EVALUATION OF SEDIMENT PARTICLE SIZE DYNAMICS AT GRAVEL BARS USED BY ROBUST REDHORSE (*Moxostoma robustum*) FOR SPAWNING IN THE UPPER SAVANNAH RIVER

C. Rhett Jackson and S. Lynsey Long
Warnell School of Forestry and Natural Resources
University of Georgia
Athens, GA 30602-2152
706-542-1772
rjackson@warnell.uga.edu

Prepared for
United States Army Corps of Engineers,
Savannah District
William Bailey, Project Manager

January 7, 2011

EVALUATION OF SEDIMENT PARTICLE SIZE DYNAMICS AT GRAVEL BARS USED BY ROBUST REDHORSE (*Moxostoma robustum*) FOR SPAWNING IN THE UPPER SAVANNAH RIVER

C. Rhett Jackson and S. Lynsey Long. January 7, 2011

Introduction

The US Army Corps of Engineers, Savannah District operates three large dams and one low-head dam on the Savannah River. During droughts, there is insufficient water for all desired uses in the reservoirs and in the river downstream. Potential impacts to fish located downstream of the dams from reducing discharges during the spring spawning period is a major concern. The extent of those impacts is dependent upon the volume of suitable spawning habitat downstream of the dams which would not be affected by low river flows. The US Army Corps of Engineers contracted with the University of Georgia to assess the dynamics of sedimentation at gravel bars located downstream of the Corps dams. This study was intended to identify changes in the sedimentation of the gravel bars that occur over the course of a year, as well as short term changes that occur in response to a limited number of specific flow events. The Corps intended to use this information to assess the feasibility of conducting a pulsed release prior to the fish spawning season to clean the gravel bars to expand the quantity of suitable spawning habitat. The information may also be helpful to assess the longer term effectiveness of cleaning spawning sites prior to the spawning season. The investigation covered the portion of the Savannah River between the New Savannah Bluff Lock and Dam (NSBL&D)(River Mile 187) and the US Highway 301 Bridge (River Mile 118.7). The work was to consist of two major tasks: (1) monitor sediment dynamics over the course of a year, and (2) monitor sediment dynamics from a specific river flow event.

From December 2009 through December 2010, personnel from the University of Georgia took integrated gravel samples (volume of each sample approx. 18 Liters) roughly every month (a total of 10 sampling dates) from transects over a large mid-channel gravel bar on the Savannah River below the New Savannah Bluff Lock and Dam. This monitoring was to quantify temporal variability in the quality of spawning gravels on this bar and evaluate whether this variability was related to variability in flow and turbidity. On November 10th 2010, three separate samples were taken from the Upper Bar and processed independently to quantify the variability in gravel composition due to random variation in sampling transects. In addition, interstitial dissolved oxygen measurements were made within the gravel deposits, and three additional gravel samples were taken from the second known spawning bar that occurs 16 km downstream to compare bed sediment composition between the spawning locations. In all, 15 gravel samples were collected and sorted over the project period. These data are important because this gravel bar is one of only two known spawning locations for the Savannah River population of an endangered fish species, and river managers need to know if and how flow dynamics affect the quality of the gravel.

The Robust redhorse (*Moxostoma robustum*) is a large bodied, long-lived sucker that occurs in a few disjoint populations in southeastern Atlantic drainage rivers from North Carolina to Georgia. Because of low population numbers, demographics that indicate recruitment problems, and a relative shortage of suitable spawning habitat, the United States Fish and Wildlife Service (USFWS) considers the Robust redhorse a Species of Concern. The species is a conservation priority for the

USFWS, the US Army Corps of Engineers (USACE), and the states of North Carolina, South Carolina, and Georgia. A Robust Redhorse Conservation Committee with representatives from these agencies, several electric utilities, and other members has studied this fish and developed a conservation strategy (reference). Within the Savannah River, the Robust redhorse is known to spawn on two mid-channel gravel bars; the upper bar is just below the New Savannah Bluff Lock and Dam, and the lower bar is located 16 river km downstream. No other spawning locations for this fish have yet been observed in the Savannah River.

Above Augusta, the Savannah River passes through three large reservoirs built and operated by the USACE for flood control, hydropower production, navigation, fish and wildlife, water supply, and recreation. Because of these reservoirs, the USACE has significant control over the river hydrograph downstream of Augusta, and the USACE has been working with The Nature Conservancy and both adjacent states to develop adaptive ecosystem flow policies for the river. Maintenance of quality spawning habitat is an important consideration in managing the river system.

The main objectives of this study were to quantify the sediment size distribution of mid-channel spawning bars on the Savannah River and to evaluate, within the limits of a 12 month monitoring period, whether flow variation affected particle size distributions. The Corps would use this information to assess the feasibility of conducting a pulsed release prior to the fish spawning season to clean the gravel bars to expand the quantity of suitable spawning habitat. Secondary objectives were to observe flow dynamics relative to spawning conditions at different flow levels and to observe/measure bedload sediment transport at various flow levels. Another objective added during the course of the study was to measure interstitial dissolved oxygen concentrations in the spawning areas.

