 0.06 mm), sandy (0.06–2.00 mm), or rocky (2.00–256 mm).

Data Analysis

Time period movement patterns

Methods similar to those of Grabowski and Isely (2006) and Grabowski and Jennings (2009) were used to determine movement patterns of radio-tagged robust redhorse. Movement patterns were grouped into time periods (n=5) based on calendar month and the migratory behavior of tagged robust redhorse. They were: 1) Summer (July – August); 2) Fall (September – November); 3) Winter (December – February); 4) Pre-spawn (March – April); and 5) Spawning/ Post-spawn (May – June). For every individual, absolute distance moved, displacement, and linear home range were calculated for each time period. Absolute distance moved was defined as the sum of the distance moved between relocations without regard to direction and was calculated as $\left| P_{t+1} - P_t \right|$, where P_t is an individual's position in rkm at time t and P_{t+1} is the same individual's position at time $t+1$. Displacement, defined as the net distance moved, was calculated as $P_{t+1} - P_t$, where upstream movements were designated as positive integers and downstream movements were designated as negative integers (Grabowski and Jennings 2009). Time period absolute movement and displacement were calculated by summing each individual's movements for each time period. Linear home range was defined as the distance between the most upstream and most downstream location in rkm for an individual within a time period (Grabowski and Isely 2006).

[1] Water quality and habitat data were not taken during the 24-hr tracking events to avoid influencing an individual's movement or behavior.

Shapiro–Wilk and Levene's tests were used, respectively, to determine whether data needed to calculate absolute distance moved, linear home range, and displacement were normally distributed and homoscedastic (Zar 1996). PROC RANK (SAS institute Inc. 2008) was used to rank transform movement data for absolute movement and linear home range, so parametric tests could be used for statistical analysis (Conover and Inman 1981; Hobbs 2009).

A mixed-model analysis of variance (ANOVA) was used to determine if absolute movement and linear home range differed among time periods (fixed effects) while controlling for individuals and year (random effects; Zar 1996). A Tukey–Kramer pair-wise comparison was used to determine differences among time-periods for both absolute movement and linear home range (SAS institute Inc. 2008). A non-parametric Kruskal–Wallis test was used to determine if mean displacement differed among time periods (Sokal and Rohlf 1995). Additionally, for each movement test, median values were calculated by time period and used to determine if the reported mean values were being skewed by variability among individual study fish.

Finally, absolute distance moved, displacement, and linear home range were used to describe 24-hr tracking events by month (October, April) and diel period (Day, Night). Median movement was not reported for 24-hr tracking data because of the limited number of individuals. A significance level (α) of 0.05 was used for all movement tests, and mean movements are reported with 95% confidence intervals (95% CI) unless otherwise noted.

Time period and directional habitat use/water quality

Methods similar to those of Grabowski and Jennings (2009) were used to determine habitat and water quality associations of radio-tagged robust redhorse.

Shapiro–Wilk and Levene's tests, respectively, were used to determine whether data needed to calculate mean depth, current velocity, temperature, dissolved oxygen (DO), and turbidity were normally distributed and homoscedastic (Zar 1996). PROC RANK (SAS institute Inc. 2008) was used to rank transform movement data for depth and current velocity so parametric tests could be used for statistical analysis (Conover and Inman 1981; Hobbs 2009). A mixed-model analysis of variance (ANOVA) was used to determine if mean depth and current velocity differed among time periods (fixed effects) while controlling for individuals and year (random effects; Zar 1996). Time period was used as a random effect when determining if depth and current velocity differed by direction (upstream or downstream) relative to the release location (Ball's Ferry Landing). A Tukey–Kramer pair-wise comparison was used to determine differences among time periods for both depth and current velocity (SAS institute Inc. 2008). A Kruskal–Wallis (non-parametric) test was used to determine if mean temperature, dissolved oxygen, and turbidity differed among time periods, and a Wilcoxon–Mann–Whitney (non-parametric) test was used to determine if those means differed by direction (upstream or downstream) relative to Ball's Ferry Landing (Sokal and Rohlf 1995). The amount of habitat (i.e., cover, substrate, depth, velocity) available to radio-tagged robust redhorse in the lower Oconee River was not assessed during this study. Therefore, all comparisons of habitat use are based only on instantaneous observations of tagged fish.

<u>Directionality</u>

Although rocky cover and substrate were present upstream of Ball's Ferry Landing and are the dominate cover and substrate type from Sinclair Dam to Hwy 22/24 in Milledgeville, there also appeared to be a considerable amount of rocky cover and substrate downstream of the release point (Ball's Ferry Landing), particularly near the city of Dublin, Georgia. Additionally, during time periods of limited movement, study fish generally were separated into two distinct groups; one group (i.e., ~75% of the study population) was located about 25 rkm upstream of Ball's Ferry Landing and the other group (i.e., the remaining ~25% of the study population) was located about 30 rkm downstream of Ball's Ferry Landing. Because of the distance and potential differences in available habitat we divided observations of radio-tagged robust redhorse into two groups based on their directional relationship to Ball's Ferry Landing (upstream or downstream) to see if there were any differences in habitat associations between the two.

A Pearson's chi-squared test was used to evaluate differences in substrate among time periods and by directionality (upstream or downstream) in relation to Ball's Ferry Landing. A Fisher's exact test and a Monte Carlo simulated Fisher's exact test were used to detect differences in cover type by directionality and time period, respectively (Sokal and Rohlf 1995; SAS institute Inc. 2008). A significance level (α) of 0.05 was used for habitat tests and means are reported with 95% confidence intervals (95% CI) unless otherwise noted.

Spawning versus non-spawning

Habitat associations were additionally separated into two spawning classification periods ("spawning" and "non-spawning"). The "spawning" period was delineated as May 1 – May 31 and was determined by the following criteria: 1) water temperatures were between 17–26.7°C (Freeman and Freeman 2001); 2) a majority of tagged fish had migrated toward areas with gravel substrate; and 3) some fish were found in close proximity to each other near gravel substrates in water velocities ≥ 0.2 m/s (EA 1994; Freeman and Freeman 2001). Robust redhorse were considered in the "non-spawning" period if all three of the criteria were not met (i.e., all other months besides May). For substrate comparisons between the spawning and non-spawning periods, rocky sediment (2–256 mm) was further separated into two size classes; gravel (2–64 mm) and cobble (64–256 mm). A mixed-model analysis of variance (ANOVA) was used to determine if depth and current velocity differed between spawning and non-spawning periods (fixed effects) while controlling for individuals and year (random effects; Zar 1996). A Pearson's chi-squared test and a Fisher's exact test were used to determine differences in substrate and cover, respectively, between the spawning and non-spawning periods (Sokal and Rohlf 1995). A significance level (α) of 0.05 was used for habitat tests and means are reported with 95% confidence intervals (95% CI) unless otherwise noted.

Annual home range

Kernel density estimates for tagged robust redhorse were calculated for the first year of the study (July 2008 – June 2009) by using a similar procedure described by Vokoun (2003). In an effort to maintain a reasonable sample size while decreasing autocorrelation caused by the variability of the tracking schedule; we only used fish that had $\geq$ 25 relocations with a minimum sampling interval of 5 days in the analysis (Otis and White 1999; Malindzak 2006). The location coordinates taken for each fish were imported into ArcMap 9.3.1 software. ArcMap 9.3.1 and digital aerial photographs from 2007–2009 were used to create a line that traced the middle of the river channel from Sinclair Dam down to the confluence. Reference points were distributed every 10 m along the entire river line and each fish location was rounded to the nearest 10-m reference point. The referenced fish locations were then exported into SAS 9.1 where kernel density estimates of home range were calculated with the Kernel Density Estimation procedure (i.e., PROC KDE). Bandwidth was selected using the Sheather–Jones plug-in method (Jones et al. 1996; Vokoun 2003), and grid points were set at 10-

unit intervals corresponding to the 10-m reference points. The utilization distribution (i.e., UD), which is a delineated distance that has a defined probability of an individual's occurrence (i.e., percentage of time spent) during a particular time period (White and Garrott 1990; Vokoun 2003), was specified to output the 99%, 95%, 90%, and 50% level home range estimates. The 50% level UD estimate has been referred to as an animal's core area and is the area in which an animal has been estimated to spend 50% of its time during the period of interest (Blundell et al. 2001). The annual linear home range was also calculated for each fish and was defined as the distance between the most upstream and downstream locations along the river line (Logan 1963; Vokoun 2003).

RESULTS

Between 23 April 2008 and 02 July 2010, there were 999 relocations of radio-tagged robust redhorse released into the lower Oconee River, Georgia. All transmitters were relocated at least three times during the study, and live individuals were relocated from 3 to 72 times. Each fish was relocated an average of 31 (95% CI = 23–40) times.

Time Period Movement Patterns

Absolute movement

Mean absolute movement during the fall, pre-spawn and spawning/post-spawn time periods were similar to each other (mean range = 41.7–58.6 rkm) but significantly higher than during the summer (8.8 ± 6.7 rkm; mean ± 95% CI) and winter (9.0 ± 5.0 rkm; mean ± 95% CI) periods ($t_{88} \leq 8.41$; $P < 0.0001$; Figure 3). Median absolute movement (median range = 2.0–40.8 rkm) was 23–72% smaller than mean absolute movement (mean range = 8.8–58.6 rkm) throughout the study.

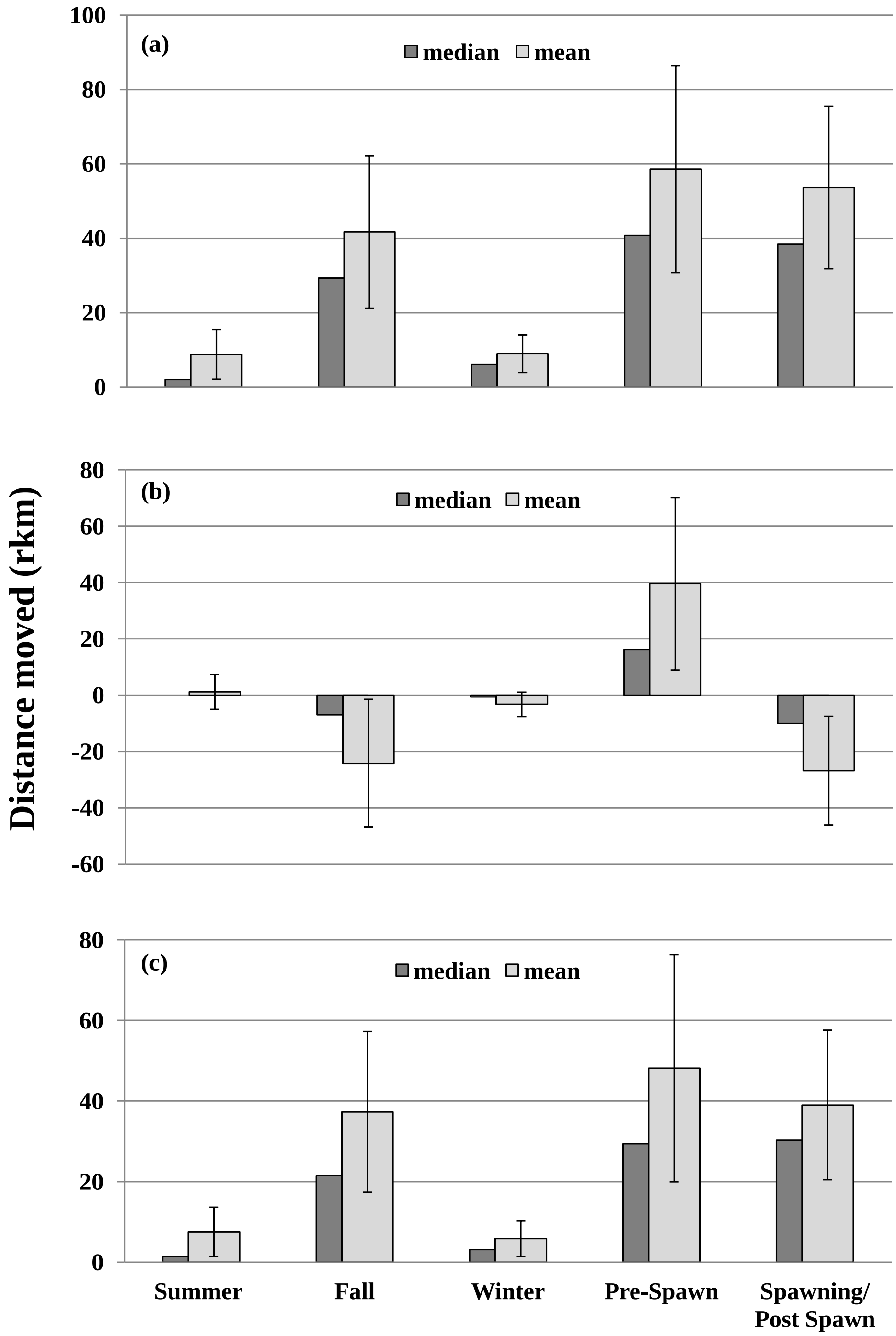


Figure 3. Mean (± 95% CI) and median time period; (a) absolute movement, (b) displacement, and (c) linear home range of radio-tagged robust redhorse in the lower Oconee River, Georgia, from July 2008 to June 2010.

