Criteria for Suitable Spawning Habitat for the Robust Redhorse *Moxostoma robustum*

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Introduction

The robust redhorse, *Moxostoma robustum*, is a large imperiled catostomid fish native to southeastern Atlantic slope drainages. The species' known native range extends from the Altamaha River drainage in Georgia northward to and including the Pee Dee River drainage in North Carolina and South Carolina. Three known extant populations are now restricted to a limited portion of the Oconee River between Milledgeville and Dublin, Georgia, the Ocmulgee River between Macon and Hawkinsville, Georgia and the Savannah River in the Fall Line Zone around and below Augusta, Georgia and North Augusta, South Carolina. A viable population may also persist in the Pee Dee drainage, where a single individual was captured in an intensive sampling effort in April 2000.

The robust redhorse is considered an imperiled species because of the large apparent reduction in species' range and abundance. Even if the robust redhorse persists in the Pee Dee as well as the Savannah and Altamaha drainages, abundances are dramatically reduced compared to E. D. Cope's (1870) accounts of fishery catches of the sucker. All remaining populations persist in rivers with flows influenced by hydropower dams. The robust redhorse is uncommon or rare in the Ocmulgee, Savannah and Pee Dee rivers. The apparently largest population, in the Oconee River, displays some evidence of recent juvenile recruitment to the population; for example, we have observed smaller males joining spawning activity during two of the past six years. However, because the population is skewed toward older age classes, concerns remain that spawning or juvenile habitat may be limiting. Effects of flow alteration by dams on population dynamics of the robust redhorse are not known. Potential loss of suitable habitat as a result of hydrologic alteration, especially for life history stages considered having the narrowest habitat requirements, is a primary management concern.

Evaluating potential effects of proposed flow regimes below dams on habitat availability for a target species requires an understanding of habitat requirements for that species. This manuscript presents criteria for suitable spawning habitat for the robust redhorse, based on observations of spawning by the Oconee River population and a single observation in the Savannah River. We intend these criteria to be used for quantifying amounts of potential spawning habitat for the robust redhorse at target locations in relation to flow regimes. However, because these criteria are largely based on observations at one known spawning site, they should be revised if and when additional data on spawning habitat become available. Criteria are presented as ranges of depths, velocities and substrate compositions considered suitable for spawning by robust redhorse.

Methods

Oconee River Study Site - We observed spawning by the robust redhorse at the Avant Mine site (Figure 1), located in western Washington County, approximately 24 air km SSE from the center of Milledgeville, Georgia (32^{o} 56´23˝N, 083^{o} 04´01˝W) near Oconee River Km 193 (RM 120). At this point the Oconee River drains 8025 km ^{2} (3100 square miles) of the piedmont physiographic region and is approximately 32 river km downstream of Georgia Power Company's Sinclair Hydroelectric project. Just upstream of this site, a large scroll meander was recently truncated, thus forming two large oxbow lakes on either side of the channel. As a result, the main current of the river is directed at a large cut bank just upstream of the spawning site. Subsequent bank erosion has exposed a lens of lag gravel in this bank. Much of the instream gravel utilized by robust redhorse during spawning appears to have been deposited as a direct result of this large-scale bank erosion.

Habitat Measurements -Spawning activities of robust redhorse were recorded at the Avant site in April and/or May, 1995 - 2000 (Table 1). In 1995, 1997, 1998 and 2000, we characterized depths and velocities by taking measurements with a wading rod and electronic current meter (Marsh-McBirney, Model 201D) at 7 to 15 locations within the spawning area. Velocities were measured with the probe positioned at 60% of water depth, measured from the water surface. Persistent high flows during the spawning seasons of 1996, and equipment failure in 1999, prevented us from making habitat measurements where fish were spawning.

To characterize substrate composition where the fish were spawning, we used a freeze-coring device developed by Dr. Ervan Garrison (UGA Dept. of Anthropology) for obtaining intact cores of substrata. The freeze-corer is a hollow stainless steel probe with a pointed tip. A small diameter copper line threaded into the larger probe extends to the bottom of the hollow tip. The small copper line transfers liquid nitrogen to the bottom of the probe. As the nitrogen evaporates, the material adjacent to the probe is frozen for intact removal. Cores, typically 15-25 cm in length, were removed from marked spawning locales. The cores were photographed and carefully removed from the probe using a hammer and chisel. The location and distribution of eggs, if present, were noted. All material from each core was returned to the laboratory where it was dried, sorted by size, and weighed. We collected freeze-core samples in 1997, 1998 and 2000.

