Population dynamics of robust redhorse *(Moxostoma robustum)* in the Oconee River, Georgia

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Executive Summary

Robust redhorse *Moxostoma robustum*, a large, riverine catostomid that was thought to be extinct for more than 120 years, was re-discovered in the Oconee River, Georgia during the summer of 1991. Since then, intensive research on the biology and ecology of these rare fish has provided much new information. None-the-less, many important questions remain, and chief among them is a reliable estimate of the number of individuals in this remnant population. This information is essential for evaluating the current status of the population and for assessing its near-term (i.e., 10-20 years) fate. Additionally, these data will help direct efforts to ensure the survival of robust redhorse in the Oconee River and to restore the species to rivers within its native range (i.e., medium to large rivers in the South Atlantic Slope).

A capture-recapture study of robust redhorse in the Oconee River (from Milledgeville, Georgia downstream to Shady Field Landing Public Boat Ramp in Lowery, Georgia) was conducted from October 1999 to February 2000. Fish were sampled with boat-mounted electrofishing gear, and Jolly-Seber population models were used to estimate the population size and other population parameters (e.g., survival and recruitment). Finally, the derived population parameters (i.e., size, recruitment, and survival) were used to simulate the long-term (100 years) fate of the robust redhorse population in the Oconee River. An estimated 607 (S. E. = 138) robust redhorse ≥417 mm total length (TL) inhabited the reach of river from about one river mile above Black Creek downstream to Dublin. This estimate was not applied to all sizes of robust redhorse or to the entire reach sampled because of limitations in the size and locations of the fish caught. For example, none of the fish caught during this study (and others) were <417 mm (TL). Therefore, this size (i.e., about 400 mm TL) seems to be the size at which robust redhorse become vulnerable to boat-mounted electrofishing gear. Also, fish caught during this study

came from a limited reach of the river, even though the species has been documented outside of this limited reach. The long-term fate of robust redhorse in the Oconee River seems promising. Our simulation results, which assumes that habitat suitable to robust redhorse remains at least as available as it is currently, suggest that the number of individuals ≥417 mm TL will be variable (mean = 278), but they will persist for many generations. Such data are encouraging, but apply to only a segment of the population and to a limited portion of the reach known to be inhabited by robust redhorse. Many questions remain about the basic biology and ecology of the these fish, and virtually nothing is known about the species' early life history. Research efforts should continue to explore the life history, including population dynamics, for all size classes of robust redhorse and for the entire reach the species inhabits.

Introduction

Robust redhorse (*Moxostoma robustum*) are large (maximum total length 760 mm), riverine catostomids. These fish were thought to be extinct for more than 120 year, but were re-discovered in the Oconee River by personnel from Georgia Department of Natural Resources (GA DNR) during the summer of 1991 (Evans 1994). In October 1997, a single adult individual was caught in the Savannah River below the New Savannah River Bluff Lock and Dam by personnel for GA DNR (T. Barrett - GA DNR, personal communication). Eventually, a second population of robust redhorse was discovered in the Savannah River near Augusta, Georgia (Evans 1999). Historically, these fish inhabited medium to large rivers in the southeastern Atlantic slope, from the Pee Dee River system in North Carolina to the Altamaha River system in Georgia (Freeman 1998). Currently, populations in the Oconee and Savannah rivers are the only known extant populations.

The Oconee River population is comprised of mostly older individuals, and concerns among biologists from private, state, and federal agencies about possible recruitment failure and eventual extinction of the species led to the formation of the Robust Redhorse Conservation Committee (RRCC). The RRCC, established in 1995 by a Memorandum of Understanding signed by GA DNR, Georgia Power Company (GPC), the US Fish and Wildlife Service, and the US Geological Survey (among others), took a pre-listing approach for organizing and developing conservation strategies to recover this species. Short term goals of the RRCC are to protect and manage the remaining populations and establish captive-breeding populations through artificial propagation; long-term goals include the establishment of refugial populations in suitable river systems within the species' former range (Evans 1999).

Since the rediscovery of robust redhorse, several studies have addressed the robust redhorse reproductive and recruitment success, potential reasons for the apparent lack of recruitment, husbandry techniques to propagate the species, and basic biology on which to base husbandry techniques. These investigations focused on the abundance and distribution of early life stages (Jennings et al. 1996, 1998), swimming performance of larval and juveniles and their availability to tolerate highly-variable flows (Ruetz 1997; Ruetz and Jennings 2000), gravel stability in spawning shoals (Freeman 1998), and the effects of fine sediment on the survival to emergence of larvae (Dilts 1999). Other factors that potentially could limit the robust redhorse population include predation by the non-indigenous, highly piscivorous flathead catfish (*Pylodictis olivaris*), water pollution, and dams that block upstream migrations (Evans 1994). Information on the physiological tolerances are given in Walsh et al. (1998). Techniques for hormone-induced ovulation of robust redhorse have been developed by Barrett (1997), and the incubation temperatures and flows that provide the highest hatch rate of fertilized robust redhorse eggs are given in Jennings et al. (1998).

The rarity of larval and juvenile robust redhorse in the Oconee River has generated much debate about the fate of the robust redhorse population in the Oconee River. Larval and juvenile stages are still rare, but some recruitment has been documented (Jennings et al. 1996, 1998). Experimental assessments of survival to emergence of larval robust redhorse suggest recruitment in the Oconee River probably is low (Dilts 1999), and whether this recruitment is sufficient to maintain the population is unknown. This question is complicated further by uncertainties surrounding the current estimate of the number of adults in the population.

Current estimates of the number of robust redhorse in the Oconee River range from 1000 to 4000 individuals (J. Evans - GA DNR, personal communication). These estimates are based on GA DNR catch data obtained in conjunction with providing broodfish for the artificial propagation program. Initial estimates are from a limited geographic distribution (i.e., an initial 1995 estimate of 683 individuals in a closed system were expanded to the whole reach of river), and may not be representative of the actual number of robust redhorse in the Oconee River (J. Evans - GA DNR, personal communication). Further, this estimate appears to conflict with catch data that indicate catch-per-unit-effort (CPUE) is decreasing over time (Evans 1999). As a result, decisions about how to best manage this species are difficult and could be harmful to the population if made without essential knowledge of population parameters (e.g., population size, survival, and recruitment).