Linear home range

Similar to absolute movement, mean linear home range during the fall, pre-spawn and spawning/post-spawn time periods were similar to each other (mean range = 37.3–48.2 rkm) but significantly higher than during the summer (7.5 ± 6.1 rkm; mean ± 95% CI) and winter (5.9 ± 4.5 rkm; mean ± 95% CI) periods ($t_{88} \leq 8.04$; $P < 0.0001$; Figure 3). Median linear home range (median range = 1.4–30.3 rkm) was 18–78% smaller than mean linear home range (mean range = 5.9–48.2 rkm) throughout the study.

Displacement

Displacement varied among time periods ($H = 33.1$; d.f. = 4; $P < 0.0001$) with the largest upstream movements having occurred during the pre-spawning period (39.6 ± 30.6 rkm; mean ± 95% CI); whereas, the largest downstream movements were observed during the spawning/post spawn (-26.8 ± 19.3 rkm; mean ± 95% CI) and fall (-24.2 ± 22.7 rkm; mean ± 95% CI) time periods (Figure 3). Mean displacement observed during the summer (1.2 ± 6.2 rkm; mean ± 95% CI) and winter (-3.2 ± 4.3 rkm; mean ± 95% CI) periods were limited. Median displacement (median range = -10.1–16.3 rkm) was 0–41% smaller than mean displacement (mean range = -26.8–39.6 rkm) throughout the study.

24-hr tracking

From 15 to 16 April 2009, four live radio-tagged robust redhorse were relocated about once every 2 hrs for 24 continuous hours; there was a total of 51 relocations with three individuals relocated 13 times and the other individual relocated 12 times. From 21 to 22 October 2009, three live individuals were relocated about once every 2.6 hrs for 24 continuous hours; there was a total of 29 relocations with two individuals relocated 10 times and the other individual relocated 9 times.

In April, absolute movement averaged 1.3 rkm (95% CI = 0.0–3.4 rkm) at night and 6.1 rkm (95% CI = 0.0–12.3 rkm) during the day (Figure 4). Similarly, linear home range averaged 0.5 rkm (95% CI = 0.0–1.3 rkm) at night and 5.1 rkm (95% CI = 0.0–11.5 rkm) during the day; displacement averaged 0.6 rkm (95% CI = -0.7–1.9 rkm) at night and 4.2 rkm (95% CI = -3.4–11.8 rkm) during the day (Figure 4). Two of the four fish moved upstream about 9.5–10.0 rkm during daylight hours (Figure 5). Of the remaining two fish, one sedentary robust redhorse demonstrated limited absolute movement throughout the 24-hr study period and the other fish exhibited limited displacement by going upstream and then returning back to its original spot (Figure 5).

In October, absolute movement averaged 0.2 rkm (95% CI = 0.0–0.5 rkm) at night and 0.4 rkm (95% CI = 0.0–1.2 rkm) during the day (Figure 4). Similarly, linear home range averaged 0.1 rkm (95% CI = 0.0–0.3 rkm) at night and 0.3 rkm (95% CI = 0.0–0.8 rkm) during the day; displacement averaged 0.0 rkm (95% CI = -0.1–0.1 rkm) at night and 0.1 rkm (95% CI = -0.5–0.7 rkm) during the day (Figure 4). Two fish made small localized moments during the day, but without obvious directional displacement and the remaining fish was mostly sedentary throughout the 24-hr study period (Figure 5).

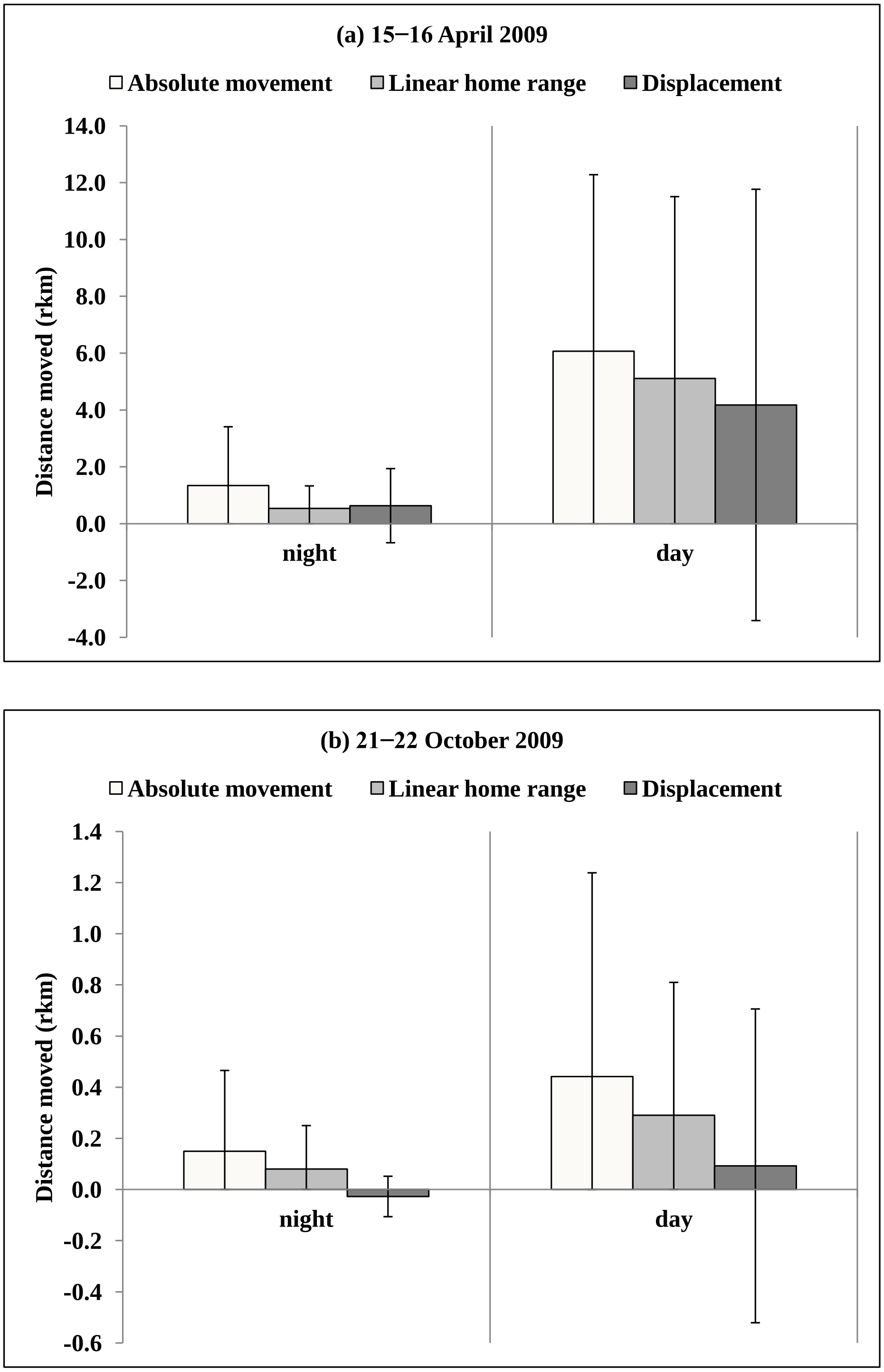
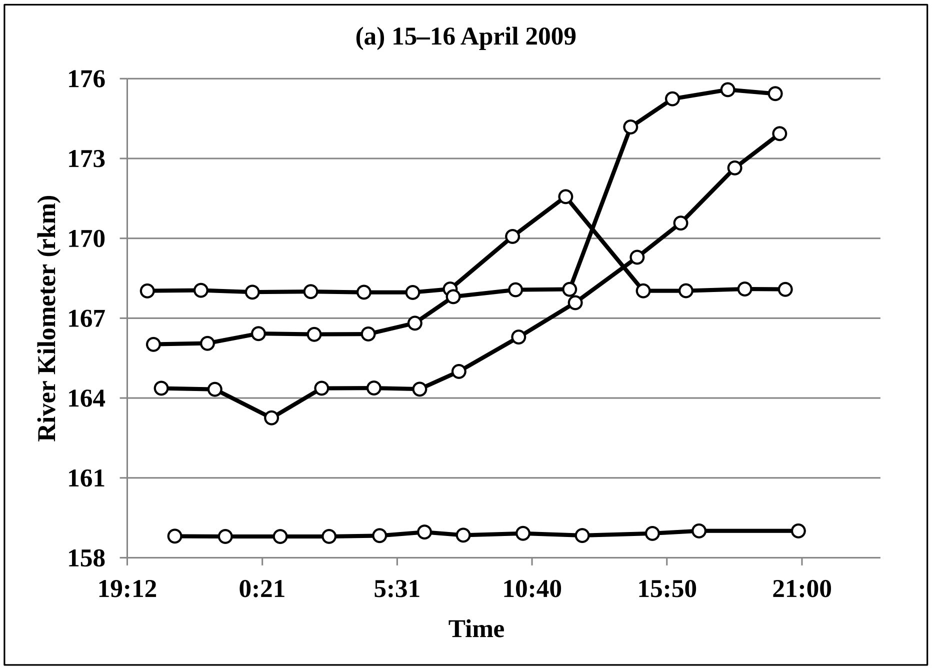


Figure 4. Mean (± 95% CI) 24-hour absolute movement, linear home range, and displacement for radio-tagged robust redhorse in the lower Oconee River, Georgia, on (a) 15–16 April 2009 and (b) 21–22 October 2009.



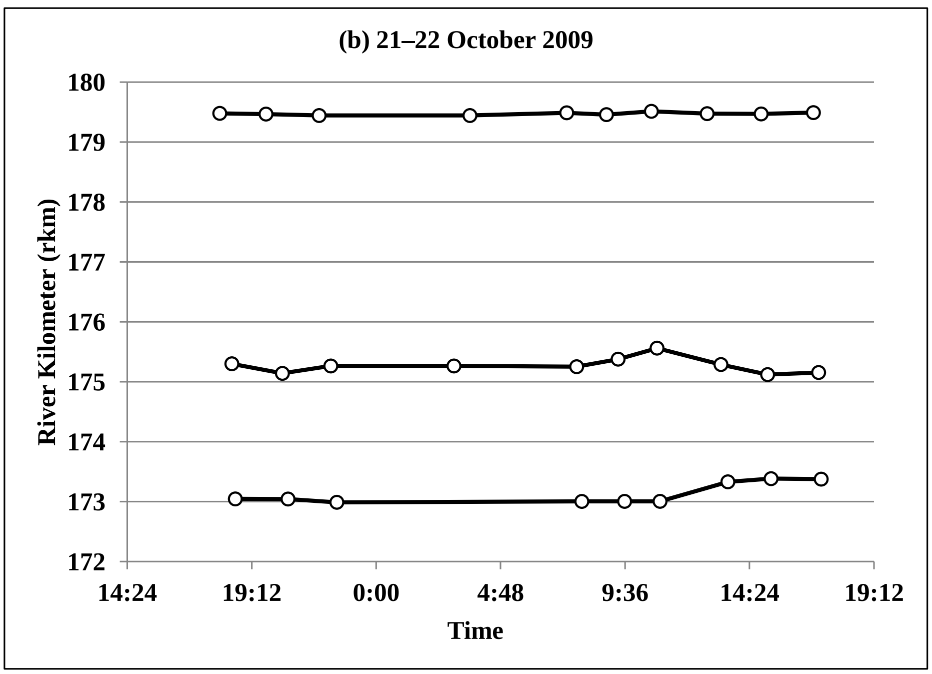


Figure 5. Relocations (rkm) of individual radio-tagged robust redhorse in the lower Oconee River, Georgia, tracked over a 24-hour period during (a) 15–16 April 2009 and (b) 21–22 October 2009.