Savannah River Observations - Robust redhorse were observed exhibiting courtship and territorial behavior at a location downstream from the New Savannah Bluff Lock and Dam (Figure 2), on 31 May 2000. We collected depth and velocity data at this site on 6 June 2000, and also photographed the substrate. We estimated dominant particle size in the spawning area from the photograph, which included a ruler for scale.

Data Analysis - We plotted depths and velocities from the Oconee spawning site to show ranges and value distributions (e.g., median, interquartile spread) for each year, to facilitate among-year comparisons. Measurements made in different years represent independent observations, however measurements made within a year do not because they were taken across the spawning area to describe local habitat. Thus, we essentially have a sample size of 4 estimates of the depths and velocities used by spawning robust redhorse. Therefore, we did not arrange the measurements in frequency distributions as would be appropriate for a larger sample size of independent habitat-use observations. We used the range of observations across the four years to estimate suitable depths and velocities for spawning robust redhorse. Data collected at the Savannah River site were inspected for concordance with suitable ranges as estimated from the Oconee data.

We computed size-fraction composition of freeze-core samples as percent of total sample weight. For estimating suitable spawning substrate, we only used data for cores taken directly from a known spawning location.

Results

Timing of spawning - We observed spawning activities by robust redhorse at the Oconee River Avant site during late April (in 1999) and into the third week of May, at temperatures ranging from 17 - 26.7 ^{o}C (Table 1). In addition to observations at the Avant site, eggs and three spawning depressions were observed on a gravel bar approximately 15 km downstream from Avant in the Oconee River on 19 May 1992, with water temperature approximately 25 ^{o}C (B. J. Freeman and N. M. Burkhead, field data). Although spawning activity was not observed at this site, nuptial robust redhorse were captured near the gravel bar on 20 May 1992. The single observation of fish exhibiting courtship behavior in the Savannah River site occurred later (31 May 2000) than the Oconee observations, at a water temperature of 21 ^{o}C. Lack of spawning activity at the Avant site on dates in April 1996 and 1999, and in late May (1997 and 2000), despite water temperatures of 19 - 25 ^{o}C suggest that spawning is triggered and terminated by factors in addition to water temperature. In any case, spawning appears most likely to occur from the latter part of April through May.

Spawning habitat - All observed spawning activities at the Oconee site occurred around a mid-channel gravel bar. Spawning activities included a suite of behaviors. In brief, males "porpoised", breaking the water surface over the spawning area and held positions over the gravel bar while periodically bumping or butting one another. Females generally remained in a deeper, lower-velocity area upstream from the riffle formed by the bar, occasionally swimming into the riffle and aligning with a male. A second male would join the pair, and spawning occurred in a trio with the males flanking the female. Females usually swam back to the pool upstream from the riffle following a spawning event.

Depths and velocities in the spawning area differed among years as a result of differences in flow levels (which differed by a factor of 2 during observations across years). However, depth and velocity ranges broadly overlapped among years (Figure 3). These data also encompassed depths (0.43-0.73 m) and estimated water velocities (0.3 - 0.5 m/s) at the spawning depressions found in the Oconee River in 1992, and depths and velocities at the Savannah River site from 2000 (Figure 3). In 1995, we measured 10 depths and velocities in the holding area used by females, immediately upstream from the spawning area; these ranged from 0.33-0.60 m deep and 0.05 -0.21 m/s, compared to 0.29 - 0.57 m and 0.35 - 0.61 m/s in the spawning area.

Substrate at all spawning sites was dominated by gravel (2-50 mm; Table 2). Freeze-core samples taken in known spawning locations at the Avant mine site in 3 years were dominated by gravel measuring at least 4.75 mm. The larger fraction of the 3 samples analyzed from 2000 was sieved into three larger fractions (2-12.5 mm, 12.5-25 mm, 25-50 mm) than in 1997 and 1998. The 2000 data showed that the spawning gravel was dominated by particles > 12.5 mm, with this fraction about evenly divided between medium (12.5-25 mm) and coarse (25-50 mm, Table 2). Fine sand (<0.25 mm) made up < 2 % (range 0.4 - 1.8%, n = 11 cores) of samples by weight. We visually estimated dominant substrate fractions at the 1992 Oconee site as 25-50 mm gravel, and at the 2000 Savannah River site as 15-30 mm gravel.