Population modeling through capture-recapture techniques is used frequently to estimate population parameters and has been used successfully to evaluate the status of threatened fishes. For example, capture-recapture techniques were used to estimate the population size and movement patterns of the endangered humpback chub (*Gila cypha*) in Arizona (Douglas and Marsh 1996), to estimate the survival of the endangered razorback sucker (*Xyrauchen texanus*) in the Middle Green River, Colorado (Modde et al. 1996), and to estimate population size and survival probabilities of the flannelmouth sucker (*Catostomus latipinnis*), a "species of concern," in the Little Colorado River, Arizona (Douglas and Marsh 1998). Therefore, population modeling similar to those used in the above studies should provide reliable information about population parameters of the robust redhorse in the Oconee River.

We examined capture data for robust redhorse in the Oconee River to estimate parameters for this population. Specifically, we conducted a capture-recapture study to determine reliable estimates of survival, capture probability, and recruitment and used these results to simulate the long-term fate of the species in the Oconee River. This population estimate and simulation modeling are critical to future management decisions and recovery efforts aimed at maintaining the species in the Oconee River. Further, an understanding of robust redhorse population dynamics will help guide future management efforts to restore this species in medium to large rivers within the species' historic range.

Methods

Study reach

Robust redhorse were sampled from a 90 river mile (rm) reach of the Oconee River (Figure 1). The study reach began at State Highway 22/24 bridge in Milledgeville, Georgia downstream to Shady Field Landing Public Boat Ramp in Lowery, Georgia. The study site is influenced by Sinclair Dam, a hydropower facility operated by GPC. Sinclair Dam, in accordance with its licence with the Federal Energy Regulatory Commision, releases seasonably-variable, minimum flows, which can cause dramatic changes in stage height and discharge in the study reach.

Existing capture data (GA DNR)

We analyzed robust redhorse capture data collected from 1994 to 1999 in the Oconee River by personnel from GA DNR. These data are reported (in part) in various project reports and RRCC annual progress reports (DeMeo 1997; Hendricks 1998; Evans 1999). The original data are compiled and maintained electronically by R. Jenkins, Roanoke College, Virginia. Robust redhorse were sampled by electrofishing primarily in the spring (April-May) between rm 85-109 (Figure 1) for broodfish collection for the artificial propagation program.

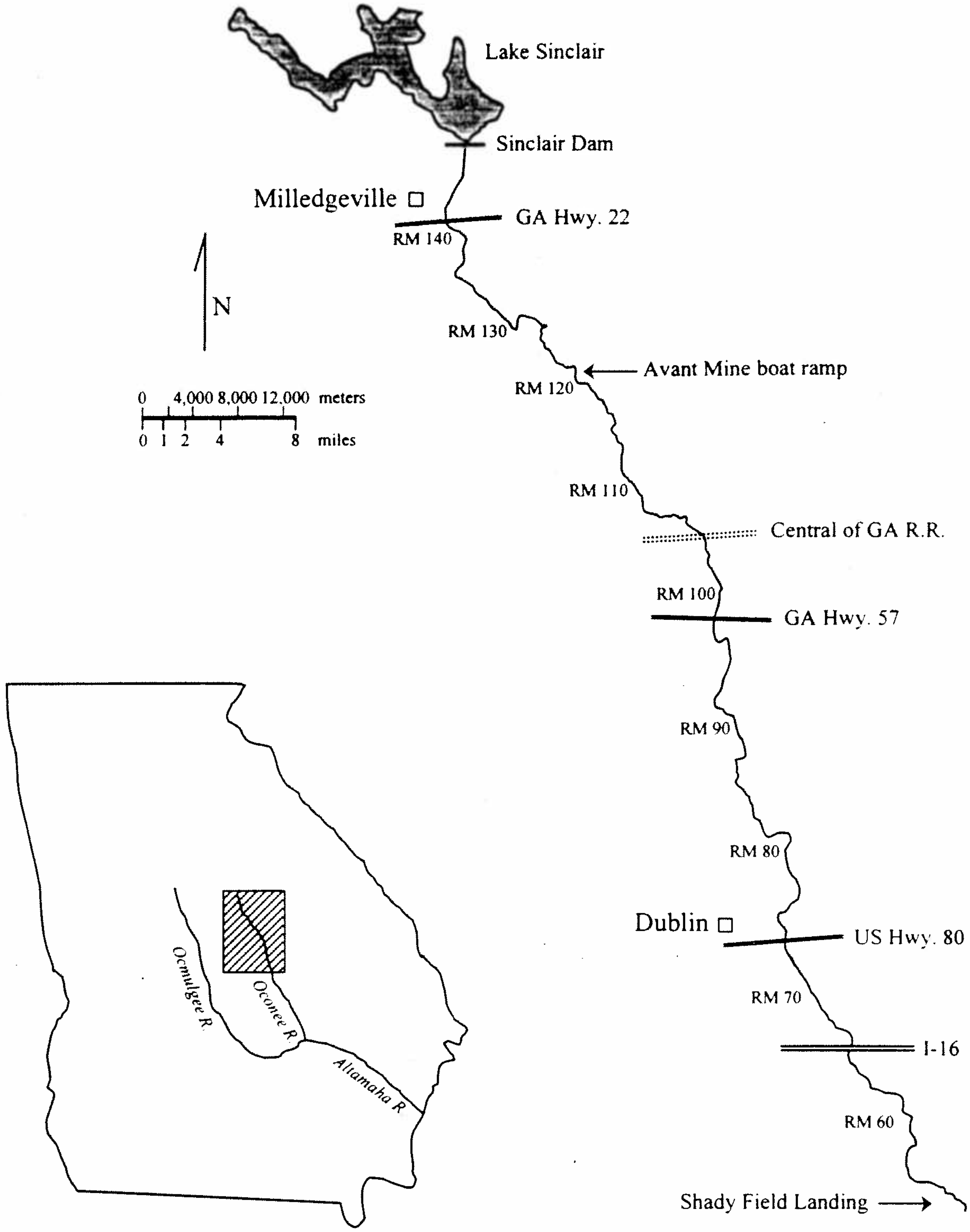

Figure 1. Map of Georgia and the study reach of the Oconee River where robust redhorse were captured during winter (October 1999 - February 2000). The catch data from GA DNR for other years (1994-1999) used in the Jolly-Seber population modeling also came from this same reach.

