Environ Biol Fish (2010) 87:43–53
DOI 10.1007/s10641-009-9561-9

Fine sediment affects on survival to emergence of robust redhorse

Cecil A. Jennings · Erik W. Dilts · James L. Shelton Jr. · Rebecca Cull Peterson

Received: 4 February 2009 / Accepted: 31 August 2009 / Published online: 12 November 2009

Abstract Robust redhorse (*Moxostoma robustum*) is a rare riverine sucker for which life history information is scarce. Spawning occurs over loose gravel substrate and eggs and larvae may be adversely affected by fine sediments among the gravel. A 2-year study was conducted to determine the threshold at which fine sediments are detrimental to successful egg incubation and larval emergence. Year 1 gravel treatments contained 0, 25, 50, and 75% fine sediments. Mean survival during Year 1 ranged from 63.5% in the 0% fine sediment treatment to 0% in the 75% fine sediment treatment. The results also indicated an adverse affect threshold between 0 and 25% fine sediment. Year 2 gravel treatments contained 0, 5, 10, 15, 20, and 25% fine sediments. Mean survival during Year 2 ranged from 69.8% in the 0% treatment to 9.1% in the 25% treatment. Year 2 results also identified the 15% fine sediment treatment as the threshold at which survival began to decline. Substrates at one known spawning area used by robust redhorse typically contain 25 to 50% fine sediment, but the spawning act cleans some fines from the egg pocket. Whether the "cleaning" that results from the spawning act reduces the fines sufficiently to avoid adverse effects is unknown. According to our results, survival rates of robust redhorse eggs and larvae are predicted to be about 8.0% or less when fine sediment is >25%.

Keywords Oconee River · Catostomidae · Sediment pollution · Survival-to-emergence · Spawning success · Warmwater river

Electronic supplementary material The online version of this article (doi:10.1007/s10641-009-9561-9) contains supplementary material, which is available to authorized users.

C. A. Jennings (✉)
U. S. Geological Survey,
Georgia Cooperative Fish and Wildlife Research Unit,
D.B. Warnell School of Forestry and Natural Resources,
University of Georgia,
Athens, GA 30602, USA
e-mail: Jennings@warnell.uga.edu

E. W. Dilts · J. L. Shelton Jr.
D. B. Warnell School of Forestry and Natural Resources,
University of Georgia,
Athens, GA 30602, USA

R. C. Peterson
Georgia Cooperative Fish and Wildlife Research Unit,
D. B. Warnell School of Forestry and Natural Resources,
University of Georgia,
Athens, GA 30602, USA

Present address:
E. W. Dilts
CenterPoint Energy,
525 Milam Street,
Shreveport, LA 71101, USA

Introduction

Robust redhorse (*Moxostoma robustum*; Castostomidae) are large, riverine suckers that occupy a limited

range in the American states of Georgia, South Carolina and North Carolina. This rare fish is found in Upper Coastal Plain and Piedmont rivers along the Atlantic slope drainage ranging from the Pee Dee River in the Carolinas to the Altamaha River system in Georgia (Evans 1994; Jennings et al. 1996). Robust redhorse were first described by Edward Drinker Cope (Cope 1870), but went unnoticed for more than 120 years until 1991 when a few individuals were collected in the Oconee River, Georgia. After the species rediscovery, a review confirmed that two unknown redhorses collected in the 1980s from the Savannah River, Georgia/South Carolina and the Pee Dee River, North Carolina, were robust redhorse. Relatively few robust redhorse of all age classes have been collected range-wide. Although a few hatchery-reared juveniles have been collected, wild-spawned juveniles have not been collected in the Oconee River since the species was rediscovered.

Robust redhorse spawn in triads composed of one female flanked by two males, and the spawning act occurs over loose gravel substrate in moderate to swift current (described in Jennings et al. 1996). The spawning trio quiver energetically and use their anal and caudal fins to make pockets in the gravel into which eggs and sperm are deposited. This process is consistent with observations of other species in the genus *Moxostoma* (Burr and Morris 1977; Jenkins and Jenkins 1980; Kwak and Skelly 1992) and results in egg burial depth of 6 to 15 cm for robust redhorse (Freeman 1998). Generally, spawning occurs during a two-week period of time and occurs when water temperatures are between 20–24°C (Ruetz and Jennings 2000). Spawning has been documented as early as the end of April and as late as the second week of June in the Oconee River. Robust redhorse eggs hatch in 3.5 days under incubation temperatures of 23°C in laboratory conditions (J. Zelco, US Fish and Wildlife Service, personal communication). Larval robust redhorse hatch and remain in the interstitial spaces of the gravel substrate until most of the yolk sac has been absorbed. Larvae emerge from the gravel and begin exogenous feeding at about 13 millimeters (mm) total length (TL; Jennings et al. 1996).

Initial concerns about this species' survival centered on a skewed length-frequency histogram in which fishes less than 400 mm TL were absent from the Oconee River population. This absence and the abundance of old, large individuals led to speculation that the population may have been senescent. However, the discovery of a spawning aggregation in the Oconee River during spring 1995 refuted that idea (Jennings et al. 1996). The gravel bar where robust redhorse spawn is located downstream of a hydropower facility, which produced highly variable flows during its generation cycle. This flow variability was the basis of the next hypothesis advanced to explain the skewed length-frequency histogram. Specifically, there was concern that high discharge during hydropeaking operations may flush eggs and newly hatched robust redhorse from incubation and rearing habitats. Research aimed at addressing this question documented a strong swimming ability of larval robust redhorse and the persistence of suitable habitat in the Oconee River during hydropower generation (Ruetz and Jennings 2000). Because robust redhorse spawn in lose gravel, concern then focused on eggs and larval survival following deposition in the gravel at the spawning site.