Time Period and Directional Habitat Use/Water Quality

Depth

Radio-tagged robust redhorse were relocated in similar shallow depths during the summer (1.8 ± 0.1 m; mean ± 95% CI) and fall (2.0 ± 0.2 m; mean ± 95% CI) periods but were located in significantly deeper water (3.4 ± 0.4 m; mean ± 95% CI) during the pre-spawning period compared to all other time periods ($t_{85} \leq 8.40$; $P \leq 0.0051$; Table 1). Mean water depth was not related to directionality upstream or downstream of Ball's Ferry Landing ($F_{1,32} = 0.08$; $P = 0.7788$; Table 1). In general, robust redhorse appeared to favor deep water regardless of time period.

Current velocity and water quality

Current velocities occupied by radio-tagged robust redhorse during the summer (0.22 ± 0.03 m/s; mean ± 95% CI) and fall (0.22 ± 0.07 m/s; mean ± 95% CI) periods were similar to each other but significantly lower than all other time periods (mean range = 0.54–0.68 m/s) ($t_{84} \leq 11.53$; $P < 0.0001$; Table 1). Mean current velocity was not related to directionality upstream or downstream of Ball's Ferry Landing ($F_{1,31} = 0.86$; $P = 0.3611$). Mean temperature (mean range = 10.9–30.2^{o}C), dissolved oxygen (mean range = 7.4–9.5 mg/l), and turbidity (mean range = 12.6–51.6 ntu) varied among different time periods ($H \leq 342.0$, d.f.= 4; $P < 0.0001$; Table 1), but did not differ by directionality upstream or downstream of Ball's Ferry Landing ($z \leq 0.14$; $P \geq 0.0672$).

Table 1. Mean (± 95% CI) and range (minimum, maximum) of environmental measurements for robust redhorse relocations and the directionality of individuals located upstream or downstream of Ball's Ferry Landing according to time period from July 2008 to June 2010.

Time Period	Depth (m)	Current Velocity (m/s)	Temperature (°C)	DO (mg/l)	Turbidity (ntu)	Directionality	
						Upstream	Downstream
Summer (July – Aug)	1.8	0.22	30.2	7.4	13.0	84% (n=21)	16% (n=4)
	(± 0.1)	(± 0.03)	(± 0.3)	(± 0.3)	(± 1.3)		
	0.5	-0.08	24.1	5.6	3.0		
	3.5	0.75	34.0	9.8	33.5		
Fall (Sept – Nov)	2.0	0.22	20.9	8.5	12.6	64% (n=14)	36% (n=8)
	(± 0.2)	(± 0.07)	(± 1.8)	(± 0.5)	(± 2.8)		
	0.5	-0.04	10.0	5.0	3.0		
	4.0	0.88	34.5	10.2	41.1		
Winter (Dec – Feb)	2.5	0.54	10.9	9.5	22.2	61% (n=11)	39% (n=7)
	(± 0.2)	(± 0.07)	(± 0.5)	(± 0.2)	(± 1.9)		
	0.8	0.00	7.0	8.1	10.2		
	5.0	1.20	16.4	11.3	50.5		
Pre-Spawn (March – April)	3.4	0.68	15.9	8.7	51.6	94% (n=16)	6% (n=1)
	(± 0.4)	(± 0.09)	(± 0.6)	(± 0.3)	(± 5.8)		
	0.8	0.10	11.0	7.4	14.1		
	5.3	1.21	21.3	12.5	85.0		
Spawning/Post Spawn (May – June)	2.6	0.65	24.7	7.4	34.6	71% (n=10)	29% (n=4)
	(± 0.2)	(± 0.05)	(± 0.5)	(± 0.1)	(± 1.9)		
	1.0	0.00	19.2	5.8	9.1		
	4.6	1.45	32.6	9.5	58.1		

Cover

During all time periods, regardless of directionality (upstream or downstream) to Ball's Ferry Landing, robust redhorse were primarily associated with woody debris (78.2%; Figure 6). Lack of cover (18.7%) and rocks (3.0%) were the second and third most observed cover types, respectively (Figure 6). The type of cover robust redhorse were associated with varied among time periods ($\chi^2 = 39.0$; d.f. = 8; $P < 0.0001$) and tagged fish were more often located in areas without cover during the pre-spawn (25.3%) and spawning/post-spawn (33.1%) periods, compared to all other time periods (range = 10.3–12.6%; Figure 7). Fish located downstream of Ball's Ferry Landing were more likely to be associated with rocky cover (13.5%) than upstream fish (0.6%) ($\chi^2 = 57.9$; d.f. = 2; $P < 0.0001$; Figure 6).

Substrate

For all time periods, regardless of directionality to Ball's Ferry Landing, robust redhorse were detected primarily over sandy substrates (59.9%; Figure 6). The type of substrate robust redhorse were associated with varied among time periods ($\chi^2 = 28.7$; d.f. = 8; $P = 0.0004$) and tagged fish were less likely to be detected over muddy substrate during the pre-spawn (16.7%) and spawning/post-spawn (14.9%) periods, compared to all other time periods (range = 25.6–30.4%; Figure 7). Robust redhorse were more likely to be associated with rocky substrate during the fall, pre-spawning, and spawning/post spawn time periods (range = 21.6–29.2%) as compared to the summer (11.6%) and winter (13.8%) periods (Figure 7). Study fish located downstream of Ball's Ferry Landing were more likely to be found over rocky substrate (35.6%) than upstream fish (13.6%) ($\chi^2 = 42.3$; d.f. = 2; $P < 0.0001$; Figure 6).

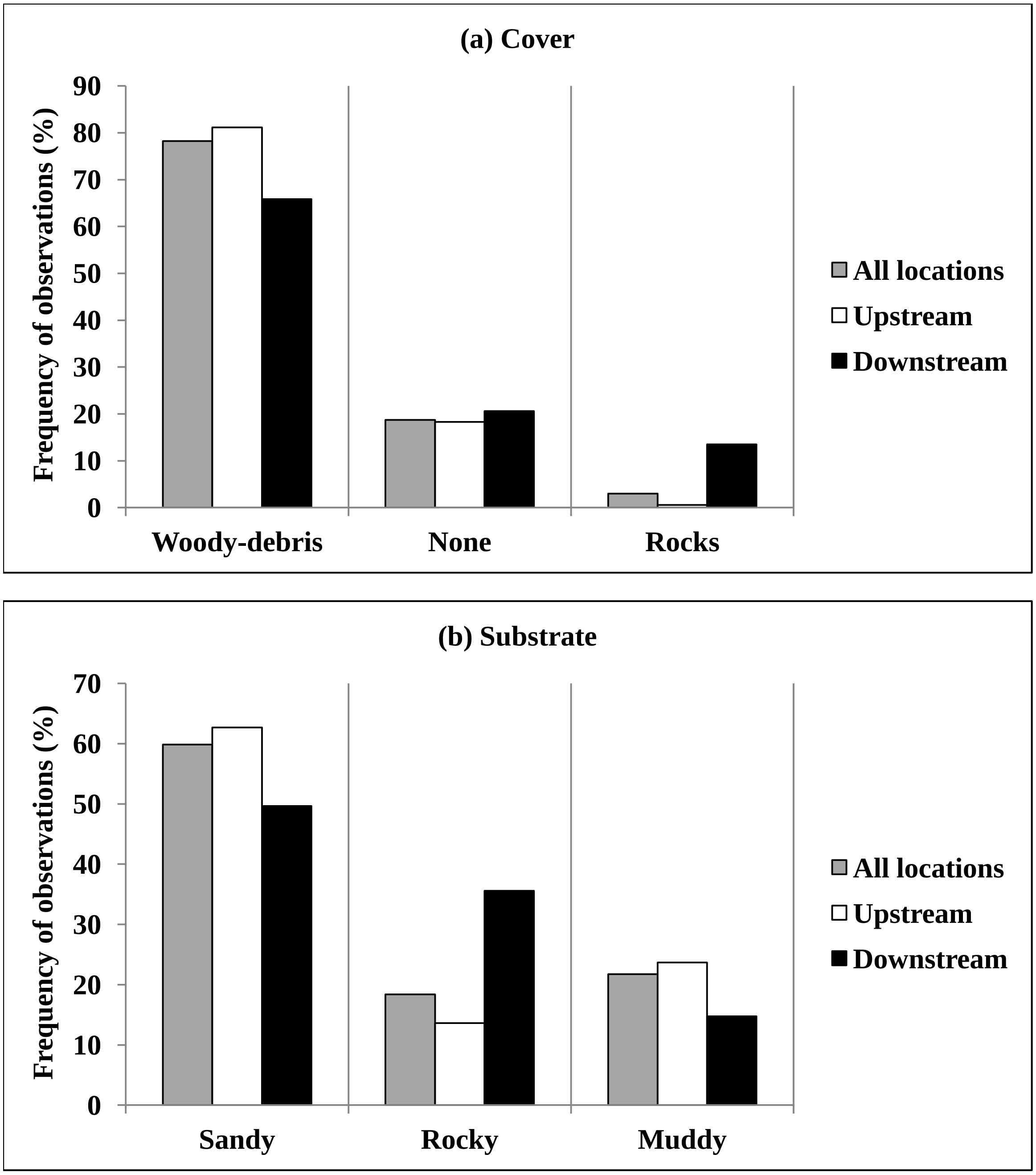


Figure 6. Frequency of radio-tagged robust redhorse locations from July 2008 to June 2010 associated with (a) cover (woody-debris, none, rocks) and (b) substrate (sandy, rocky, muddy) in the lower Oconee River, Georgia, as well as locations that are either upstream or downstream relative to Ball's Ferry Landing.

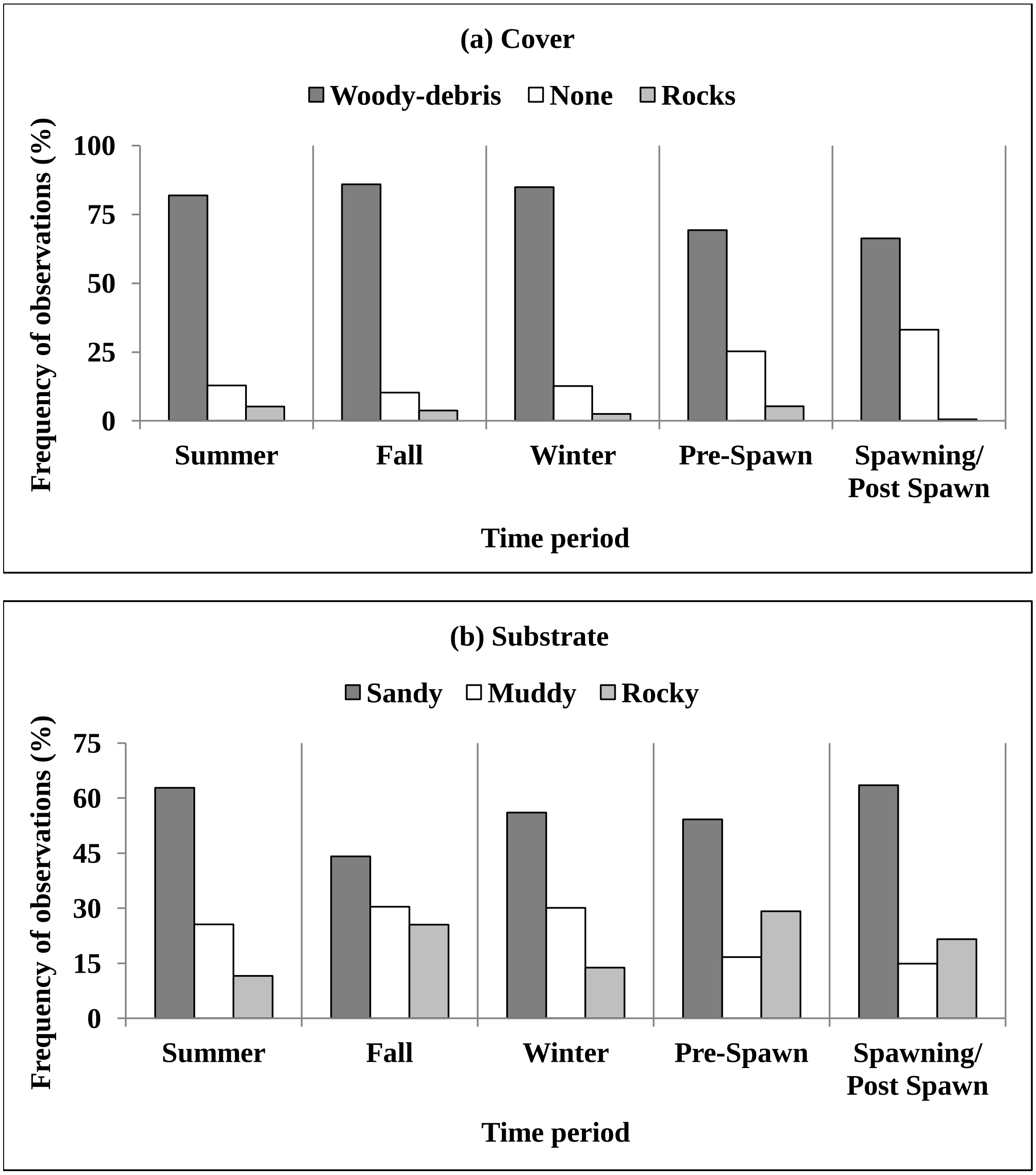


Figure 7. Time period frequency of radio-tagged robust redhorse locations associated with (a) cover type (woody-debris, none, rocks) and (b) substrate (sandy, muddy, rocky) in the lower Oconee River, Georgia, from July 2008 to June 2010.