Fish sampling and water quality (present study)

In the present study, robust redhorse were sampled from the Oconee River from Milledgeville downstream to Shady Field Landing Public Boat Ramp in Lowery; sampling began on October 28, 1999 and continued to February 8, 2000. Robust redhorse were collected with a boat-mounted electrofisher. Effort was recorded as the number of seconds fished each sampling trip. Total length (mm) and weight (g) of each robust redhorse were recorded at the time of capture; location of capture (latitude and longitude) was recorded from a Trimble® global positioning unit, and a global position was determined by consulting United States Geological Survey quadrangle maps. Water quality variables were measured at each sampling location. Water temperature (°C) and dissolved oxygen (mg/l) were measured with a YSI® Model 52 dissolved oxygen/temperature meter. Also, water turbidity (NTU) was measured with a Hach® portable turbidmeter.

Capture techniques

Capture-recapture techniques were used to estimate the number of robust redhorse in the Oconee River. Each robust redhorse was examined visually for the presence of serially-numbered Floy anchor tags and electronically for the presence of a passive integrated transponder (PIT) tag. A Destron Fearing® Mini Portable Reader 2 was used to scan each robust redhorse for PIT tags. If either was detected, the number(s) were recorded, missing tags added, and the fish were released near the point of capture. If the fish did not have a tag, it was considered a new capture, and two serially-numbered Floy tags were anchored near the rear base of the dorsal fin. Also, a PIT tag was injected just posterior of the dorsal fin. Robust redhorse with tags that were attached prior to the sampling year were considered recaptures (same year recaptures were released without being counted).

Data compilation, evaluation, and testing model assumptions

Population estimates were generated from a dataset that was comprised of a subset (1994-1999) of the data collected by GA DNR and data collected during the present study (1999-2000). The pooled data was separated into six time periods (i.e., years). The capture history for each robust redhorse was compiled into matrix format for data analysis (Arnason et al. 1998). The classic Jolly-Seber (J-S) model, adjusted for small sample size (Pollock et al. 1990), was used to estimate population size, survival rate, recruitment, and capture probability (Table 1 and 2).

Open population techniques have several underlying assumptions that can significantly affect the accuracy of the estimates. Survival rate may change between time periods, but the model assumes all members of the population have the same probability of survival at each sampling event. Similarly, capture rate changes between time periods, but the model assumes all members of the population have the same probability of capture at each sampling event. Therefore, population estimates are biased because of heterogeneity of survival and capture of marked and unmarked individuals during sampling. These assumptions (i.e., data homogeneity is sufficient to provide reasonable estimates) were tested by evaluating the capture data with a chi-square goodness of fit test ($\alpha = 0.05$), which was contained in the software program POPAN-5 (POPulation ANalysis; Pollock et al. 1990; Arnason et al. 1998). This test did not reveal evidence of heterogeneity in survival ($\chi^2 = 2.651$, df = 3, $P > 0.05$) and capture rates ($\chi^2 = 0.241$, df = 4, $P > 0.05$) among years. These results indicated the capture data met the assumptions of the J-S model used to estimate population size.

Table 1. Notation for terms used in the Jolly-Seber model (modified from Pollock et al. 1990 and Arnason et al. 1998).

Parameter Abbreviation	Definition
n_i	sample size at *i*
m_i	number of marked animals captured in the *i*th sample
L_i	number of animals lost on capture (not released)
R_i	number of the n_i that are released after the *i*th sample (n_i-L_i)
r_i	number of R_i animals released at *i* that are captured again
z_i	number of animals captured before *i*, not at *i*, and captured again later
M_i	number of marked animals in population
N_i	population size at *i*
B_i	recruitment between *i* and *i*+1
ϕ_i	survival rate between *i* and *i*+1
p_i	capture probability for all animals in the *i*th sample

Table 2. Equations used by the Jolly-Seber population models to estimate various population parameters (Pollock et al. 1990).

$$\hat{M}_i = m_i + \frac{(R_i + 1)z_i}{r_i + 1} \quad (1.0)$$

$$\hat{N}_i = \frac{(n_i + 1)\hat{M}_i}{m_i + 1} \quad (2.0)$$

$$\hat{\phi}_i = \frac{\hat{M}_{i+1}}{\hat{M}_i - m_i + R_i} \quad (3.0)$$

$$\hat{B}_i = \hat{N}_{i+1} - \hat{\phi}_i(\hat{N}_i - n_i + R_i) \quad (4.0)$$

$$\hat{p}_i = \frac{m_i}{\hat{M}_i} \quad (5.0)$$

Sampling effort for robust redhorse was not uniform throughout the study (i.e., effort differed among sampling trips and among years). Because unequal CPUE can bias the population estimates, studies with unequal CPUE need to be adjusted. Therefore, SAS® was used to perform a one-way ANOVA, which was used to evaluate differences in CPUE among the six years (SAS 1985). If CPUE was significantly different ($\alpha \leq 0.05$) among years, population models would be adjusted, with CPUE as a covariate (Douglas and Marsh 1998). CPUE was not significantly different among years ($F = 0.76$; $P > 0.43$); therefore the models were not adjusted for effort.

Population estimation

Estimates of the number of robust redhorse in the Oconee River were derived with the Jolly-Seber population model as presented in the software program POPAN-5 (Arnason et al. 1998). In addition to the general J-S model, POPAN-5 derived population estimates with three related J-S models, each with a variation in the population parameters (e.g., survival). The estimate derived from the J-S full model was compared to estimates derived with models that held survival constant or held catch probability constant or held both survival and catch probability constant. These four models were evaluated with a goodness of fit test (i.e., UFIT in POPAN-5), which compared each constant probability model (e.g., survival and catch probability) to the J-S full model to determine which model best fit the capture data (Arnason et al. 1998; Lebreton et al. 1992). The model deemed to best fit the data was used to estimate the number of robust redhorse in the study reach.

The potential long-term fate (i.e., next 100 years) of the robust redhorse in the Oconee River was evaluated with the Simulate option of the POPAN-5 software program. Specifically, the current population size, survival rate, capture probability, number of new recruits, and the stochastic variation inherent in those data (for the six-year dataset) were used to estimate the size of the robust redhorse population in the study reach each year for the next 100 years. This simulation was run 200 times. The results of these replications were averaged for each year (Ferson et al. 1989; Ratner et al. 1997) and used to make inferences about the trends and possible extinction risk for the population of robust redhorse in the Oconee River (Arnason et al. 1998).