Although spawning has been observed at only one area in the lower Oconee River, gravel substrates similar in composition to the observed spawning location occur within the known range of the Oconee population (EA 1994). Robust redhorse eggs have been collected from the gravel substrate at the known spawning site and larvae have been collected nearby, which suggests that spawning adults are successful in depositing fertilized eggs in the gravel (Jennings et al. 1996). However, low numbers of larval robust redhorse have been collected from the lower Oconee River (Jennings et al. 1996). Whether the low abundance of larvae in samples is related to their actual abundance or sampling inefficiency (e.g., gear or habitat) is unknown. As a result, questions exist about the survival-to-emergence (STE) from the gravel substrate in which the eggs are deposited.

The hyporheic zone is an area in gravel substrates that contain interstitial voids of flowing environments (Shields et al. 1992). Deposition of fine sediments in the hyporheic zone of gravel substrates adversely affects reproduction of fish that spawn within gravel substrates (Shields et al. 1992). Effects of sediments on reproductive success of coolwater fishes such as salmonids are well documented (Koski 1966; Bjornn 1969; Hall and Lantz 1969; Phillips et al. 1975; Hausle and Coble 1976; Chapman 1988; and many others), but there is less research and documentation of the affects of sediment pollution on warmwater fish

species (Muncy et al. 1979). Ichthyofaunal studies have found a correlation between siltation of spawning habitat and a decline in some warmwater fish populations (Smith et al. 1973; Berkman and Rabeni 1987), but these studies have not identified the actual limiting factor causing the decline.

There are several characteristics of gravel beds that are important for successful hatching and larval emergence of lithophilic–spawning fishes. For example, there needs to be appropriate size and availability of interstitial voids in which developing eggs and larvae can reside. There also needs to be sufficient gravel permeability to allow hyporheic flow to supply dissolved oxygen (DO) to developing eggs and larvae and to disperse metabolic wastes (Coble 1961). In addition, loose gravel substrates are important because larval emergence could be prevented if surface sediments are armored (Waters 1995).

In this paper, we present the results of a 2-year, laboratory-based experiment to determine if the low larval densities and absence of juvenile robust redhorse in the Oconee River could be related to excessive amounts of fine sediment in the spawning substrate used by adult robust redhorse. Objectives for this study were to: 1) measure STE of larval robust redhorse across a large scale of percent fine sediment during Year 1; 2) based on results from Year 1, refine the scale of percent fine sediment and measure STE of larval robust redhorse during Year 2, and 3) document DO concentrations to which developing robust redhorse eggs and larvae are exposed while they are in the gravel.

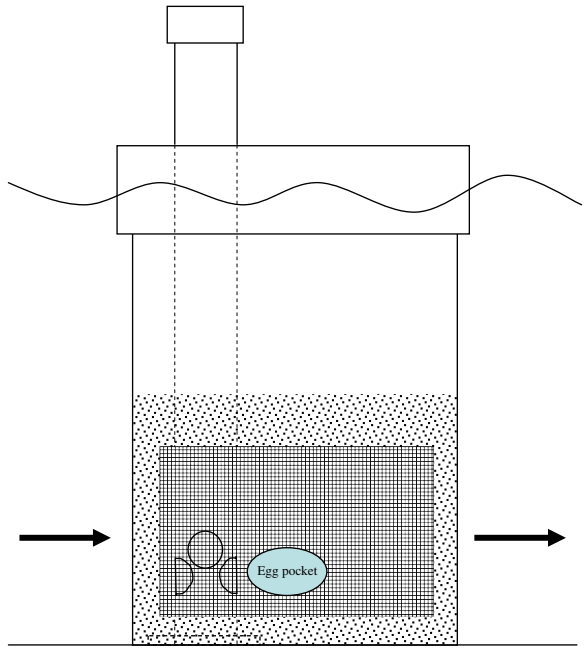

Fig. 1 Diagram of incubation cell (15.5 L square bucket) used to house gravel treatments and incubate robust redhorse eggs and larvae. The grid is the 15×10 cm fiberglass mesh screen and the small dots represent the gravel mixture. The standpipe (3.2 cm diameter, 40 cm long) with holes (1.9 cm diameter) allowed dissolved oxygen concentrations to be monitored at depth of the egg pocket. Arrows denote direction of water flow

Methods

Experimental apparatus

Incubation cells were produced by cutting a 15×10-cm panel out of each of the four sides of a 15.5-L plastic square bucket (Fig. 1). The resulting openings were covered with 2 mm fiberglass mesh that was glued in place with 100% silicone. This mesh size allowed cell contents to be retained without impeding water flow through the cell. A polyvinyl chloride (PVC) standpipe, 3.2 cm diameter and 40 cm long, attached to a small plexiglass base was placed near the egg pockets in each cell (Fig. 1). These standpipes were perforated with eight, 1.9-cm diameter holes around their circumference and covered with a strip of 2 mm fiberglass mesh to prevent intrusion of the incubation cell contents into the standpipe. These perforations were positioned such that DO concentrations at the depth of egg burial could be measured. The standpipes were capped between observations to minimize surface–water gas exchange. A larger PVC standpipe (7.6 cm diameter, 15 cm long) was temporarily inserted in each of the incubation cells to facilitate the introduction of fertilized robust redhorse eggs to the incubation cell and was removed before the experiments commenced.

Incubation cells were placed in two large holding tanks (4.8 m in length, 1.4 m wide, and 0.8 m deep) and set in a grid-like pattern so incubation cells were interspersed around non-incubation cells, which did not contain perforations or eggs (Fig. 2). This arrangement minimized channeling of water flow around the incubation cells. Experimental gravel mixtures (i.e., % fine sediment treatment) were randomly assigned to each incubation cell.