Criteria for suitable spawning habitat - Based on these observations, we propose the following criteria be used to evaluate habitat suitability for spawning *Moxostoma robustum*::

Suitable water depth: 0.29 - 1.1 m

Suitable average water column velocity: 0.26 - 0.67 m/s

Suitable substrate: dominated by medium - coarse gravel, 12-50 mm, with < 30 % sand (0.25-2 mm) and minimal fine particles (<0.25 mm)

Discussion

Spawning habitat conditions described for the robust redhorse agree well with spawning habitat reported for other species of *Moxostoma*. Jenkins and Burkhead (1994) review known spawning behavior and habitat use by five redhorse sucker species, including the river redhorse *M. carinatum*, the likely sister taxon to *M. robustum*. Although spawning habitat has not been well quantified for most redhorse species, qualitative descriptions generally report the suckers spawning over gravel or small rubble in riffles, runs or pool tails. Jenkins and Burkhead cite one report of silver redhorse *M. anisurum* spawning in a water depth of 1.5 m and note that, if valid, "this would be deeper than that known for most redhorses".   The river redhorse is known to spawn in "shallow area at the head of gravel-bottom riffles", with depths ranging from 0.2-1.2 m and velocities (measured near the substrate) of 0.6-1.0 m/s (work by Hackney, reviewed by Jenkins and Burkhead 1994). This description closely corresponds to our observations for the robust redhorse.   Recent studies of black redhorse *M. duquesnei* and golden redhorse *M. erythrurum* (Kwak and Skelly 1992) and of greater redhorse *M. valenciennesi* (Cooke and Bunt 1999) similarly report these species spawning in depths of < 1 m with moderate to swift velocities (averaging 0.28 to 0.55 m/s across species) in riffles or shoals. Dominant substrate used in these studies ranges from fine gravel (2-8 mm) for golden redhorse, to "pebble" (16-64mm) for greater redhorse, to small cobble (64-130 mm) for black redhorse.

Despite general consistency in spawning habitat descriptions across redhorse species, the functional significance of habitat requirements is incompletely known. We hypothesize that substrate characteristics are most critical; substrate particles must be small enough to moved and allow egg deposition by spawning fish and yet large enough to provide interstitial spaces for eggs and developing larvae (Table 3). We suspect that sufficient intragravel flow to maintain dissolved oxygen levels and remove metabolic wastes also forms a critical component of suitable spawning habitat. As described by Kondolf (2000), intragravel flow depends on substrate permeability and hydraulic gradient. Permeability will be reduced by fine sediment in the gravel. A laboratory study has demonstrated reduced survival of robust redhorse larvae in gravel with $\geq$ 25% by weight sand (Dilts 1999). The amount of fine sediment is likely reduced when substrate is disturbed during spawning (Kondolf 2000; our observations); however, gravels with large amounts of sediments < 1mm are unlikely to provide suitable spawning habitat. Hydraulic gradient, the second component in intragravel flow, is created by a drop in water surface elevation over a gravel bed, as occurs at the interface of a pool and downstream riffle (Kondolf 2000). We hypothesize that this mechanism makes shallower areas more suitable for spawning the deep water, where hydraulic gradient and intragravel flow would be reduced (Table 3).

The spawning habitat criteria we present differ from an earlier set of robust redhorse spawning habitat criteria produced for use in an instream flow study in the Oconee River (EA 1994). The earlier criteria show optimal depth as about 0.76 to 1.8 m (2.5 - 6 ft), with suitability decreasing to 0 at 3.6 m depth (12 ft). Optimal velocities from the earlier criteria, 0.23 to 0.53 m/s (0.75 to 1.75 ft/s), agree more closely with our data. However the earlier criteria give "simple woody cover" as optimal, and give suitability values of 0.2 and 0.5 to coarse sand and cobble/irregular bedrock, respectively. (Optimal sutiablity is assigned to small and large gravel). None of our observations support the use of substrates dominated by sand, cobble or bedrock, nor do considerations of substrate requirements (Table 3). With respect to cover use, spawning fish at the Avant site do sometimes occur around mid-channel snags. However, we hypothesize that this association is incidental to the fact that the snags are part of, and may help detain, gravel deposits. We have many observations of spawns in gravel areas with no cover nearby. The earlier criteria are primarily based on conditions where nuptial fish have been captured in the Oconee River, likely explaining the greater depths and wider range of substrates reported as optimal. It is possible that captured fish had in fact been spawning in those locations; it is also possible that fish had been captured in staging areas or in route to spawning sites.

The criteria we present entail three sources of uncertainty.

- The criteria are based on data collected at one site in the Oconee River over four different years. The habitat conditions used by spawning robust redhorse have been remarkably consistent among years despite variation in flows and changes in channel morphology as a result of erosion and deposition processes. Habitat data collected at a single spawning site in the Savannah River are congruent with the Oconee data. However, clearly, data are needed from additional locations to test the generality of the criteria based on observations at the Avant site.
- The criteria are necessarily based on observations made at lower relative flows. It is possible that the redhorse also spawns during higher flows, and thus deeper water, when direct observations are impossible. The only evidence we have that this is not the case is our observation that spawning activity, first porpoising and male interactions, followed by spawning, gradually increases as water levels fall. We

hypothesize that if fish spawn during high and low flows, we would see fish fully engaged in spawning activity as soon as the water level was low enough to permit observations.