Results

Fish sampling and water quality

During the 5-month (October-February of 1999-2000) field season, we made 25 sampling trips and expended 80.2 hours in about 80 rm of the Oconee River. This effort resulted in the capture of 26 robust redhorse that ranged in length from 417 to 688 mm TL (mean = 615 mm; s.d. = 65 mm TL); their weight ranged from 1100 to 4900 g (mean =3600 g; s.d. = 821 g; Figure 2). Twelve of the 26 fish caught were recaptures.

Water quality varied with weather conditions and river flows. Water temperatures at sampling locations ranged from 7.3 to 19.9 $^{\circ}$C (Figure 3). Dissolved oxygen ranged from 6.9 to 10.5 mg/l (Figure 4). Finally, river turbidities, which increased following rain events and during water release from Sinclair Dam, ranged from 4 to 53 NTU (Figure 5).

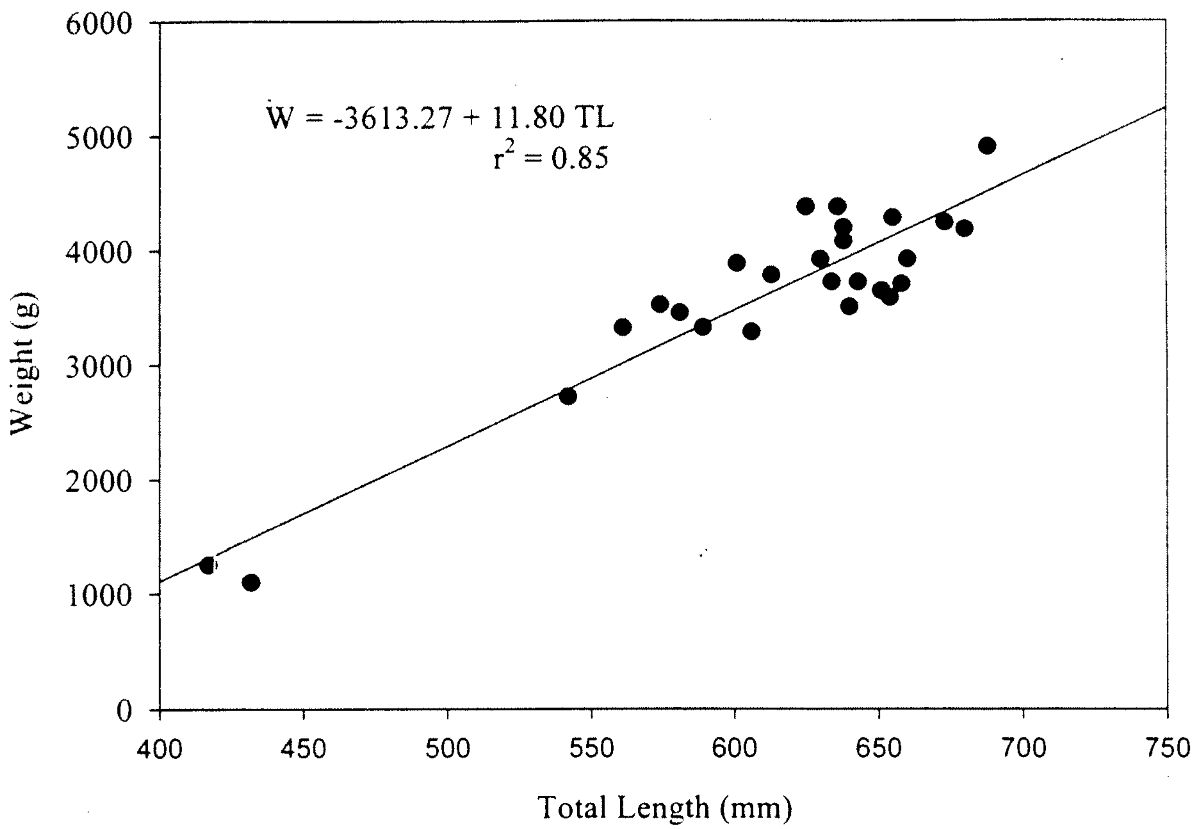

Figure 2. Total length (mm) and weight (g) of 26 robust redhorse (*Moxostoma robustum*) sampled from the Oconee River, Georgia during the winter (October 1999 - February 2000).