Spawning versus non-spawning

During the spawning season (May) of 2009, radio-tagged robust redhorse migrated toward the Avant Mine site and occupied the area between Black Creek (rkm ~ 175) and rkm ~ 195 (Figure 8). None of the tagged fish were located at the historic Avant Mine gravel bar; however, an aggregate of tagged fish was located about 1.4 rkm upstream in an oxbow cut through (Figure 9). Within 0.2 km of the cut through, 50% of live individuals (7 of 14) were located at least once during the spawning season, and three of those fish were relocated multiple times (range = 2–5). Eighty-six percent of those individuals (6 of 7) located within 0.2 km of the cut through, were located over gravel substrate at least once, and four of those fish were relocated over gravel multiple times (range = 2–4; Figure 9). Additionally in May 2009, seven radio-tagged robust redhorse were located at least once, and four of those were relocated multiple times (range = 2–3) in a 1-km stretch of river about 2 rkm downstream of the Avant Mine gravel bar (Figure 10). Fifty-seven percent (4 of 7) of those individuals were located over gravel substrate once during the spawning period (Figure 10).

During the 2010 spawning season (May), none of the remaining fish (n=3) were relocated in the cut through area, and sandy substrate was detected at locations that contained gravel substrate the previous spawning season. However in May 2010, two of the three remaining tagged fish were detected in that same 1-km stretch of river located about 2 rkm downstream of the Avant Mine gravel bar and one of those individuals was relocated over gravel substrate (Figure 10).

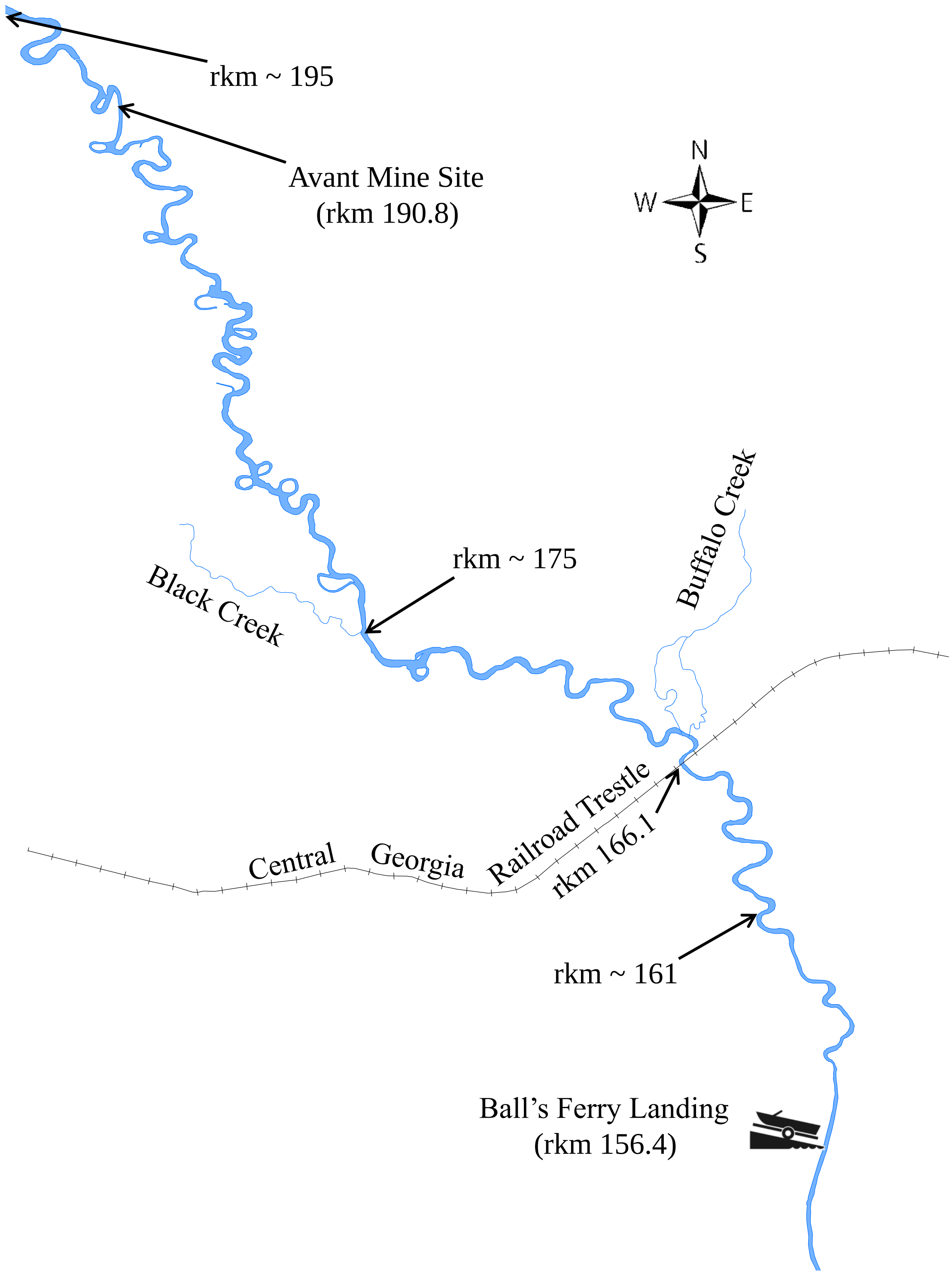


Figure 8. Map of the study area on the lower Oconee River, Georgia, from Ball's Ferry Landing at rkm 156.4 to rkm ~ 195.

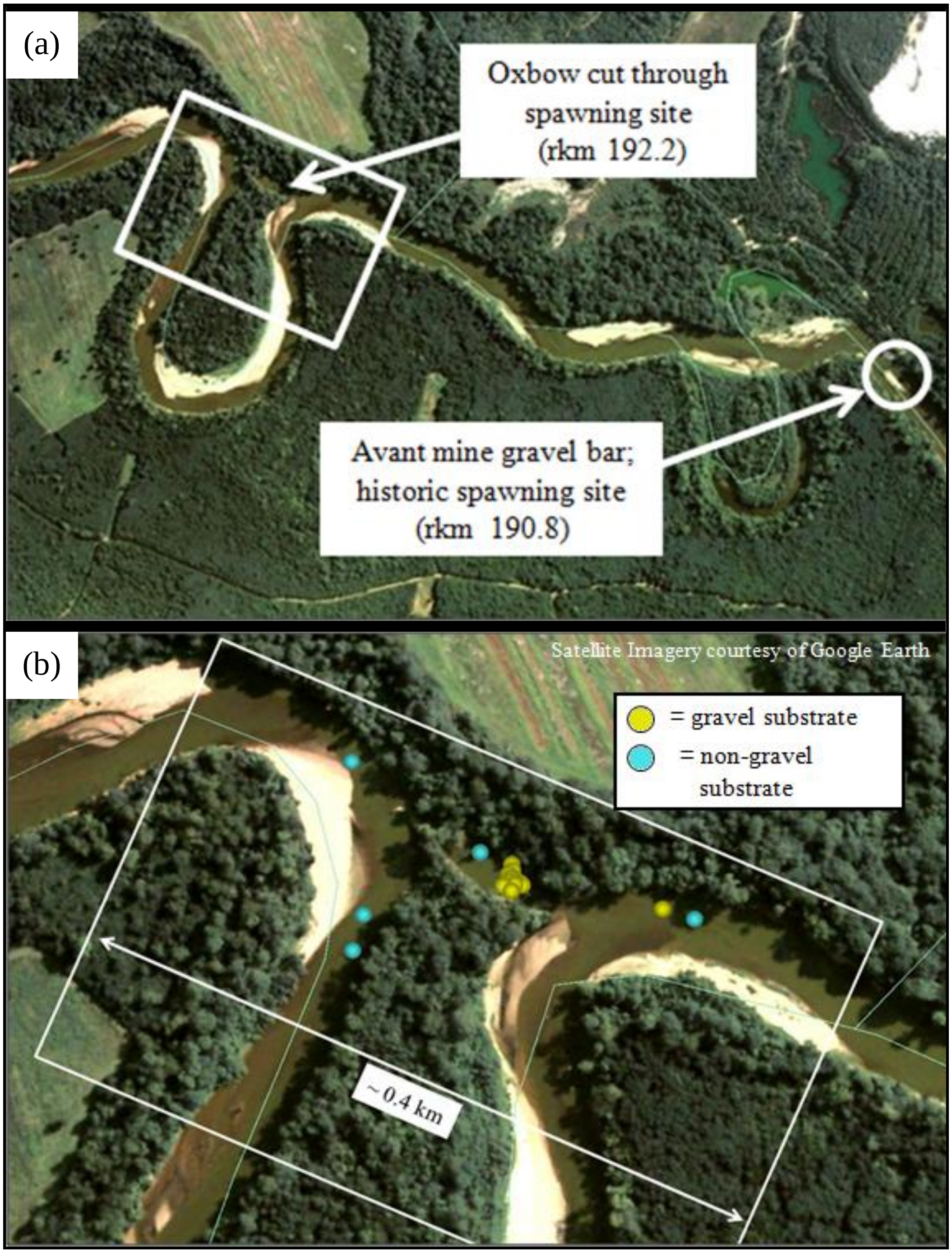


Figure 9. Satellite image of; (a) the oxbow cut through spawning location in relation to the historic Avant Mine gravel bar and (b) the oxbow cut through during the spawning period of 2009, where the yellow dots indicate relocations of radio-tagged robust redhorse over gravel substrate and blue dots indicate relocations over non-gravel substrate.

Figure 10. Satellite image of the downstream spawning locations of radio-tagged robust redhorse in relation to the historic Avant Mine gravel bar. Yellow dots indicate relocations of tagged individuals over gravel substrate and blue dots indicate relocations over non-gravel substrate during the 2009 and 2010 spawning periods (combined).

Cover

The type of cover radio-tagged robust redhorse were associated with was significantly different between the spawning and non-spawning time periods ($\chi^2 = 37.7$; d.f. = 2; $P < 0.0001$), as encounters were more frequent near woody debris during the non-spawning period (82.3%) than during the spawning period (63.5%; Figure 11). Additionally, tagged fish were more likely to be located in an area without cover during the spawning period (35.8%) than during the non-spawning period (14.0%; Figure 11).

Substrate

The type of substrate radio-tagged fish were associated with was significantly different between the spawning and non-spawning time periods ($\chi^2 = 32.7$; d.f. = 3; $P < 0.0001$); robust redhorse were more likely to be located over muddy substrate during the non-spawning period (26.2%) than during the spawning period (7.9%; Figure 11). Also, during the spawning period, study fish were more likely to be located over gravel substrate (19.5%) than during the non-spawning period (9.8%; Figure 11).