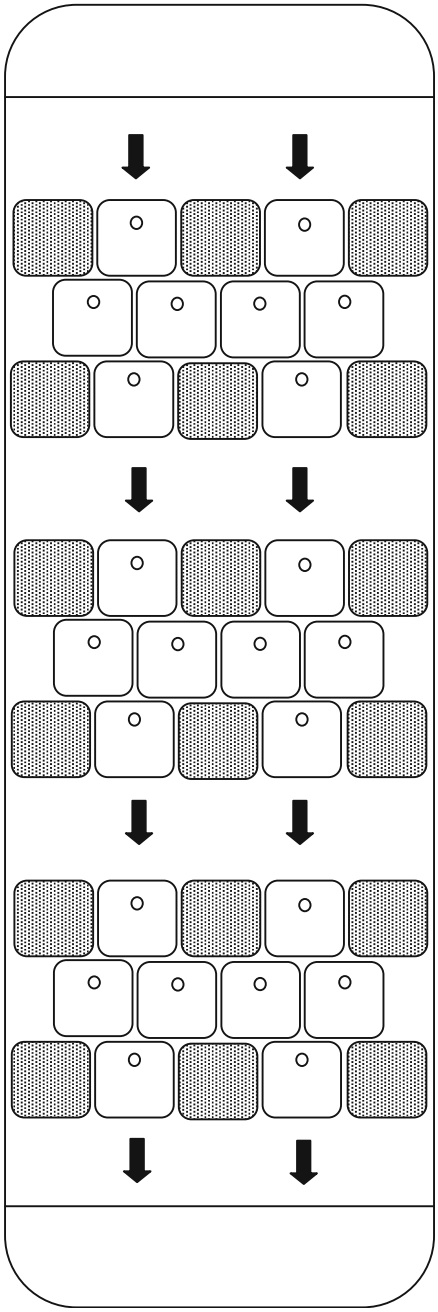

Fig. 2 Grid-like arrangement of incubation cells (white) and non-incubation cells (shaded) used to test the affects of fine sediment on survival of eggs to larval emergence robust redhorse. Circles represent standpipes used to monitor dissolved oxygen concentrations, which are upstream of egg pockets. Arrows denote direction of water flow

Water level of the holding tanks covered about 95% of the height of the incubation cells and prohibited emergent larvae from swimming out of the incubation cells into the main tanks. Water flow was supplied by gravity return of water from the recirculation system head-tank and was supplemented with two submersible sump pumps in each tank. Acrylic baffles of differing heights aerated tank water and created directional flow through the tank. This system enabled a total flow rate of 255 L^{-min} to be maintained through each tank over the duration of the experiment. Water temperature was regulated between 21 and 23°C with a 1-hp water chiller. These temperatures matched those commonly observed in the Oconee River during the spawning period of robust redhorse (Ruetz and Jennings 2000).

Gravel treatments

This experiment was conducted over two years. Year 1 experimental gravel treatments contained 0, 25, 50, and 75 % fine sediments; and based on Year 1 results, Year 2 experimental gravel treatments contained 0, 5, 10, 15, 20 and 25% fine sediments. The general design of the experiment was based on similar studies conducted on salmonid survival to emergence (Phillips et al. 1975; Hausle and Coble 1976).

Year 1

Commercially available rolled river rock was washed and shaken through a series of five standard sieves (2.0-, 8.0-, 16.0-, 25.0-, and 50.0-mm) to obtain four size classes of gravel. These separate classes of gravel were then combined to obtain a control mixture that consisted, by volume, of 20% 2.0–7.0 mm, 10% 26.0–50.0 mm, 30% 8.0–15.0 mm, and 40% 16.0–25.0 mm diameter gravel. This control gravel mixture reflected the relative abundances of the size classes of gravel at a known robust redhorse spawning site in the Oconee River (EA 1994) and preliminary field surveys at other locations in the river. Commercially available sand was chosen as a suitable representation of the fine sediment (particles <2.0 mm in diameter) found in the lower Oconee River. Prior to being placed into the incubation cells, the experimental gravel mixture was inoculated with sufficient amounts of sand to obtain four experimental gravel treatments containing 0, 25, 50, and 75% fine sediment by volume. There were three replicates of each experimental mixture.

Year 2

The rolled river rock used in Year 2 was slightly smaller than those used in Year 1 and more similar to that found in the lower Oconee River. River rock was washed and shaken through a series of five standard sieves (2.0-, 8.0-, 16.0-, 25.0-, and 37.5-mm) to obtain four size classes of gravel. This mixture consisted (by volume) of 10% 25.0 - 37.5 mm, 40% 16.0–25.0 mm, 30% 8.0–16.0 mm, and 20% 2.0–8.0 mm diameter gravel. Prior to being placed in the incubation cells, the experimental gravel mixture was then inoculated with sufficient amounts of sand to obtain six experimental gravel treatments containing 0, 5, 10, 15, 20 and 25% fine sediment by volume, with four replicates of each experimental mixture.