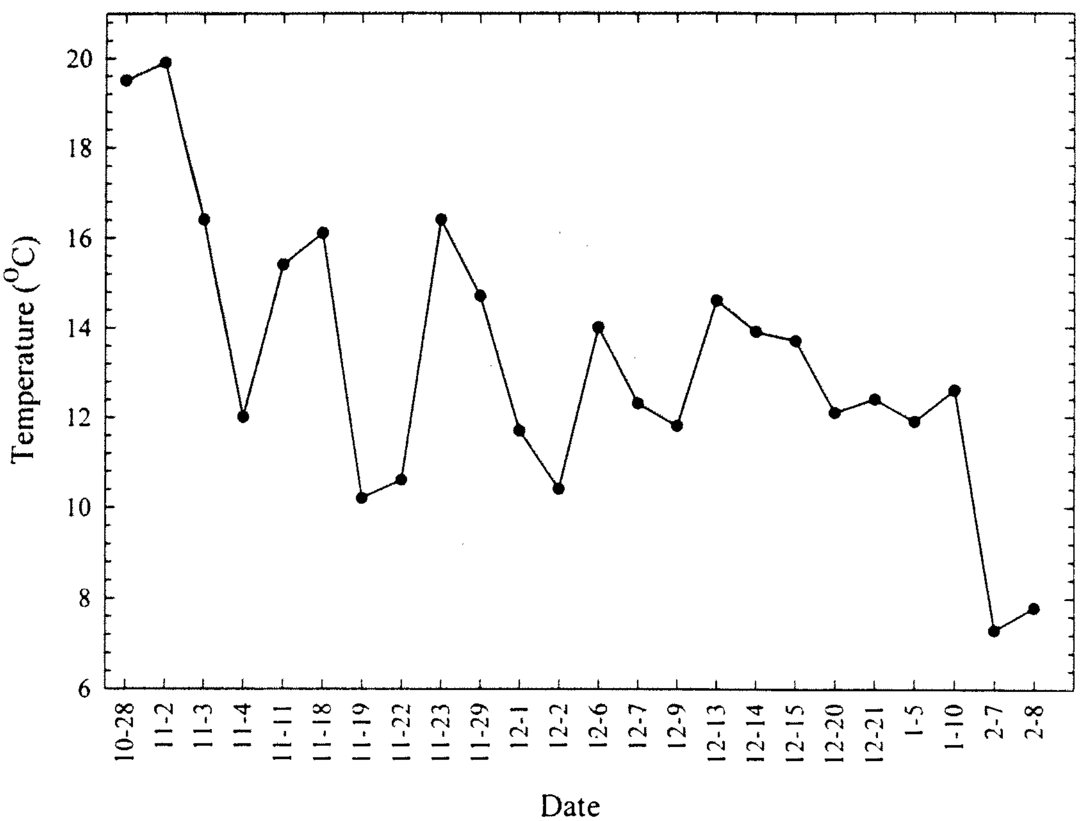

Figure 3. Water temperatures measured in the study reach of the Oconee River, Georgia from October 1999 - February 2000. Data were collected during electrofishing for the robust redhorse (*Moxostoma robustum*) population dynamics study.

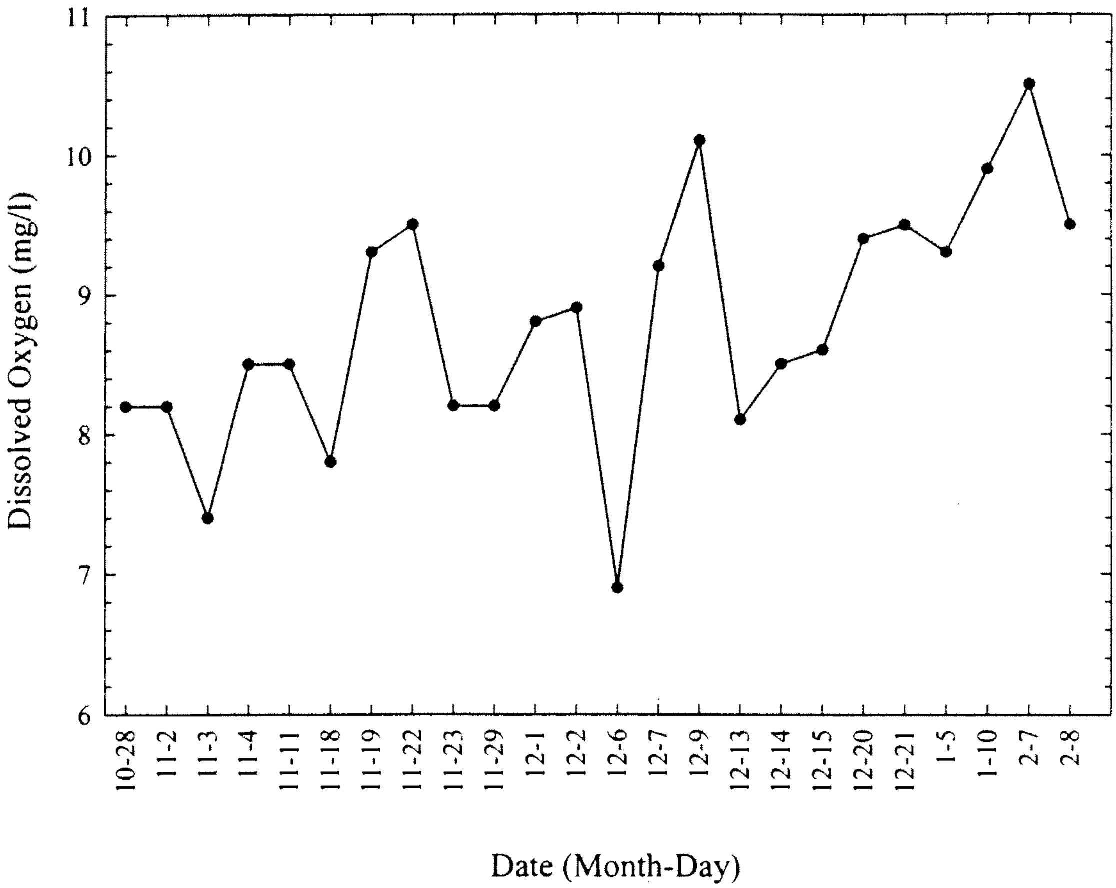

Figure 4. Dissolved oxygen (mg/l) measured in the study reach of the Oconee River, Georgia from October 1999 - February 2000. Data were collected during electrofishing for the robust redhorse (*Moxostoma robustum*) population dynamics study.