Depth and Velocity

Radio-tagged robust redhorse were located in similar water depths during the spawning (2.4 ± 0.2 m; mean ± 95% CI) and non-spawning (2.2 ± 0.1 m; mean ± 95% CI) periods ($F_{1,45} = 2.39$; $P = 0.1294$). In general, robust redhorse were located in water depths between 1–3 m throughout the study (Figure 12). The mean current velocity in which radio-tagged robust redhorse were located was significantly higher during the spawning period (0.69 m/s ± 0.04 m/s; mean ± 95% CI) than during non-spawning (0.38 m/s ± 0.03 m/s; mean ± 95% CI) ($F_{1,44} = 114.48$; $P < 0.0001$; Figure 13). During the

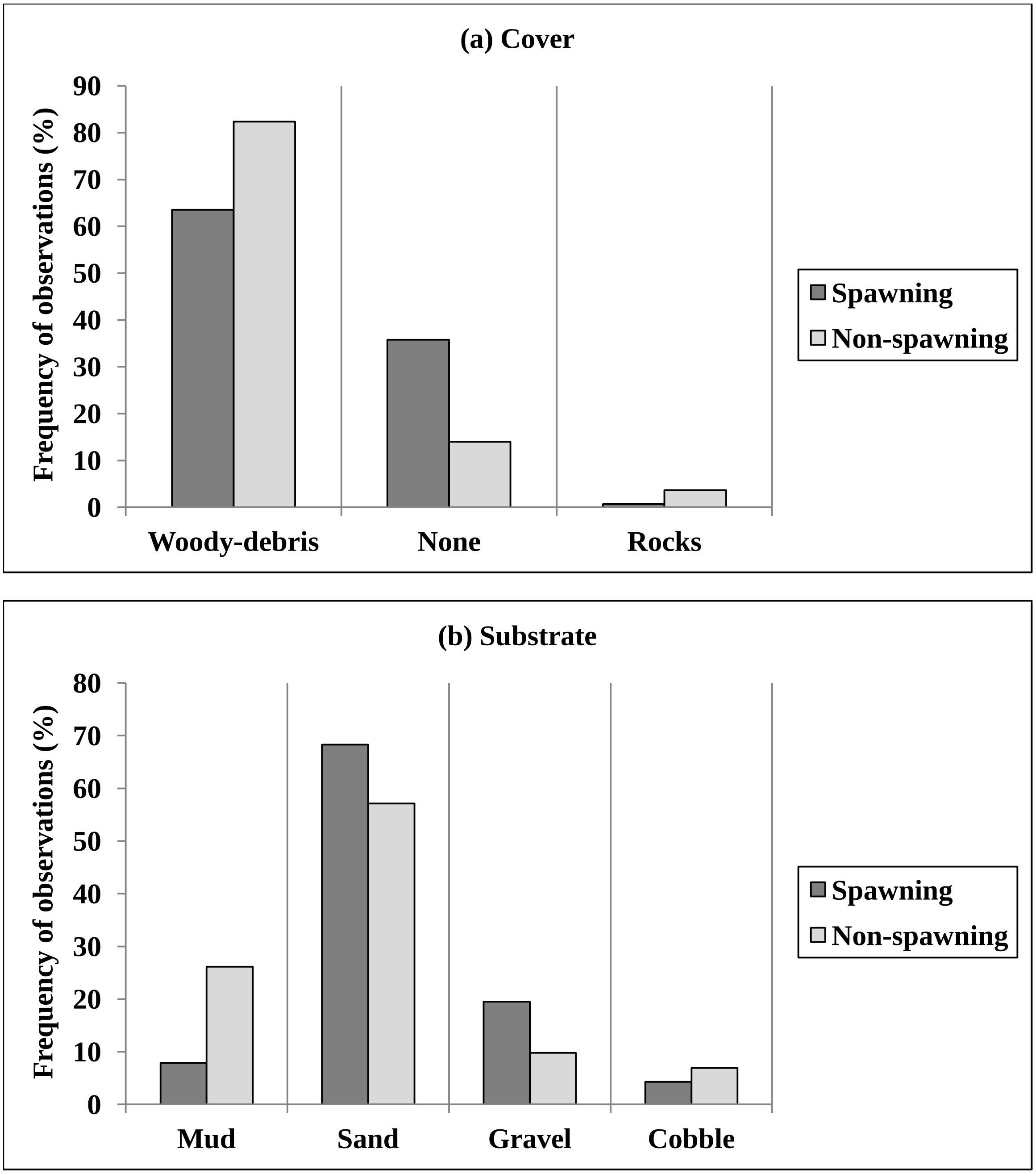


Figure 11. Frequency of radio-tagged robust redhorse locations associated with (a) cover type (woody-debris, none, rocks) and (b) substrate (mud, sand, gravel, and cobble) in the lower Oconee River, Georgia, during the spawning and non-spawning periods.

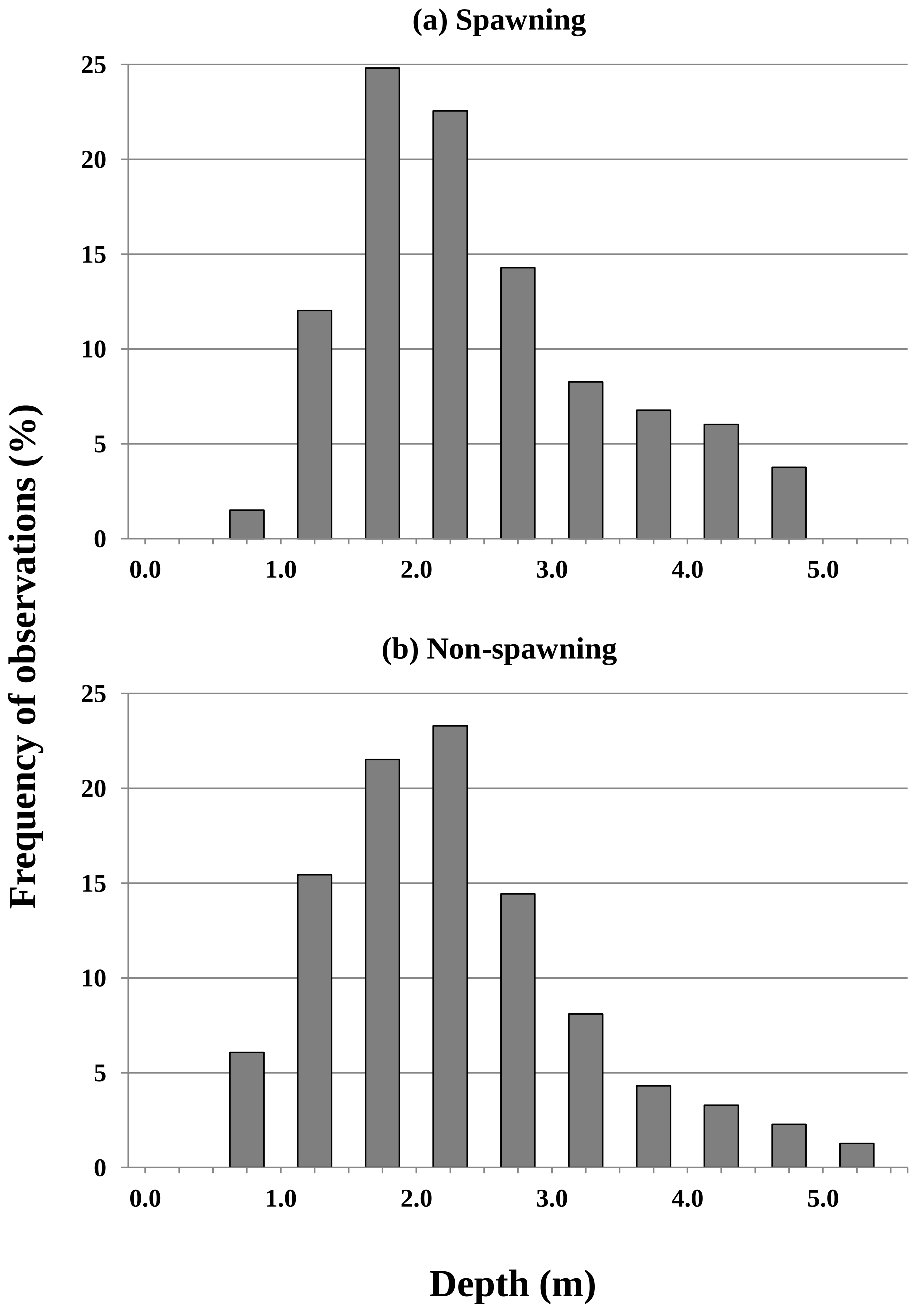


Figure 12. Frequency distribution of observed depths (m) at locations of radio-tagged robust redhorse in the lower Oconee River, Georgia, during the (a) spawning period and (b) non-spawning period.

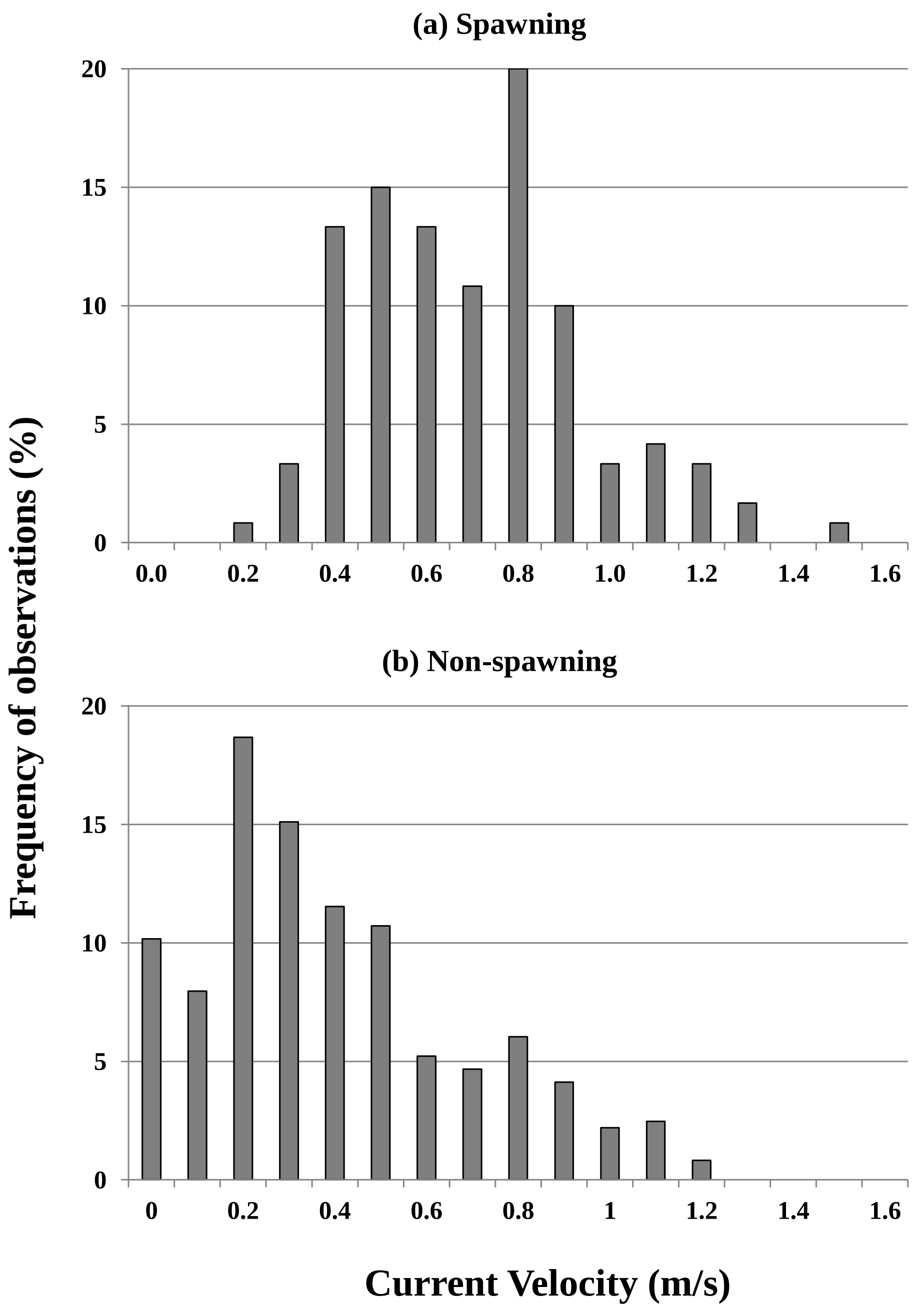


Figure 13. Frequency distribution of observed current velocities (m/s) at locations of radio-tagged robust redhorse in the lower Oconee River, Georgia, during the (a) spawning period and (b) non-spawning period.

spawning period, robust redhorse were mostly found in water velocities between 0.4–0.9 m/s and during the non-spawning period, fish were mostly located in water velocities between 0–0.5 m/s (Figure 13). Radio-tagged robust redhorse tended to occupy areas with flowing water regardless of time period but periodically targeted swifter currents during the spawning season.

Annual Home Range

Annual linear home range estimates for robust redhorse (n=12) averaged 57.3 rkm in size and ranged from 25.6 to 138.3 rkm; the 99% kernel estimate of home range was slightly larger (~ 4.9 rkm) than the linear home range for all fish (Table 2). Overall, mean kernel density estimates were similar for each individual at the 95% and 90% levels. The 50% level core estimates averaged 12.7 rkm but ranged widely from 2.3 to 43.4 rkm; the size of the 50% level core estimates did not appear to be related to the size of the linear ranges (Table 2). The mean upper (rkm 202) and lower (rkm 140) limits of the 99% level estimates were slightly larger than the mean linear range estimates (upper = rkm 199, lower = rkm 142; Table 3). The mean limits of the 95% (upper = rkm 199, lower = rkm 155) and 90% (upper = rkm 199, lower = rkm 156) level estimates were similar to each other but larger than the mean limits of the 50% (upper = rkm 184, lower = rkm 171) level core estimates (Table 3). Seven fish (n=12) had 100% and one fish had approximately 75% of their respective core areas (50% kernel density estimates) fall between the Avant Mine site (rkm ~191) and the Central Georgia Railroad Trestle (CGRT; rkm ~166) (examples; figure 14 and 15).