Egg introduction and monitoring protocol

Fertilized eggs were obtained from a single crossing of wild-caught brood each year. Eggs were immediately transported (three hour drive) from temporary holding and incubation facilities on the Oconee River to the Whitehall Fisheries Laboratory at the University of Georgia. Ten ml of fertilized eggs were placed in each incubation cell during each year of this experiment. In Year 1, there was a mean of 27.9 eggs·ml^{-1}, and in Year 2 there was a mean of 24.5 eggs·ml^{-1}. Eggs were placed in the center of the screened-in section of the egg chamber. Percent STE was calculated as the number of larvae collected divided by the mean number of eggs placed in the incubation cell. At the time of the experiment, egg deposition depth in gravel substrate was unknown; therefore, eggs were placed at a depth of 5 or 10 cm during Year 1. Results from Year 1 indicated that there was not a significant difference in STE between the two depths (i.e., 0% fines=~60% STE, 25% fines=~8% STE, and 50% and 75% fines=~0% STE; Dilts 1999); therefore, all eggs were buried at a depth of 5 cm deep during Year 2.

Daily observations for larval emergence in experimental cells were conducted, and DO concentration (mg·L^{-1}) within each cell was recorded at egg burial depth with a calibrated YSI® Model 55 dissolved oxygen meter. Larvae were collected and preserved in 10% formalin upon emergence from the gravel. Emergence was deemed complete when no larvae emerged from all treatments for two consecutive days following peak emergence. Preserved larvae were later enumerated, and total lengths were measured to the nearest 0.1 mm with a dial caliper.

Data analysis

All data were tested for normality with the Shapiro-Wilkes test (SAS Institute 1990) and for homogeneity of variances with Hartley's F-max test (Sokal and Rohlf 1981). Results of the Shapiro-Wilkes test indicated that the STE data were not normally distributed. Transformation failed to normalize the distribution, and an F-max test indicated that the variances of the data set were homogeneous. In Year 1, differences in mean STE between the gravel treatments examined were analyzed with analysis of variance (ANOVA) of the ranked data (McCullagh and Nelder 1983). Orthogonal contrasts were used to evaluate differences in mean larval STE among treatments. In Year 2, a three-parameter sigmoidal regression model was used to describe the relationship between STE and percent fine sediment infestation. Mean DO concentrations among treatments were compared with repeated measures ANOVA and means separation tests. An alpha=0.05 was used to evaluate the significance of all statistical tests.

Results

An unexpected complication arose during the course of this study. The 2-mm mesh screen used in the incubation cells was a sufficient size to prevent robust redhorse egg loss from the incubation cells, but not of sufficient size to fully contain pre-swim-up (i.e., yolk sac) robust redhorse larvae that exhibited lateral migration. Consequently, 334 larvae were collected outside the incubation cells during Year 1. These escaped larvae represented 5.0 % of the initial amount of eggs placed in each of the trials. In Year 2 there were 596 larvae outside the incubation cells, which represented about 10% of the total number of eggs. This loss was deemed nominal. Because we could not determine the origin of the larvae swimming free outside the incubation cell, the escapement rate was

assumed to be equally distributed among treatments and replicates.

Year 1

Incubation period and timing of larval emergence

Larval emergence began five days after egg fertilization; peak emergence occurred at 16 days post-fertilization. After peak emergence, larvae continued to emerge intermittently at low rates until day 35. Larvae that emerged on day 11 and later actively swam throughout the water column in the incubation cells, but most remained near the surface. Larvae exhibited an avoidance response during collection periods, with some larvae attempting to seek refuge in the substrate in the incubation cells. These larvae would either seek refuge in the interstitial spaces of the upper substrate layer or lie motionless just above the substrate. Their coloration effectively camouflaged them against the substrate.

Larval emergence

Mean larval length (TL) at emergence varied significant among the treatments ($p<0.0001$). Larvae that emerged from the 75% fine sediment treatment were significantly smaller (10.4 mm TL, SE=0.055) than the larvae that emerged from the other treatments. Mean lengths of emerging larvae were the same from the 0% (12.9 mm TL; SE=0.011), 25% (12.9 mm TL; SE=0.025), and 50% (12.9 mm TL; SE=0) fine sediment treatments.

There was an inverse relationship between larval robust redhorse STE and increasing levels of fine sediment, with a mean STE that ranged from 63.5% in the 0% fine sediment treatment to 0% in the 75% fine sediment treatment (Fig. 3). Variation in mean percent STE between treatments containing differing concentrations of fine sediment was significantly different ($P<0.0001$). Mean larval STE in the 0% fine sediment treatment was highest compared to 25, 50, and 75% fine sediment concentrations ($P<0.0001$; Fig. 3). Mean larval emergence at 25% fine sediment concentration was significantly greater than the 50 and 75% fine sediment ($P<0.0002$; Fig. 3). Mean larval STE in 50 and 75% fine sediment treatments were not different ($P=0.48$; Fig. 3).

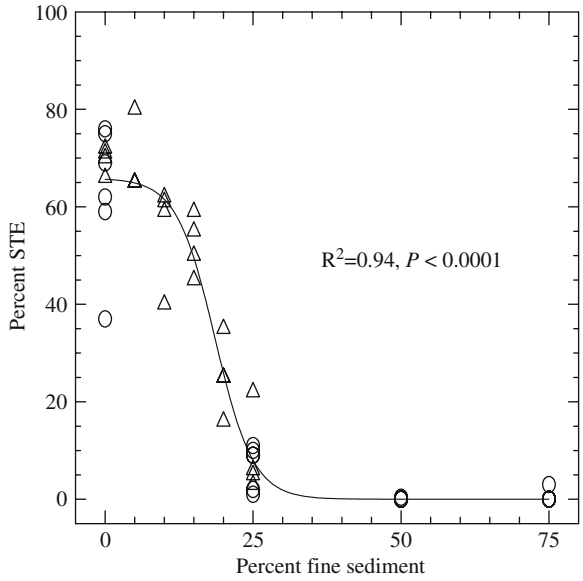

Fig. 3 The affect of increasing levels of fine sediment on survival to emergence of robust. Emergence rates observed in individual replicates during Year 1 are represented by (○) and those observed in individual replicates during Year 2 are represented by (△)

Year 2

Incubation period and timing of larval emergence

Larval emergence began 11 days after fertilization and peaked at days 16 and 17 post-fertilization. Low levels of intermittent larval emergence were observed until day 27 post-fertilization. Larvae that emerged after day 11 swam actively throughout the water column enclosed by the incubation cells, but most aggregated near the surface. Larvae exhibited an avoidance response similar to that displayed during collection attempts in Year 1.