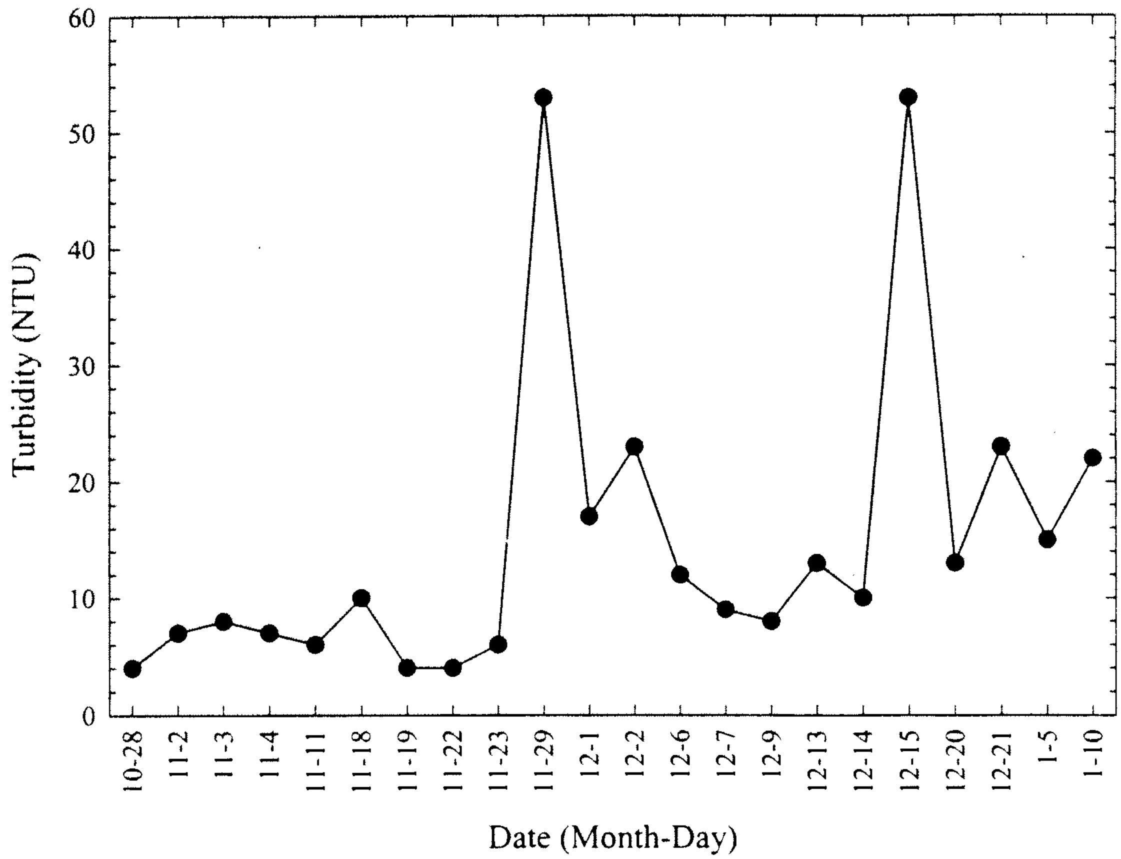

Figure 5. Water turbidities (NTU) measured in the study reach of the Oconee River, Georgia from October 1999 to January 2000. Data were collected during electrofishing for the robust redhorse (*Moxostoma robustum*) population dynamics study.

Model selection and population parameter estimation

The model selection results from POPAN-5 indicated that of the four model tested (i.e., J-S full, J-S with constant survival, J-S with constant capture probabilities, and J-S with constant survival and capture probabilities), the J-S full best fit the available catch data. According to this model, there were an estimated 607 (S. E. = 138) robust redhorse ≥ 417 mm TL in the study reach during 1998 (Table 3). This model does not compute estimates for the first or last year of sampling (e.g, 1999-2000) because previous or future capture data needed to derive the estimates are not available.

The J-S full model also estimated survival rate and number of new individuals recruited to the population. Our analysis indicated that survival of individual robust redhorse from year to year was high (e.g., ≥0.6054) for three of the four years for which there were estimates (Table 3). Additionally, new individuals (from about 5-57 % of the estimated population size) were recruited to the population annually.

The simulation results indicate that robust redhorse will persist in the study reach over the next 100 years, but the number of individuals will be variable (mean = 278; S. E. = 104) (Figure 6). Further, none of the 200 simulation-based estimates of future populations sizes were below about 100 individuals, and some estimates were as high as 1,200 individuals (Figure 6).

Table 3. Population estimates and standard errors (S. E.) for the Jolly-Seber full model (adjusted for small sample size) of robust redhorse (*Moxostoma robustum*; ≥417 mm TL) collected from the Oconee River, Georgia, between river miles 75 and 115. Jolly-Seber equations do not allow for estimates in the first and last years of a study (shown as – in the table).

	Population size		Capture probability		Survival rate		Recruits	
Year	$\hat{N}_i$	(S.E.)	$\hat{p}_i$	(S.E.)	$\hat{\phi}_i$	(S.E.)	$\hat{B}_i$	(S.E.)
1994	–	–	–	–	–	–	–	–
1995	475	(68)	0.2524	(0.0406)	0.6054	(0.0908)	48	(58)
1996	335	(62)	0.2835	(0.0565)	0.9900[a]	(0.0000)	191	(72)
1997	520	(79)	0.2171	(0.0370)	0.9900[a]	(0.0000)	92	(144)
1998	607	(138)	0.0478	(0.0138)	0.1044	(0.0198)	29	(17)
1999	–	–	–	–	–	–	–	–

[a]estimated to be 1.0000 by POPAN-5 (Arnason et al. 1998); manually entered as 0.9900 (to avoid out of range errors for survival rates > 1.0000), which causes S.E. to be set to 0.0000.