Table 2. Annual home range size estimates for radio-tagged robust redhorse with at least 25 relocations (n=12) in the lower Oconee River, Georgia, from July 2008 to June 2009. Linear range is the distance in river kilometers (rkm) between the most upstream and downstream relocations for each individual fish. Kernel density estimates for the 99%, 95%, 90%, and 50% levels represent utilization distributions at that specified percentage.

		Home range (rkm)				
Transmitter frequency	Number of relocations	Linear	99% kernel	95% kernel	90% kernel	50% kernel
40.011	25	138.3	145.3	36.4	33.8	10.1
40.091	26	56.2	72.7	70.3	70.0	14.3
40.141	33	44.7	49.8	49.7	49.1	2.8
40.630	26	73.3	83.8	81.3	81.0	8.0
40.641	34	43.3	44.9	41.6	41.4	11.3
40.661	36	52.5	53.9	20.2	19.3	5.6
40.671	34	26.2	29.2	28.2	27.7	3.4
40.681	34	25.6	27.5	25.0	24.6	18.1
40.771	33	77.0	78.3	36.8	34.6	28.6
40.791	33	43.1	45.4	28.3	27.8	4.0
40.821	28	74.1	78.5	75.5	74.4	43.4
41.233	34	33.0	37.4	37.4	36.4	2.3
Mean	31	57.3	62.2	44.2	43.3	12.7

Table 3. Annual home range boundary estimates (~ rounded) for radio-tagged robust redhorse (n=12) in the lower Oconee River, Georgia, from July 2008 to June 2009. Linear range is the river kilometer (~ rkm) associated with the most upstream (Upper) and downstream (Lower) relocations for each individual fish. Kernel density range estimates for the 99%, 95%, 90%, and 50% levels represent the estimated upstream (Upper) and downstream (Lower) utilization distribution locations (rkm) at that specified percentage.

			Kernel density estimate (~ rkm)							
Transmitter frequency	~ Linear		~ 99%		~ 95%		~ 90%		~ 50%	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
40.011	222	84	229	84	227	190	226	192	219	209
40.091	217	161	226	153	224	154	224	154	219	205
40.141	184	139	186	137	186	137	186	137	184	181
40.630	193	120	198	114	197	115	196	115	135	127
40.641	210	166	211	166	210	168	210	168	182	171
40.661	192	140	194	140	194	173	193	174	182	176
40.671	192	166	194	165	193	165	193	165	170	166
40.681	192	167	194	167	194	169	193	169	189	171
40.771	193	116	195	116	193	156	192	158	190	162
40.791	209	166	209	164	193	164	192	164	179	175
40.821	194	120	194	115	192	116	191	116	164	121
41.233	190	157	193	155	193	155	192	156	190	188
Mean	199	142	202	140	199	155	199	156	184	171

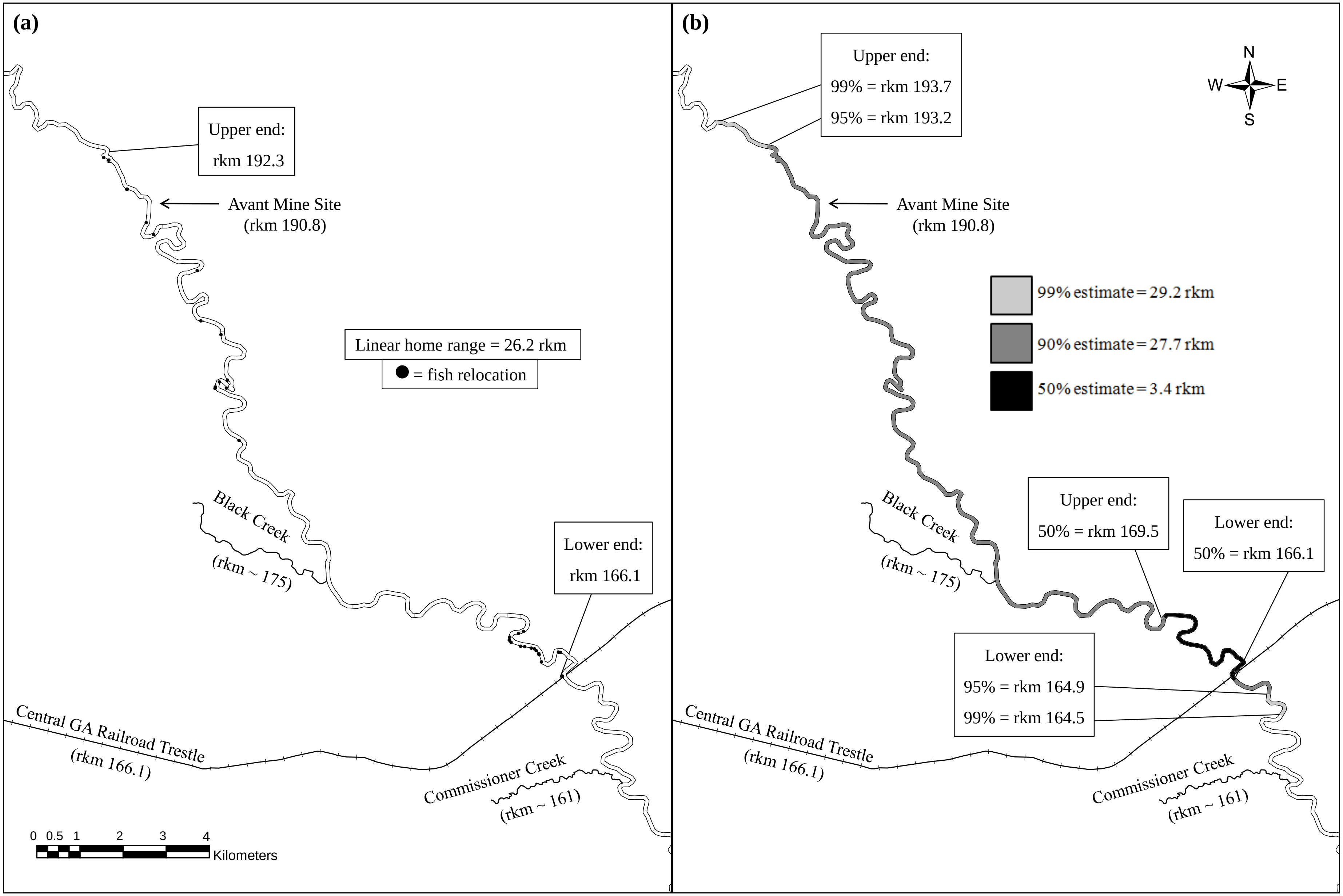


Figure 14. (a) Distribution of relocation points and corresponding linear home range; and (b) corresponding 99%, 90%, and 50% kernel density estimates for robust redhorse transmitter frequency 40.671 in the lower Oconee River, Georgia, from July 2008 to June 2009.

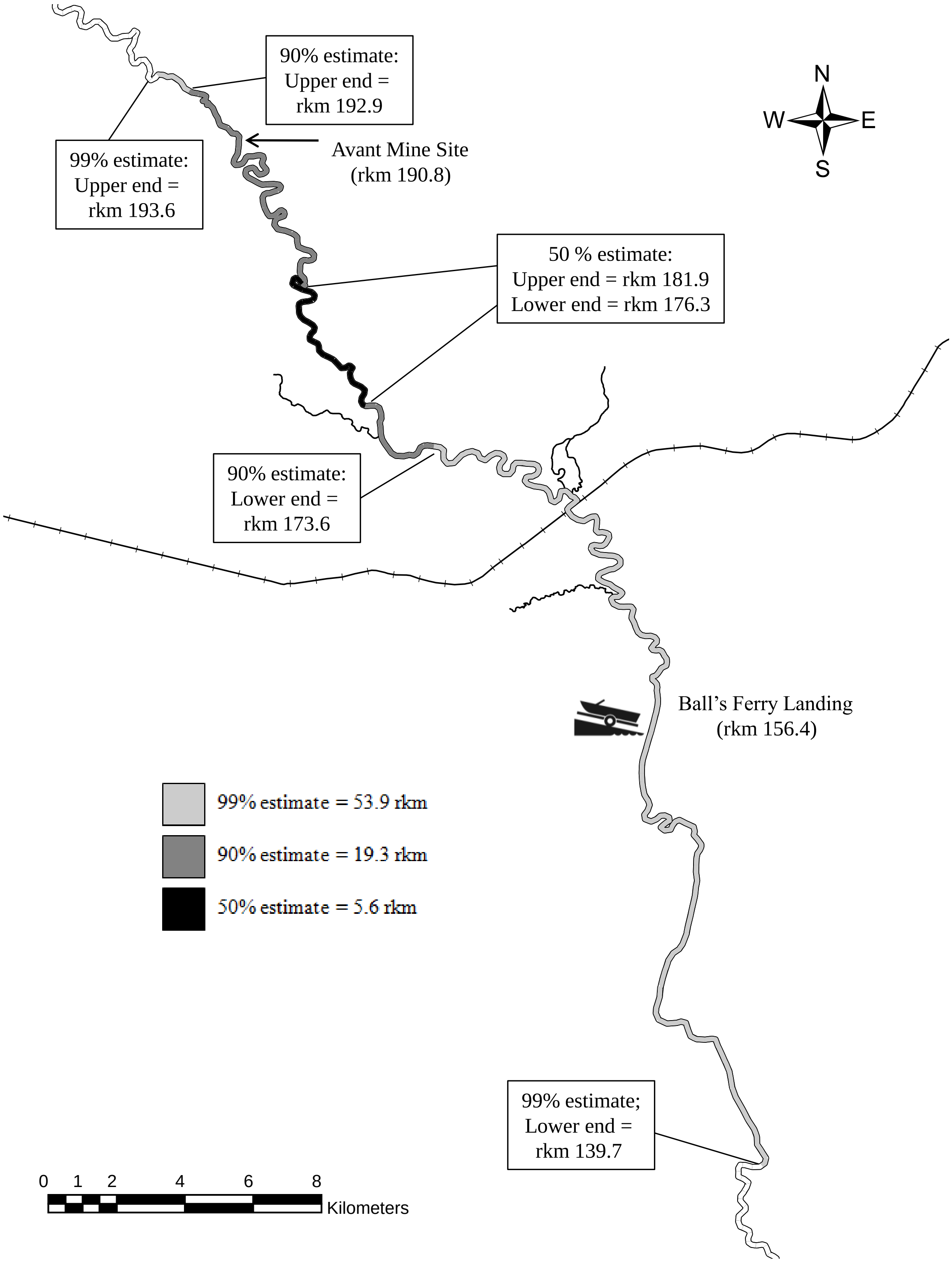


Figure 15. Mapped example of the 99%, 90%, and 50% kernel density estimates for robust redhorse transmitter frequency 40.661 in the lower Oconee River, Georgia, from July 2008 to June 2009.

Additional Observations

Within two weeks of transporting and releasing the study fish into the lower Oconee River, about 79% (n=19) of live relocated robust redhorse (n=24) were detected 8.0 rkm (95% CI = 2.6–13.4 rkm) upstream of the release point at Ball's Ferry Landing. Within four weeks of release, about 29% (n=7) of live relocated fish had traveled an average of 33.7 rkm (95% CI = 32.7–34.8 rkm) upstream and were detected near the historic Avant Mine site between rkm 185 and 195 (Figure 16). The following two springs (2009 and 2010), all of the remaining tagged fish migrated toward and were detected in the vicinity of the historic Avant Mine site during spawning season (Figure 17). Following spawning, fish generally returned downstream close to their previous pre-spawning migration location (Figure 17).

During the first winter time period (December 08 – February 09), following a high water event, an individual (transmitter frequency = 40.101) who had been previously located during fall was determined to be missing from the lower Oconee River. Tracking for this individual was extended downstream the entire length of the Altamaha River without success. During the pre-spawning period of 2009, tracking continued into the Ocmulgee River where the fish was relocated on 05 March 2009, approximately 65 rkm upstream of the confluence. That individual later re-entered the lower Oconee River and was detected on 25 March 2009 just south of Dublin, Georgia, an approximate absolute distance of 143 rkm from its previous location (Figure 17). Over the course of April 2009, fish # 40.101 continued traveling upstream another 123 rkm until it was relocated multiple times near the Avant Mine site during spawning season.