Larval emergence

Mean larval emergence during Year 2 varied among the treatments and was highest in the control mixture without fine sediment (69.8%; SE=0.01) and lowest in the 25% fine sediment treatments (9.1%; SE=0.04). STE in the treatments containing 20 and 25% fine sediments were drastically lower than STE in the treatments containing <20% fine sediments (Fig. 3). An inverse relationship existed between percent fine sediment levels and larval STE ($P<0.0001$). This relationship was non-linear ($P<0.0001$) and was best

described by a three-parameter sigmoidal model (R^2= 0.89). Combining emergence data from Year 1 and Year 2 resulted in a better fit of this model (R^2=0.94; Fig. 3).

Affect of fine sediment on dissolved oxygen concentration

Year 1

Repeated measures ANOVA indicated that dissolved oxygen concentrations varied significantly over the course of the experiment (P<0.0001). Regardless of egg burial depth (i.e., 5 or 10 cm), mean dissolved oxygen concentrations in treatments that contained 0 and 25% fine sediment were higher (7.5–7.6 mg·L^{-1}) than those in the 50% and 75% fine sediment treatments (6.3–7.5 mg·L^{-1}; Fig. 4). On days 2 and 3, DO in the 50% and 75% treatments fell below 5.0 mg·L^{-1}, but returned to above 5.0 mg·L^{-1} on day 4 and remained there for the duration of the study. Mean dissolved oxygen concentrations in treatments that contained 75% fine sediment and an egg burial depth of 5 cm did not differ from those in 0 and 25% fine sediment treatments. This lack of difference was attributed to substrate settling in the 75% fine sediment treatments, which exposed perforations in the standpipe of the 5-cm burial depth treatments. Consequently, dissolved oxygen concentrations measured in replicates of this treatment were more indicative of water column conditions than hyporheic conditions. Comparison of daily mean DO concentrations demonstrated that DO concentrations in the 50 and 75% fine sediment treatments were much lower than those in the 0 and 25% fine sediment treatments for several days following egg introduction. After that period, dissolved oxygen concentrations in the higher fine sediment treatments increased, but never equaled those of the lower fine sediment treatments.

Year 2

Mean DO concentrations in the treatments ranged from 7.8 mg·L^{-1} (SE=0.00) to 7.9 mg·L^{-1} (SE= 0.029) and did not vary within treatments (P= 0.1377). Similarly, mean DO concentration did not differ among the five treatment levels of fine sediment (P=0.7006).

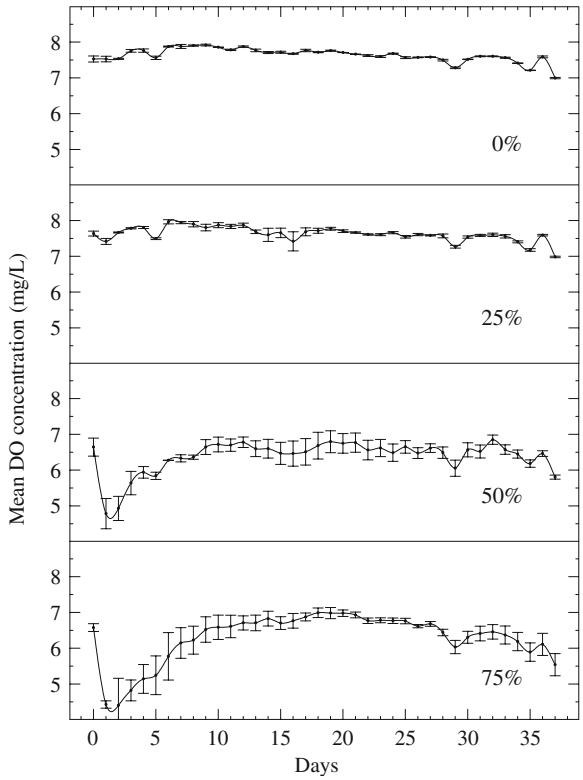

Fig. 4 Mean daily dissolved oxygen (mg/L) concentrations for Year 1 in 0, 25, 50, and 75% fine sediment for egg burial depth at 10 cm. Error bars represent standard error. Dissolved oxygen (DO) dropped below 5 mg·L^{-1} on days 2 and 3 for 50, and 75% fine sediment. DO was in acceptable ranges for all other days and treatments

Discussion

Incubation period and larval behavior

Larval incubation and emergence periods were similar in both study years with peak emergence at 16 days. This is similar to reports made in other laboratory or hatchery conditions (Ruetz and Jennings 2000; Weyers et al. 2003). Generally, larval robust redhorse begin to swim-up about 11 to 14 days following fertilization, with larval emergence completed about 30 days post-fertilization. These data suggest that emergence of larvae in the wild may continue for much longer than the 2-week emergence time suspected previously. Therefore, emerging larvae may be affected by fluctuating river flows during the spawning and rearing period for longer than anticipated. In addition, such flows might prematurely scour developing eggs and larvae from incubation

substrates (Montgomery et al. 1996). For example, simulated river flows greater than 35 $cm \cdot s^{-1}$ adversely affected the ability of emerged larvae to swim to the surface to inflate their air-bladders, which causes lower survival (Weyers et al. 2003). High-velocity flows also may cause further infiltration of fine sediments into the gravel matrix (Sear 1993). Fine sediment pollution is one of many factors that affect reproductive success in fishes that spawn in gravel substrates (e.g., Meyer et al. 2005). We did not directly evaluate these factors (e.g., suspended sediment flux or predation) in our laboratory trial, but they too may influence the STE of wild-spawned larval robust redhorse.