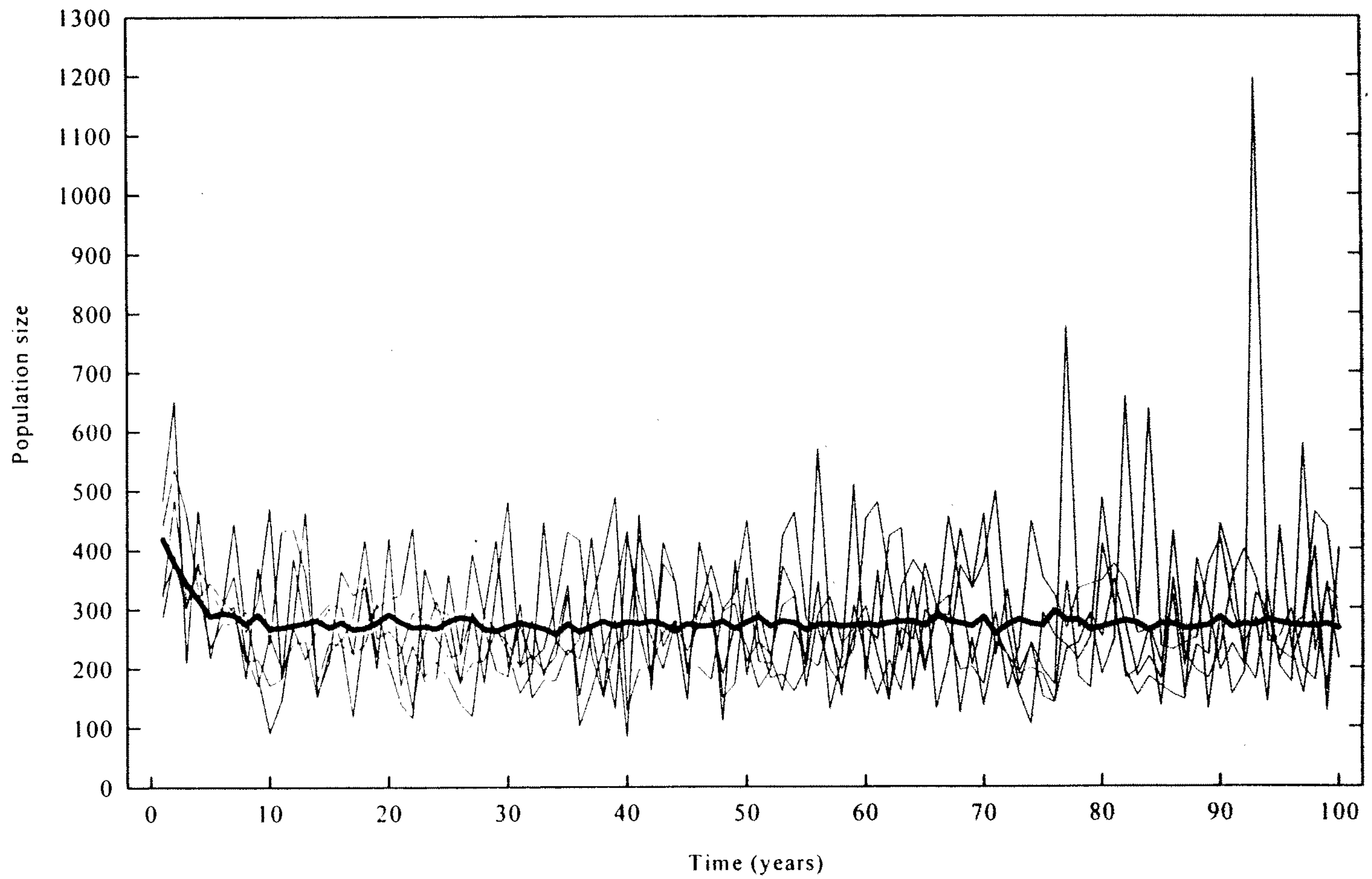

Figure 6. Five possible trajectories of estimated population sizes of robust redhorse (*Moxostoma robustum*) in the Oconee River, GA. These estimates were calculated with the Simulate option in the POPAN-5 program and were based on 200 replications, the grand mean of which is indicated in bold.

Discussion

Questions about the number, sizes, and distribution of robust redhorse in the Oconee River have existed since the species was rediscovered in 1991. These data are needed to assess the current status of the species in the Oconee River, to help develop conservation strategies to maintain the species in the Oconee River, and to establish self-sustaining populations in other medium to large rivers in the species' historic range. Progress has been made toward resolving some of these questions (e.g., distribution). Other questions, such as the number and sizes of robust redhorse in the river remain unknown, and the available data are inconclusive.

In this study, our objectives were to sample the entire reach where robust redhorse are suspected to occur and estimate the number of individuals in that reach. We estimated that about 607 robust redhorse $\geq$ 417 mm TL inhabited a specific portion of the study reach (Table 3). We were unable to estimate the number of individuals in the entire reach because we did not capture all sizes of fish (none were < 417 mm TL) and those we caught came from a relatively short reach (about 38% of that sampled). Low water conditions in the Oconee River during our study made navigation and sampling difficult. As a result, we were able to sample about 78 of the 90 river miles (about 87%) in the reach. Further, we only found fish in a 30-rm reach. River discharge, water depth, and the abundance of in-stream woody debris can affect the distribution of robust redhorse. Also, anecdotal observations of hatchery-reared robust redhorse suggest that the species is sensitive to disturbance and seems to prefer turbid water. We suspect that some of these factors may have affected our catch rates, but we are uncertain of which factor or combination of factors were responsible for the distribution of robust redhorse that we observed. As a result, our estimate, which may be conservative, applies only to the sizes of robust redhorse we caught and the reach of river where we found these fish.

Robust redhorse seem to avoid shallow (i.e., < 1 m), clear (turbidity < 10 NTU) water, which may have influenced catchability during our study. For example, robust redhorse were sampled from Dublin (about rm 75) upstream to about one rm above Black Creek (about rm 115). Although Jennings et al. (1996) documented robust redhorse upstream of this reach, we sampled upstream of Black Creek and downstream of Dublin without success (Figure 1). In another instance, we sampled the area just upstream of the Central of Geogia Railroad Bridge during a period when water depths were < 1 m and water turbidity was < 10 NTUs and did not capture any robust redhorse (Figure 1). However, after a single rain event that raised water level by about 2 m and increased turbidity to about 50 NTUs, we sampled this area again and caught robust redhorse (Figure 5). These results suggest that robust redhorse may have avoided much of the study reach during winter 1999-2000 because of shallow, clear water conditions brought on by drought conditions.

Robust redhorse may not become vulnerable to boat-mounted electrofishing gear until they reach a length of about 400 mm TL. The 417 mm TL specimen we caught is the smallest specimen ever collected with this gear. This apparent gear bias seems to be substantiated by the collection of small (200-300 mm TL) individuals in gillnets from an area where sampling with electrofishing was ineffective (Jennings, unpublished data; E. Betross - GA DNR, personal communication). Therefore, the absence of robust redhorse < 417 mm TL from all collection efforts (this study and others) may reflect gear-related, size-selectivity bias and not the effects of recent recruitment failure.

Despite the absence of robust redhorse < 417 mm TL in electrofishing samples from the Oconee River, new individuals are being recruited to the population annually (Figure 2). Further, the estimated probability of survival of these individuals from year to year was moderately high (mean = 67%). This is not surprising for a long-lived species with an estimated life span of at least 27 years (R. Jenkins - Roanoake College, personal communication). Therefore, the absence of significant declines in estimated population sizes or survival rate and a variable recruitment rate (Table 1) suggests that the Oconee River robust redhorse population is dynamic rather than static.

The population simulation results support the conclusion that the number of robust redhorse in the Oconee River is dynamic rather than stable and suggest that the species will persist for several generations (Figure 6). However, the simulation is unable to account for all variables in a system (Ferson and Burgman 1995). For instance, the simulated population parameters may not account for extreme environmental conditions that can be present in the Oconee River. Additionally, human effects on the ecosystem are difficult to predict and further complicate the interaction between robust redhorse and their environment. Additional information about age-specific survivorship (e.g., that of juveniles), lifetime fecundity, and age-distributions is still needed for more precise simulations.