Robust redhorse were typically located within the main channel of the Oconee River throughout the study except during a few pre-spawning (March – April) high-water events in which some fish moved into floodplains and tributaries. On 04 March 2009, a fish was located on a flood plain near Commissioner Creek (rkm ~ 161); and on 01 April 2009, five different individuals entered flooded timber areas around Black Creek (rkm ~ 175; Figure 8). During mid-April 2009, one fish that had been previously detected near Black Creek was relocated about a kilometer into Buffalo Creek just upstream of the Central Georgia Railroad Trestle (CGRT; rkm ~ 166) near Oconee, Georgia (Figure 8).

A total of 22 robust redhorse (67%) either expelled their tags or died over the course of the study (four within one month; 10 between 2–6 months; eight between 11–26 months). An individual was considered to be dead or have an expelled transmitter if the transmitter did not change location over the course of 30 days. After a fish was deemed to have died or shed its transmitter, additional data were not recorded for this fish. Transmitters that were not moving were still relocated periodically throughout the study to ensure that receiver units were operating properly. Two of the non-moving transmitters were found along the shoreline during periods of low water. Transmitters that were previously thought to be in live fish but could not be relocated were considered missing[2]. By fall 2009, the number of missing fish had increased to seven individuals. As a result, tracking was extended into both the Altamaha and Ogeechee rivers in search of missing fish to no avail. A proportion of previously known non-moving transmitters (used for testing receivers) were discovered to have stopped producing a signal. By comparing the proportion of failed, non-moving transmitters to the number of missing fish, eight missing transmitters were deemed to have failed prematurely.

[2] We have evidence that some of the batteries in the transmitters did not last as long as was advertised (i.e., failed prematurely) and believe that this phenomenon contributed to the high incidence of “missing” fish.

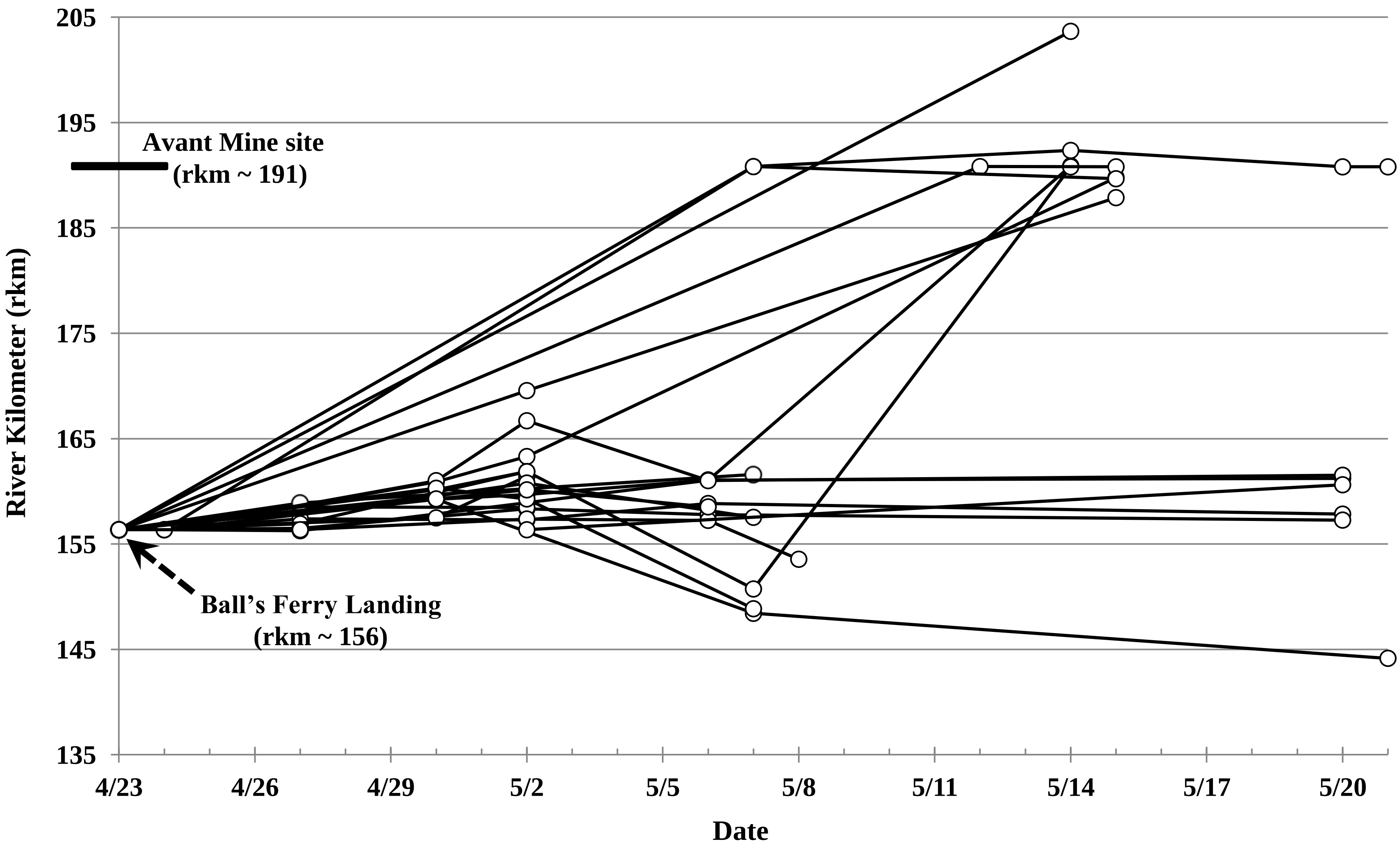


Figure 16. Initial locations (rkm) of radio-tagged robust redhorse released into the lower Oconee River, Georgia, from 23 April 2008 to 21 May 2008. The points represent individual locations and the lines represent the time between relocations. The general location of the Avant Mine site (rkm ~191) and Balls Ferry Landing (rkm ~ 156) are shown by a short black line and a dashed arrow, respectively.

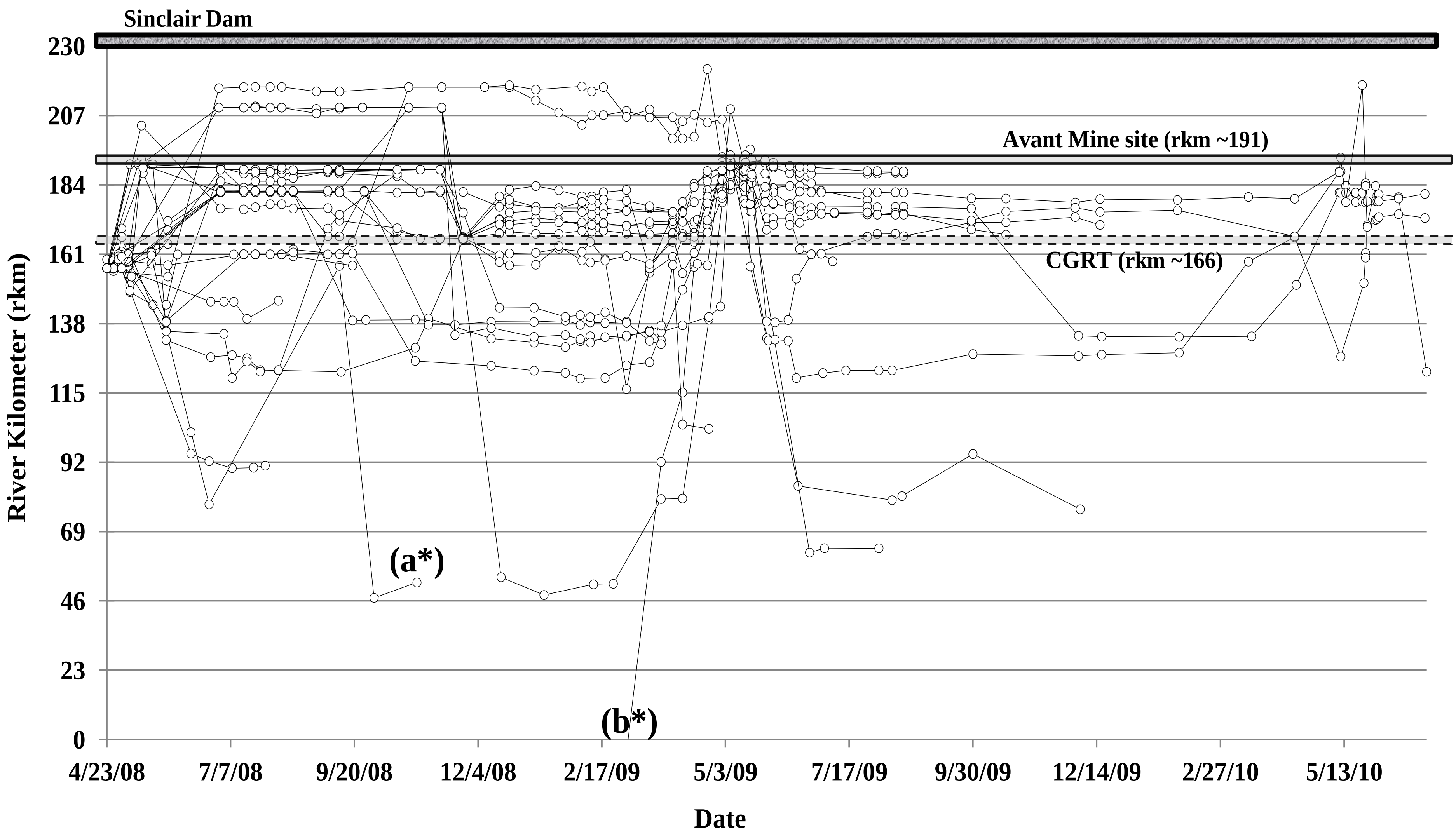


Figure 17. Locations (rkm) of radio-tagged robust redhorse in the lower Oconee River, Georgia, from 23 April 2008 to 02 July 2010. The points represent individual relocations and the lines represent the time between relocations. (a*) represents the last known location of fish 40.101 prior to being relocated in the Ocmulgee River. (b*) represents the relocation of fish 40.101 ~65 rkm into the Ocmulgee River. The general location of the Avant Mine site (rkm ~191) and the Central Georgia Railroad Trestle (CGRT; rkm ~ 166) are shown by solid and dashed lines, respectively.

DISCUSSION

Habitat use and movement patterns exhibited by fish in the present study were consistent with the findings of previous telemetry-based investigations of both wild and hatchery-produced, radio-tagged robust redhorse in other southeastern rivers (Grabowski and Isely 2006; Grabowski and Jennings 2009; Fisk 2010). For example, during the spawning season, radio-tagged robust redhorse transplanted into the Oconee River seemed to form spawning aggregates and were more likely to be located in habitat associated with gravel substrates, fast current, and without cover. Some fish migrated long distances to spawning grounds and then returned to preferred, non-spawning habitat (woody debris over sandy substrates, deep water with current) for the remainder of the year. Tagged individuals in the present study also exhibited potamodromous behavior similar to other sucker species such as the greater redhorse *Moxostoma valenciennesi* (Bunt and Cooke 2001), razorback sucker *Xyrauchen texanus* (Tyus and Karp 1990), and blue sucker *Cycleptus elongates* (Neely et al. 2009). Seasonal movements of robust redhorse in the Oconee River were smaller than those of the blue sucker (Neely et al. 2009) but larger than those of river redhorse *Moxostoma carinatum* (Hackney et al. 1968) and greater redhorse (Bunt and Cooke 2001). Seasonal movements of fish in the current study were similar to those observed for wild adult robust redhorse in the Savannah River, Georgia/South Carolina (Grabowski and Isely 2006) but larger than those of robust redhorse found in the Pee-Dee River, North Carolina/South Carolina (Fisk 2010).

Previous telemetry studies have shown that hatchery-reared robust redhorse transplanted into the Ocmulgee River, Georgia, exhibited a downstream movement for up to 120 days post release before adopting behaviors like wild fish (Jennings and Shepard

2003; Grabowski and Jennings 2009). In contrast, most of the transplanted hatchery-reared fish in the present study moved upstream immediately following release, with a portion being relocated about 35 rkm upstream near the historic Avant Mine spawning site. This upstream movement mimics spawning migration patterns similar to those of wild spawning robust redhorse in other river systems (Grabowski and Isely 2006; Fisk 2010). There were similarities between my methods and those of Grabowski and Jennings (2009). In both studies, robust redhorse were collected from the Ogeechee River, surgically implanted with radio transmitters, and transplanted to a major tributary of the Altamaha River during the beginning of spawning season. Consequently, differences in initial direction and distances moved between the studies may not be related to the time of year and the presence of spawning cues when the fish were released. In the present study, tagged fish were released at a location that was about 75 rkm downstream of Sinclair Dam, which is the nearest migration barrier. Conversely, Grabowski and Jennings (2009) released their fish at a location that was about 0.5 rkm below Lloyd Shoals Dam, which would block upstream migration. Further, hydropower generation from Lloyd Shoals Dam could have increased turbulent flows and induced the tagged fish in the Grabowski and Jennings (2009) study to move downstream with increased discharge.