The presence of pre-swim up larvae (i.e., yolk-sac larvae) outside the incubation cells confirms that incubating larval robust redhorse move laterally among interstitial spaces in gravel substrates. We could not determine which treatments were the sources of the free-swimming larvae; therefore, we attributed these larvae equally as coming from all treatments. With such a low occurrence (5–10%) we don't believe our findings were compromised. During Year 1 the lateral movement observed was hypothesized to be related to excessive amounts of fine sediments; however, lateral movement also occurred during Year 2. Whether the lateral movement by escaped larvae was in response to unfavorable microhabitat conditions associated with fine sediment pollution or is a preparatory behavior in response to imminent ontogenetic shifts in habitat (i.e., preparing to swim up) is unknown. If interstitial lateral movement is preparatory behavior for swimming up, then the small area of the incubation cell may explain why these larvae encountered the mesh screen and escaped. However, if the lateral movement is in response to excessive fine sediment, the threshold (i.e., 15%) at which reduced STE occurred in this study may provide a meaningful management objective to ensure continued or improved recruitment of larval robust redhorse in Oconee River.

Sediment pollution could result in premature larval emergence. In the present study, larvae from the 75% fine sediment treatment emerged earlier (day 5) and were smaller (10.4 mm TL) and less developed (i.e., yolk sac not absorbed) than those in the other treatments (days 12–13; 12.9 mm TL; yolk mostly absorbed). Early larval emergence of yolk-sac larvae from gravel substrates can have adverse affects on survival in the wild because of decreased swimming performance of less-developed larvae (Ruetz and Jennings 2000). Premature larval emergence may result in increased mortality associated with downstream displacement and increased vulnerability to predation (Harvey 1987 and 1991).

Effect of fine sediment on larval emergence

At the time of the experiments, robust redhorse egg deposition depth was unknown and five to ten centimeters were chosen as plausible egg burial depths. In a subsequent field study, freeze cores of gravel where robust redhorse had been observed spawning, indicated egg burial depths ranging from 6–15 cm (Freeman 1998). Therefore, the laboratory-based experiments were held at appropriate egg burial depths.

The inverse relationship between STE of larval robust redhorse and fine sediment pollution in rearing substrates during Year 1 demonstrated that the threshold at which STE declined was between 0 and 25% fine sediment. During Year 2 that threshold was indentified to be about 15% fine sediment. The nonlinear nature of this inverse relationship implies that robust redhorse larvae are reasonably tolerant of fine sediment until that threshold concentration is reached. Above this threshold, larval emergence declines rapidly. Generally, the STE patterns observed for larval robust redhorse is consistent with reported results for salmonids. For example, mean emergent survival for coho salmon ranged from 96% in a control gravel mixture lacking fine sediment (less than 3.3 mm diameter) to 8% in gravel containing 70% fine sediment (Phillips et al. 1975). In addition, fine sediment (smaller than 3.3 mm) was highly correlated with decreased survival in coho salmon (Koski 1966).

Affect of fine sediment on hyporheic dissolved oxygen concentration

Large amounts of fine sediment reduce intragravel water velocities of gravel substrates (Reiser and White 1988), which may reduce DO within the substrate. The reduction in DO may adversely affect developing eggs and larvae buried by either a direct decrease of oxygen, and/or allow metabolic waste to accumulate resulting in a decreased supply of oxygen

(Tappel and Bjornn 1983; Chapman 1988; Reiser and White 1988; Greig et al. 2005). DO in the 50% and 75% treatments fell below 5.0 $mg{\cdot}L^{-1}$ on days 2 and 3, but returned to above 5.0 $mg{\cdot}L^{-1}$ on day 4 in Year 1. These results suggest that fine sediment greater than 50% reduces DO concentrations compared to gravel substrates with 25% fine sediment load. This temporary drop in DO may have been caused by decomposition of larvae and eggs in the incubation cells. DO concentrations during Year 2 remained well above the 5 $mg{\cdot}L^{-1}$ recommended for survival and growth of most fishes (Piper et al. 1982).

Oxygen requirements of salmonid embryos rise to a maximum just before hatching (McNeil 1966; Greig et al. 2005), with larvae tolerating lower dissolved oxygen concentrations than embryos (McNeil 1966). Year 1 results suggested low initial DO and entombment as the two primary mechanisms responsible for the reduced larval STE. In Year 2, DO was well above the levels that affect fish survival; therefore, the declines in larval emergence observed probably resulted from larval entrapment.

Implications for recruitment

The present condition of many streams in the Midwest and Southeast is drastically different from that which existed prior to European settlement and agricultural development (Fajen and Layzer 1993). Since the turn of the 19th century, poor silvicultural and agricultural practices throughout the Oconee River watershed have drastically increased the sediment load in the rivers within the basin (Trimble 1977; Luft 1986; EA 1994). The Oconee River was still recovering from this massive sediment increase, which peaked in the early 1900s (Luft 1986), when Sinclair Dam was constructed in Milledgeville, Georgia in 1953. The reservoir formed by Sinclair Dam acts as an efficient sediment trap; however, the river remains in disequilibrium and continues to entrain, transport, and redeposit previously stored sediments (Trimble 1977; Ruhlman and Nutter 1999). Consequently, the current bed load of the Oconee River is probably still representative of historical inputs of excessive fine sediment, and the gravel deposits used by spawning robust redhorse are typically composed of 25 to 50% fine sediment (EA 1994).