Conclusions

Our results suggest that about 607 (S. E. = 138) robust redhorse ≥417 mm TL inhabited a limited reach (roughly from just upstream of the Central of Georgia Railroad trestle downstream to the city of Dublin) during the period for which we have data. However, low-water conditions and the relatively large size at which robust redhorse become vulnerable to electrofishing mandate that our estimate be viewed as conservative. New individuals were recruited to the populations annually; once recruited, their probability of surviving from year to year was moderately high. Finally, our simulation results, which assume that habitat suitable to robust redhorse remains at least as available as it is currently, suggest that the number of individuals ≥417 mm TL will be variable (mean = 278), but will persist for many generations. Although robust redhorse in the Oconee River seem not to be in imminent (e.g., 5-10 years) danger of extinction, their native range has been reduced, and unforeseen changes (i.e., environmental and anthropogenic) could still greatly affect the fate of this rare species.

This study was hindered by factors (i.e., low water conditions and gear-related size selectivity) beyond our control, which may have affected our results. Consequently, questions remain about the status of the species in the Oconee River. Questions about how best to sample juveniles also remain unanswered. Our results also suggest that water depth and clarity may be additional criteria that need to be considered in the evaluation of habitat availability for robust redhorse. Resolving these questions is critical to a better understanding of the population dynamics of robust redhorse in the Oconee River and elsewhere. Research aimed at addressing these questions should be given the highest priority.

Acknowledgments

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References

Arnason, A. N., C. J. Schwarz, and G. Boyer. 1998. POPAN-5: a data maintenance and analysis system for mark-recapture data. Scientific Report, Department of Computer Science, University of Manitoba, Winnipeg. viii+318 p.

Barrett, T. A. 1997. Hormone induced ovulation of robust redhorse (*Moxostoma robustum*). Master's thesis. University of Georgia, Athens, Georgia.

DeMeo, T. 1997. Robust redhorse conservation committee, annual meeting. Institute of Community and Area Development, Georgia Department of Natural Resources, Wildlife Resources Division. Social Circle, Georgia.

Dilts, E. W. 1999. Effects of fine sediment and gravel quality on survival to emergence of larval robust redhorse (*Moxostoma robustum*). Master's thesis. University of Georgia, Athens, Georgia.

Douglas, M. E. and P. C. Marsh. 1996. Population estimates/population movements of *Gila cypha*, an endangered cyprinid fish in the Grand Canyon region of Arizona. Copeia 1:15-28.

Douglas, M. E. and P. C. Marsh. 1998. Population and survival estimates of *Catostomus latipinnis* in northern Grand Canyon, with distribution and abundance of hybrids with *Xyrauchen texanus*. Copeia 4:915-925.

Evans, J. W. 1994. A fishery survey of Oconee River between Sinclair Dam and Dublin, Georgia. Georgia Department of Natural Resources, Wildlife Resources Division. Final Report, Federal Aid Project F-33. Social Circle, Georgia.

Evans, J. W. 1999. Recovery activities for the robust redhorse (*Moxostoma robustum*), April 1, 1997 - March 31, 1998. Georgia Department of Natural Resources, Wildlife Resources Division. Annual Progress Report prepared for the Robust Redhorse Conservation Committee. Charlie Elliott Wildlife Center, Mansfield, Georgia.

Ferson, S., L. Ginzburg, and A. Silvers. 1989. Extreme event risk analysis for age-structured populations. Ecological Modelling 47:175-187.

Ferson, S. and M. A. Burgman. 1995. Correlations, dependency bounds and extinction risks. Biological Conservation 73:101-105.

Freeman, B. J. 1998. Ecological studies on the robust redhorse (*Moxostoma robustum*) in the Oconee and Broad River Systems, Georgia. Final Report. United States Geological Survey, Biological Resources Division Research Work Order Number 37.

Hendricks, A. S. 1998. The conservation and restoration of the robust redhorse *Moxostoma robustum*. Volume 1. Georgia Power Company, Environmental Laboratory. Prepared for the Federal Energy Regulatory Commission. Washington, DC.

Jennings, C. A., J. L. Shelton, Jr., B. J. Freeman, and G. L. Looney. 1996. Culture techniques and ecological studies of the robust redhorse *Moxostoma robustum*. Annual Report for Project 25-21-RC295-378. Submitted to Georgia Power Company, Atlanta, Georgia.

Jennings, C. A., J. L. Shelton, Jr., and G. L. Looney. 1998. Culture techniques and ecological studies of the robust redhorse *Moxostoma robustum*: assessment of reproductive and recruitment success and incubation temperatures and flows. Annual Report for Project 25-21-RC295-378. Submitted to Georgia Power Company, Atlanta, Georgia.

Lebreton, J.-D., K. P. Burnham, J. Clobert, and D. R. Anderson. 1992. Modeling survival and testing biological hypotheses using marked animals: a unified approach with case studies. Ecological Monographs 62(1):67-118.

Modde, T., K. P. Burnham, and E. J. Wick. 1996. Population status of the razorback sucker in the Middle Green River (U.S.A.). Conservation Biology 10(1):110-119.

Pollock, K. H., J. D. Nichols, C. Brownie, and J. E. Hines. 1990. Statistical inference for capture-recapture experiments. Wildlife Monographs 107:1-97.

Ratner, S., R. Lande, and B. B. Roper. 1997. Population viability of spring chinook salmon in the South Umpqua River, Oregon. Conservation Biology 11:879-889.

Ruetz III, C. R. 1997. Swimming performance of larval robust redhorse: implications for recruitment in the Oconee River, Georgia. M.S. Thesis submitted to the University of Georgia, Athens.

Ruetz III, C. R. and C. A. Jennings. 2000. Swimming performance of larval robust redhorse (*Moxostoma robustum*) and low velocity habitat modeling in the Oconee River, Georgia. Transactions of the American Fisheries Society 129:398-407.

SAS Institute, Inc. 1985. SAS user's guide: statistics. Ver. 5 ed. Statistical Analysis Systems Institute, Inc., Cary, NC.

Walsh, S. J., D. C. Haney, C. M. Timmerman, and R. M. Dorazio. 1998. Physiological tolerances of juvenile robust redhorse, *Moxostoma robustum*: conservation implications for an imperiled species. Environmental Biology of Fishes 51:429-444.