During the fall of 2008, most tagged robust redhorse traveled in a downstream direction with some intermittent upstream movements. This behavior is similar to the post-release exploratory patterns (i.e., movements outside areas of normal activity; Kramer and Chapman 1999) exhibited by hatchery-reared juvenile and adult robust redhorse released into the Ocmulgee River (Jennings and Shepard 2003; Grabowski and Jennings 2009) as well as other stocked migratory species such as steelhead trout

Oncorhynchus mykiss (Wampler 1984) and razorback sucker (Mueller et al. 2003). The delayed exploratory movements probably were related to an increase in water level following drought conditions, coupled with a seasonal decrease in water temperatures. This behavior may not be typical of fall movement patterns for wild or naturalized fish because the tagged fish in the present study did not display this type of behavior during the second year of the study. Further, exploratory movements have not been observed in the fall for robust redhorse in other rivers (Grabowski and Isely 2006; Grabowski and Jennings 2009).

For the 24-hour tracking events, mean movements (absolute, displacement, and linear range) were larger in April 2009 than they were in October 2009 regardless of diel period, and fish appeared to move less at night than during the day regardless of month. Similarly, wild adult robust redhorse in the Savannah River, Georgia/South Carolina moved significantly more during the day than at night regardless of season (Grabowski and Isely 2006).

Median movement was consistently less than mean movement throughout most of the present study, which indicated that a small portion of fish sometimes moved considerably more than the majority of study fish. For example, three fish in the present study had linear home ranges of over 100 rkm during at least one time period. Similar phenomenon has also been observed for radio tagged wild robust redhorse in both the Savannah (Grabowski and Isely 2006) and Pee Dee (Fisk 2010) rivers. This behavior could be the result of historically patchy distribution of suitable habitat, such that some individuals had to range far to find suitable feeding, overwintering/oversummering habitat, or spawning grounds.

Home range estimates of fishes in lotic systems are typically reported as linear ranges (Logan 1963; Clapp et al. 1990; Daughtry and Sutton 2005), which is the distance between the most upstream and downstream locations for an individual during a specified period of time. Although linear home ranges are easy to calculate and useful in determining and comparing distance boundaries, they do not describe the internal structure of a home range (Vokoun 2003; Hodder et al. 2007). Kernel home range estimates are non-parametric density estimators calculated from relocations that take into account the amount of time an animal spent in any given area of the home range and can be sectioned into levels of use categories called utilization distributions (Worton 1989). Kernel density estimates of home range have mostly been used for studying terrestrial animals but have recently been applied to fish species such as flathead catfish (Vokoun 2005; Malindzak 2006) and robust redhorse (Fisk 2010).

In the present study, the 99% kernel estimates were larger than the corresponding linear home ranges for all robust redhorse. Volkoun (2005) also found that 99% kernel estimates for flathead catfish were greater than their corresponding linear home ranges. This is a common result for kernel estimates at the 99% level because the method estimates the probability that a fish may have traveled beyond the observed points needed to calculate linear range (Vokoun 2003). The 50% level core estimates of robust redhorse ranged from 2.3 to 28.6 rkm and did not appear to be related to the size of their corresponding linear ranges. Smaller core ranges may indicate that some robust redhorse spent most of the year within a small section of the river except during migratory and/or exploratory movements. Larger core ranges may indicate that some robust redhorse moved throughout their home range during the year, including seasonal migrations and/or exploratory movements. Overall, annual core ranges and seasonal linear ranges in the present study were larger than those reported by Fisk (2010) for robust redhorse in the Pee Dee River, North Carolina/South Carolina. Conversely, seasonal linear home range estimates and other movement patterns were similar to those reported by Grabowski and Isely (2006) for radio tagged robust redhorse in the Savannah River, Georgia/South Carolina. Home ranges of robust redhorse have been suggested to be larger in the Savannah and Altamaha drainages than in the Pee Dee River because of dams that limit access to suitable habitat found in Piedmont reaches (Grabowski and Isely 2006; Fisk 2010). Findings from the Graboswki and Isely (2006) study support this hypothesis as a small portion of their tagged fish were able to pass above the dam and occupy Piedmont reaches throughout the year without displaying any seasonal movements. However, in the present study, none of the tagged fish were ever located in the 6 to 7 km reach of Piedmont habitat that was available directly below Sinclair Dam. Although access to this section of river may be limited during periods of low water, study fish did not appear to attempt to enter this reach at all during the study as fish were rarely relocated in the vicinity of the area even during periods of high water with increased accessibility. Why tagged robust redhorse did not attempt to access this Piedmont reach is unclear; however, additional research to assess the amount and suitability of habitat in this section of river may help to address this question.

Increased discharge and subsequent high water levels during the spring may play an important role in initiating spawning behavior and movements of robust redhorse. During the pre-spawning period (March – April 2008 – 2010), river discharge increased and a majority of tagged fish made upstream migrations towards historic spawning grounds. Spawning migrations in response to rising flows have also been documented for other potamodromous species such as the paddlefish *Polyodon spathula* (Miller and

Scarnecchia 2008), sacramento sucker *Catostomus occidentalis* (Jeffres et al. 2006), and humpback chub *Gila cypha* (Muth et al. 2000). Tagged robust redhorse usually stayed within the main channel of the Oconee River except during spring high-water events when some occupied nearby floodplains and tributaries. This behavior has been documented for both hatchery-reared and wild-spawned robust redhorse in the Ocmulgee and Savannah rivers (Grabowski and Isely 2006; Grabowski and Jennings 2009). Grabowski and Isely (2006) suggested that robust redhorse could be using the floodplain for foraging to improve condition and fecundity in preparation for spawning. Our findings support this hypothesis as tagged individuals were only detected in the floodplains and tributaries prior to the spawning period, despite periodic high-water events providing access to these areas throughout the year.

Habitat use of robust redhorse sometimes varied between times periods and directionality (upstream or downstream of Ball's Ferry Landing) and is probably related to the amount of suitable habitat that is available as well as fish behavior (e.g, spawning, overwintering). For example, fish were located in shallower and lower flowing water during the summer and fall, which also had the lowest recorded discharge and water levels. The substrate type with which robust redhorse was associated was less variable in the summer and winter periods when fish movement was the most limited. Tagged robust redhorse located downstream of Ball's Ferry Landing were more likely to be associated with rocky cover and substrate than upstream fish. This distribution is probably a function of increased available rocky habitat near Dublin, Georgia. Woody debris did not seem to be a limiting factor, as it was consistently abundant throughout the entire river. Although robust redhorse require gravel substrates to spawn, the rocky substrate downstream may have been unsuitable for spawning. For example, during spawning season, tagged fish located near and below Dublin migrated upstream to areas in the vicinity of the Avant Mine site that contained gravel substrates. As previously mentioned, tagged fish did not attempt to enter the Piedmont reach directly below Sinclair Dam, which is dominated by rocky substrates (including gravel). Future research should focus on determining the amount and suitability of spawning and non-spawning habitat available to robust redhorse in the lower Oconee River.

The lower Oconee River is a dynamic system where morphological changes such as the creation of oxbows, and the recruitment and location of gravel substrates can ultimately influence the location of spawning robust redhorse. Over the past three spawning seasons (2008, 2009, and 2010), spawning activity of robust redhorse has not been visually observed nor have any tagged fish been relocated at the historic Avant Mine gravel bar. Lack of new gravel input, attributed to a shift of the main river channel, is considered to be a primary reason for the decline in robust redhorse use of the historic Avant Mine spawning site. The importance of morphological changes on the location of spawning radio-tagged robust redhorse was demonstrated during the 2009 and 2010 spawning seasons. In May 2009, an aggregate of tagged fish was believed to have spawned about 1.4 rkm upstream of the historic Avant Mine site in an oxbow "cut through" associated with swift current and loose gravel substrates. A recent shift in the main channel eroded away the remaining land that separated two bends in the channel. The result was the "cut through", which formed an oxbow lake and seems to have exposed and/or collected gravel and created the new spawning location. However, during the following spawning season in 2010, study fish were not relocated at the "cut through", and sandy substrate was detected at locations around the cut through that previously contained gravel substrate. High flows seemed to have widened the "cut through" and subsequently washed away or buried the gravel substrate, which made the site unsuitable for spawning. However, during the 2009 and 2010 spawning periods, study fish were located in the area about 2 rkm downstream of the historic gravel bar; this new site contained gravel substrate. Whether fish were successfully spawning in this area is unknown, but gravel substrates were still present as of May 2010.

Since 1994, declining annual electrofishing catch rates and population estimates indicate a severe reduction in the abundance of adult robust redhorse in areas of the lower Oconee River typically sampled during the spring. However, distribution data, historical catch rates, and related abundance estimates may be biased because sampling has generally been restricted to river sections between the Central Georgia Railroad Trestle (CGRT) and Dublin, GA. However, during April 2004, May 2010, and May 2011, electrofishing surveys from the top of the study reach (i.e., Sinclair Dam) down to Dublin, GA were conducted. This effort was a multi-agency collaboration to address whether historic catch rates reflected overall population decline or if the population distribution shifted into areas above the CGRT that previously received limited sampling effort (Jimmy Evans, Georgia Department of Natural Resources, personal communication). The specific objective of the May 2010 and May 2011 electrofishing surveys was to sample areas where tagged fish had been located during the previous spawning season (i.e., sections above the CGRT) to determine if wild individuals were occupying the same river sections[2]. In April 2004, eight adult robust redhorse were captured and 75% (6 of 8) of those fish were collected above the CGRT. Robust redhorse were not collected during the May 2010 and May 2011 surveys (Jimmy Evans, Georgia Department of Natural Resources, personal communication). Results of the

[3] In 2010, inclement weather limited sampling to only sections of river outside of the area where tagged fish were located during the previous spawning period (Jimmy Evans, GADNR, personal communication).

2004 survey documented a continued decline in catch rate from previous years (RRCC 2010) but also indicated that most of the population was located in the previously restricted sampling area above the CGRT. Telemetry results of the present study were similar to the general distribution of robust redhorse collected in April 2004. The 50% kernel density estimates from the present study indicate that most radio-tagged robust redhorse are located between the Avant Mine site (rkm ~ 191) and the CGRT (rkm ~ 166) throughout the year; and during spawning season, study fish were concentrated between rkm ~ 195 and Black Creek (rkm ~ 175). However, the absence of robust redhorse from the 2010 and 2011 electrofishing surveys suggest that the abundance of wild-spawned adult robust redhorse has continued to decline even though telemetry results suggest that robust redhorse, if present, would be located in the reach between the Avant Mine site and the CGRT. However, sampling data for the previously restricted area above the CGRT is still limited and additional electrofishing surveys in this area would help to verify the actual abundance and fate of adult robust redhorse in the lower Oconee River, Georgia.

Conclusions

This study provided long-term data on movement patterns, habitat use, and home range size (linear and kernel density) of hatchery-produced adult robust redhorse released into the lower Oconee River, Georgia. Hatchery-produced individuals used in the present study behaved similar to those of wild-born fish in other studies and led to the discovery of previously unknown potential spawning sites. The current research suggests that the dynamic morphology of the main channel of the lower Oconee River (i.e., creation of oxbows, and the recruitment and location of gravel substrate) can affect the location of spawning robust redhorse. Telemetry results of the present study suggest that fish distribution was similar to distribution noted during sampling of robust redhorse collected during April 2004. However, the absence of robust redhorse from the 2010 and 2011 electrofishing surveys suggest that the abundance of wild-spawned adult robust redhorse has continued to decline even though telemetry results indicate that robust redhorse, if present, would be located in the reach between the Avant Mine site and the CGRT. However, sampling data for the previously restricted area above the CGRT is still limited and additional electrofishing surveys in this area would help to verify the actual abundance and fate of adult robust redhorse in the lower Oconee River. Taken in total, the new information provided by this study could help in the establishment of a standardized sampling protocol for adult robust redhorse in the lower Oconee River and thus assist managers in making decisions for restoring or enhancing the species.

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