Our research suggests that fine sediment pollution of gravel substrates may be a potential threat faced by incubating robust redhorse eggs and larvae in the Oconee River. STE rates are predicted to be about 8.0% when fine sediment composition is 25%. However, the percentage of fine sediment in spawning substrates is not uniform, and fine sediments are swept from the gravel substrates as robust redhorse deposit eggs (i.e., a sediment plume commonly observed during spawning). This "gravel cleaning" during spawning has been observed in other species. For example, clay and silt particles have been suspended and swept downstream during salmonid spawning; interestingly, sand particles remained in the egg burial site during this process (Kondolf et al. 1993). The extent to which robust redhorse recruitment in the Oconee River is constrained because of fine sediment infestation or whether the current level of larval recruitment is sufficient to maintain the population is unknown.

Runoff control and soil stabilization projects, particularly procedural controls (Wesche 1993), combined with effective interdiction measures have the potential to reduce the sediment load of the Oconee River and improve the spawning habitat available to adult robust redhorse.

Restorative processes that remove excessive fine sediment from the spawning gravel in the Oconee River would benefit the robust redhorse; however, such processes are time consuming and costly (see review by Waters 1995). Flushing flows and stream alterations can remove fine sediment from some areas, but may also increase fine sediment concentrations farther downstream. Sediment traps and gravel cleaning devices may be better solutions as they can result in a net removal of fine sediment from the system (Mih and Bailey 1981; Waters 1995).

Gravel augmentation is another approach for restoration. For example, gravel augmentation provided improved spawning areas in the Mokelumne River, California, and salmon responded to the improved sites within several months (Merz and Setka 2004). The improved conditions appeared to persist for several spawning seasons (Merz and Setka 2004). In the fall of 2007, restoration of the known robust redhorse spawning site on the Oconee River was initiated by augmenting with gravel consistent in size and material as the spawning gravel bed (J. Evans, GA Department of Natural Resources, personal communication). The gravel was deposited at a bend above the known spawning gravel bar to allow

natural high flows to distribute the new gravel. Though high flows have occurred during spring 2009, gravel distribution has not yet been quantified.

Conclusions

Robust redhorse eggs incubated in gravel substrates infested with varying levels of fine sediment experienced severe reductions in STE when fine sediment levels were >15%. Fine sediment concentrations in spawning substrates at known spawning locations in the Oconee River are well above this level. However, fine sediment is removed from egg deposition sites during robust redhorse spawning. Further, larvae exhibit lateral interstitial movements within gravel sediments. Whether the gravel is sufficiently free of fine sediments or the developing larvae can move to areas with sufficiently clean gravel to ensure high STE in the wild is unknown.

The results of this research and other published studies strongly suggest that reducing fine sediment infestation improves the reproductive success of substrate spawners. Therefore, any measures to decrease the amount of fine sediment on gravel bars used by robust redhorse for spawning may increase the number of larvae that emerge successfully from the substrate. Restoration and remediation measures will require decreases in fine sediment levels; therefore, control of fine sediment through prevention and interdiction should be encouraged. Reduced fine sediment levels may help improve the long-term prospects for a self-sustaining population of robust redhorse in the Oconee River, as well as throughout the historic range of the species.

Acknowledgements This research was funded by Georgia Power Company. The Georgia Cooperative Fish and Wildlife Research Unit is sponsored by the Georgia Department of Natural Resources, the Wildlife Management Institute, the U.S. Fish and Wildlife Service, the U.S. Geological Survey, and the University of Georgia. We thank Don Dennerline, Brent Hess and Matt Lichtenwalner for technical assistance.

References

Berkman HE, Rabeni CF (1987) Effect of siltation on stream fish communities. Environ Biol Fishes 18:285–294

Bjornn TC (1969) Embryo survival and emergence studies. Job No. 5, Federal Aid in Fish and Wildlife Restoration. Job Completion Report Project F-49-R-7. Idaho Fish and Game Department

Burr BM, Morris MA (1977) Spawning behavior of the shorthead redhorse, *Moxostoma macrolepidotum*, in Big Rock Creek, Illinois. Trans Am Fish Soc 99:546–559

Chapman DW (1988) Critical review of variables used to define effects of fines in redds of large salmonids. Trans Am Fish Soc 117:1–21

Coble DW (1961) Influence of water exchange and dissolved oxygen in redds on survival of steelhead trout embryos. Trans Am Fish Soc 90:469–474

Cope ED (1870) Partial synopsis of the fishes of the fresh waters of North Carolina. Proc Amer Phil Soc 11:448–495

Dilts EW (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, GA

EA Engineering Science and Technology Inc (1994) Sinclair hydroelectric project relicensing technical studies: Oconee River fluvial geomorphology report (FERC Project No. 1951). Report submitted to Georgia Power Company, Atlanta, GA

Evans JW (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

Fajen OF, Layzer JB (1993) Agricultural practices. In: Bryan CF, Rutherford DA (eds) Impacts on warmwater streams: guidelines for evaluation. American Fisheries Society, Southern Division, Bethesda, pp 257–270

Freeman BJ (1998) Ecological Studies on the robust redhorse (Moxostoma robustum) in the Oconee River and Broad River systems, Georgia. Final Report. US Geological Survey, Biological Resources Division research work order number 37. University of Georgia, Athens, Georgia

Greig SM, Sear DA, Carling PA (2005) The impact of fine sediment accumulation on the survival of incubating salmon progeny: implications for sediment management. Sci Total Environ 344:241–258