- Spawning success in relation to variation in substrate characteristics, depth or water velocity is not known. Thus, although fish may be observed spawning over a range of conditions, the entire range may not provide equal levels of egg and larval survival.

Clearly, additional study of robust redhorse spawning habitat, including relations between habitat characteristics and reproductive success (e.g., Dilts 1999 study), is warranted. In particular, we believe study of intragravel flow in spawning locations is needed to improve our understanding of habitat-related mechanisms promoting reproductive success. We propose that until and if we can observe spawning at greater depths (e.g., with remote videography), the criteria based on spawning conditions at the Oconee site are the most appropriate descriptors of suitable spawning habitat.

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Table 1. Dates and water temperatures when *Moxostoma robustum* were observed spawning at the Avant Mine site, Oconee River, Washington County, Georgia.

Year	Dates Spawning Observed	Mid-day Water Temperature	Dates No Spawning Observed (Water Temperature)
1995 [1]	14 - 16 May 22 May	25 - 26.7 ^{o}C 24 ^{o}C	No Data
1996	20 May	25 ^{o}C	28 April (20 ^{o}C)
1997	10 - 13 May	20 ^{o}C	20-21 May (23-24 ^{o}C)
1998	17 - 19 May	24.5 ^{o}C	
1999	27 April 29 April 1 May 3 May 18 May	22.2 ^{o}C 18.8 ^{o}C 17 ^{o}C 21.6 ^{o}C	10 April (20 ^{o}C) 15 April (18.8 ^{o}C) 29 May (25 ^{o}C)
2000	23, 25, 26, 29 April 1, 4 May	18 - 19 ^{o}C 21 ^{o}C	

[1] Anglers reported see spawning activity for previous 2 weeks; kaolin-mine workers reported seeing suckers spawn at an upstream gravel bar as late as June during 1994, and that the gravel bar had shifted downstream to the "Avant site" in 1995.

Table 2. Substrate composition in *Moxostoma robustum* spawning locations, as measured by size fraction composition of sediment freeze-core samples. The fraction > 2 mm was sieved differently in 2000 than in 1997 and 1998. Values are percents of total sample weight.

Year	Number of cores	Fines <0.25 mm	Sand 0.25-2 mm	Fine Gravel 2-4.75 mm	Fine Gravel 2-12.5 mm	Medium - Coarse Gravel >4.75 mm	Medium - Coarse Gravel 12.5 - 50 mm
1997	3	0.6	22.8	10.0	-	70.5	-
1998	5	1.2	26.9	5.1	-	65.9	-
2000	3	0.7	16.1	-	14.3	-	68.9[1]

[1] This fraction comprised 32% in 12.5-25 mm and 37% in 25-50 mm size classes.

Table 3. Habitat requirements to support spawning by redhorse suckers and empirical data for spawning robust redhorse.

Habitat Feature	Requirements	Field Data
Substrate	• moveable by spawning fish to allow egg deposition • resist scour and provide spaces for eggs and larvae and sufficient interstitial flow to maintain DO, remove wastes	Gravel substrate, most particles 12 - 50 mm; < 2 mm fraction < 30% of substrate by weight; < 0.25 mm fraction < 2%
Water Depth	• sufficient to accommodate courtship and spawning [sets minimum] • sufficient to maintain flow over eggs and larvae [sets minimum; possibly maximum if increasing depth reduces hydraulic gradient]	Range of observed spawning depths = 0.29 to 1.04 m
Water Velocity	• sufficient to maintain flow over eggs and larvae [sets minimum] • low enough to limit substrate scour	Range of observed average water column velocities in spawning areas = 0.26 to 0.67 m/s
Habitat juxtaposition	• provide holding areas for females adjacent to suitable spawning area • hypothesized: create hydraulic gradient to promote interstitial flow in spawning area	At Oconee River Avant site, spawning occurs in shallow area immediately downstream from a lower-velocity, pool where females hold while not spawning

Figure 3. Box and Whisker plots for depth (m) and average current velocities (m/sec) recorded in Robust Redhorse spawning areas in the Oconee and Savannah Rivers. Central horizontal bar represents the median value recorded; the upper and lower horizontal bars represent the 75^{th} and 25^{th} percentiles. Whiskers span plus and minus 1.5 times the interquartile width; asterisks represent values within 3 times the interquartile width.