Hall JD, Lantz RL (1969) Effects of logging on the habitat of coho salmon and cutthroat trout in coastal streams. In: Northcote TG (ed) Symposium on salmon and trout in streams. University of British Columbia, Vancouver, pp 355–375

Harvey BC (1987) Susceptibility of young-of-the-year fishes to downstream displacement by flooding. Trans Am Fish Soc 116:851–855

Harvey BC (1991) Interactions of abiotic and biotic factors influencing larval fish survival in an Oklahoma stream. Can J Fish Aquat Sci 48:1476–1480

Hausle DA, Coble DW (1976) Influence of sand in redds on survival and emergence of brook trout (*Salvelinus fontinalis*). Trans Am Fish Soc 105:57–63

Jenkins RE, Jenkins DJ (1980) Reproductive behavior of the greater redhorse, *Moxostoma valenciennesi*, in the Thousand Islands region. Can Field Nat 94:426–430

Jennings CA, Shelton JL Jr, Freeman BJ, Looney GL (1996) Culture techniques and ecological studies of the robust redhorse *Moxostoma robustum*. Annual Report (1995) prepared for Georgia Power Company, Environmental

Affairs Division, Atlanta, Georgia Project Number 25-21-RC295-387 University of Georgia, Athens

Kondolf GM, Sale MJ, Wolman MG (1993) Modification of fluvial gravel size by salmonids. Water Resour Res 29:2265–2274

Koski KV (1966) The survival of coho salmon (*Onchorynchus kisutch*) from egg deposition to emergence in three Oregon coastal streams. Master's thesis, Oregon State University, Corvallis, OR

Kwak TJ, Skelly TM (1992) Spawning habitat, behavior, and morphology as isolating mechanisms of the golden redhorse, *Moxostoma erythrurum*, and the black redhorse, *M. duquesnei*, two synoptic fishes. Environ Biol Fishes 34:127–137

Luft ER (1986) Channel changes along the lower Oconee River, Georgia: 1805–1949. Master's thesis, University of Georgia, Athens, GA

McCullagh P, Nelder JA (1983) Generalized linear models. Chapman and Hall, New York

McNeil WJ (1966) Effects of the spawning bed environment on reproduction of pink and chum salmon. U. S. Fish Wildl Serv Fish Bull 65:495–523

Merz JE, Setka JD (2004) Evaluation of a spawning habitat enhancement site for Chinook salmon in a regulated California river. N Am J Fish Manage 24:397–407

Meyer CB, Sparkman MD, Klatte BA (2005) Sand seals in coho salmon redds: do they improve egg survival? N Am J Fish Manage 25:105–121

Mih WC, Bailey GC (1981) The development of a machine for the restoration of stream gravel for spawning and rearing of salmon. Fisheries 6(6):16–20

Montgomery DR, Buffington JM, Peterson NP, Schuett-Hames D, Quinn TP (1996) Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival. Can J Fish Aquat Sci 53:1061–1070

Muncy RJ, Atchison GJ, Bulkley RV, Menzel RW, Perry LG, Summerfelt RC (1979) Effects of suspended solids and sediment on reproduction and early life history of warm-water fishes: a review. US Environmental Protection Agency EPA600/3-79-042 Washington, DC

Phillips RW, Lantz RL, Claire EW, Moring JR (1975) Some effects of gravel mixtures on emergence of coho salmon and steelhead trout fry. Trans Am Fish Soc 104:461–466

Piper RG, McElwain IB, Orme LE, McCraren JP, Fowler LG, Leonard JR (1982) Fish hatchery management. U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC

Reiser DW, White RG (1988) Effects of two sediment size-classes on survival of steelhead and chinook salmon eggs. N Am J Fish Manage 8:432–437

Ruetz CR III, Jennings CA (2000) Swimming performance of larval robust redhorse Moxostoma robustum and low-velocity habitat modeling in the Oconee River, Georgia. Trans Am Fish Soc 129:398–407

Ruhlman MB, Nutter WL (1999) Channel Morphology evolution and overbank flow in the Georgia piedmont. J Am Water Res Assoc 35:277–290

SAS Institute Inc (1990) SAS Procedures Guide, Version 6, 3rd edn. Cary, NC

Sear DA (1993) Fine sediment infiltration into gravel spawning beds within a regulated river experiencing floods: ecological implications for salmonids. Regul Rivers Res Manage 8:373–390

Shields FD Jr, Milhous R, Adams JR, MacAuthor RC (1992) Sediment and aquatic habitat in river systems. J Hydrau Eng 118:669–687

Smith HG, Burnard RK, Good EE, Keener JM (1973) Rare and endangered vertebrates of Ohio. Ohio J Sci 73:257–271

Sokal RR, Rohlf FJ (1981) Biometry: the principles and practice of statistics in biological research, 2nd edn. WH Freeman and Company, New York

Tappel PD, Bjornn TC (1983) A new method of relating size of spawning gravel to salmonid embryo survival. N Am J Fish Manage 3:123–135

Trimble SW (1977) The fallacy of stream equilibrium in contemporary denudation studies. Am J Sci 277:876–887

Waters TF (1995) Sediment in streams: sources, biological effects, and control. American Fisheries Society Monograph 7, Bethesda, Maryland

Wesche TA (1993) Watershed management and land-use practices. In: Kohler CC, Hubert WA (eds) Inland fisheries management in North America. American Fisheries Society, Bethesda, pp 181–203

Weyers RS, Jennings CA, Freeman MC (2003) Effects of pulsed, high-velocity water flow on larval robust redhorse and V-Lip redhorse. Trans Am Fish Soc 132:84–91