Numerous fish species use the gravel bars to spawn. These include the Federally-listed endangered Shortnose sturgeon and the Georgia-listed Robust redhorse. The life history, demographics, spawning behavior, and movement of the Robust redhorse have been studied for nearly two decades by scientists from Clemson University and the University of Georgia including Tim Grabowski, Jeff Isely, Cecil Jennings, Bud and Mary Freeman, Jay Shelton, and others. Before this sediment monitoring program began, we interviewed most of these scientists to identify the important bars and locations within bars for monitoring and to consider the relative merits of different sampling methods.

Spawning Habitat Requirements of the Robust redhorse

The Robust redhorse reproduces by triad spawning on mid-channel gravel bars (Bryant et al. 1996, Weyers et al. 2003, Freeman and Freeman 2001, Grabowski and Isely 2006). Two males and a female choose a redd site and use their tails to excavate a redd six to fifteen centimeters deep (Freeman and Feeman 2001) in which the eggs are deposited and covered. The eggs develop within the gravel over approximately five days, and the larvae develop within the gravel for another five to ten days before emerging into the water column (Weyeres et al. 2003), although Jennings et al. (2010) observed emergence up to 30 days past fertilization.

Spawning has been observed from mid-April through late May in water temperatures ranging from 17 to 27 ^{o}C (Freeman and Freeman 2001, Graboswski and Isely 2007a), with most spawning observations in the first half of May. Once spawning began, spawning aggregations in 2005 and 006,

were short-lived, lasting only 12 days (Grabowski and Isely 2008). Water depths at spawning sites have ranged from 0.25 to 2.0 m (average 0.74m) (Graboswski and Isely 2007a). Bed composition at spawning sites has featured 16 to 27% sand, with the remainder being gravel mostly in the range of 12.5 to 50 mm (Freeman and Freeman 2001). Freeman and Freeman (2001) noted that deposition of fine sediments was a problem at spawning sites when velocities approached zero. They recommended that spawning sites be managed to provide water depths of 0.3 to 1.1 m, velocities of 0.26 to 0.70 m/s, and sand fractions less than 30%.

Oxygen deprivation or entombment due to high percentages of sand in spawning sediments have been hypothesized as problems for Robust redhorse recruitment. Jennings et al. (2010) conducted a laboratory experiment to study the effect of the amount of sand in spawning sediments on reproductive success of Robust redhorse. They planted fertilized eggs in gravel with sand fractions ranging from 5% to 75%. They found that survival to emergence was greatly reduced when the sand fraction exceeded 15%. They inferred from their data that entombment, rather than oxygen deprivation, was the main cause of reduced emergence, as oxygen levels remained high in all treatments. They used commercially available sand in their experiments, but they did not measure the size distribution of the sand fraction, so it isn't possible to determine how much of the sand was coarse, medium, or fine sand. Because of the Freeman and Freeman (2001) observations and the results of the Jennings et al. (2001) experiments, the amount of fine sediment present in spawning gravels has become a management concern.

Identification of Gravel Bars for Study

We reviewed all of the literature on *Moxostoma robustum* spawning in the Savannah River and we interviewed most of the researchers who have studied Robust redhorse on the river, and we thus identified two gravel bars important for spawning. The most important is a large bar (approx. 25,500 m^2, Grabowski and Isely 2008) directly downstream of the New Savannah Bluff Lock and Dam (Figs. 1 and 2, see Appendix also) at river km 299.4, but spawning also occurs on a much smaller mid channel bar (approx. 4200 m^2, Grabowski and Isely 2008), located 16 river kilometers downstream (Figs. 3, 4, see Appendix also).

Figure 1. Google Earth image (Jan 31, 2007) of upper spawning gravel bar below Lock and Dam.

Figure 2. Google Earth image (October 6, 2010) of upper bar.

Figure 3. Lower mid-channel spawning bar located 16 km downstream of Lock and Dam.

Figure 4. Google Earth image (October 6, 2010) of lower bar.

Figure 5. Google Earth image of reach between upper and lower gravel bars. Upper bar is just above the bare field at the top of the picture and the lower bar is just upstream of the S-N bend at the bottom of the picture. White arrows point to the approximate locations of each bar.

Sampling Methodology

During the drought conditions of the last few years, flows below the Lock and Dam were frequently lower than 6,000 cfs, even during winter months. At these flow levels, the bars are wadeable. We originally developed bed sediment sampling methods and surface particle size distribution sampling methods on wading the bar. We planned to set up transect rays emanating from a central point on the bar marked with a concrete monument, and to measure surface pebble size every meter on each ray for a total of 300 points. At every 10th meter, we would take a small sample to a depth of 12 cm using a Helley-Smith 6”x6” bedload sampler, composite all these samples, and take them back to the lab for sieving. On September 30th, 2009, the investigators visited the bar by kayak to test the proposed methodology. This sampling scheme worked well under wadeable conditions.

When Ms. Long and a technician returned to the gravel bar on November 4rth to begin sampling, the bar was completely submerged and the water was too deep to allow wading. With the USGS stage information, we determined that sampling by wading was only possible when flows were below about 6,200 cfs. However, flows were over 20,000 cfs for most of November and December 2009 (Figure 6). Based on the El Nino climate conditions experienced Fall 2009 and expected to continue through the winter, we realized that we would have to develop a sampling system that could be conducted by boat.

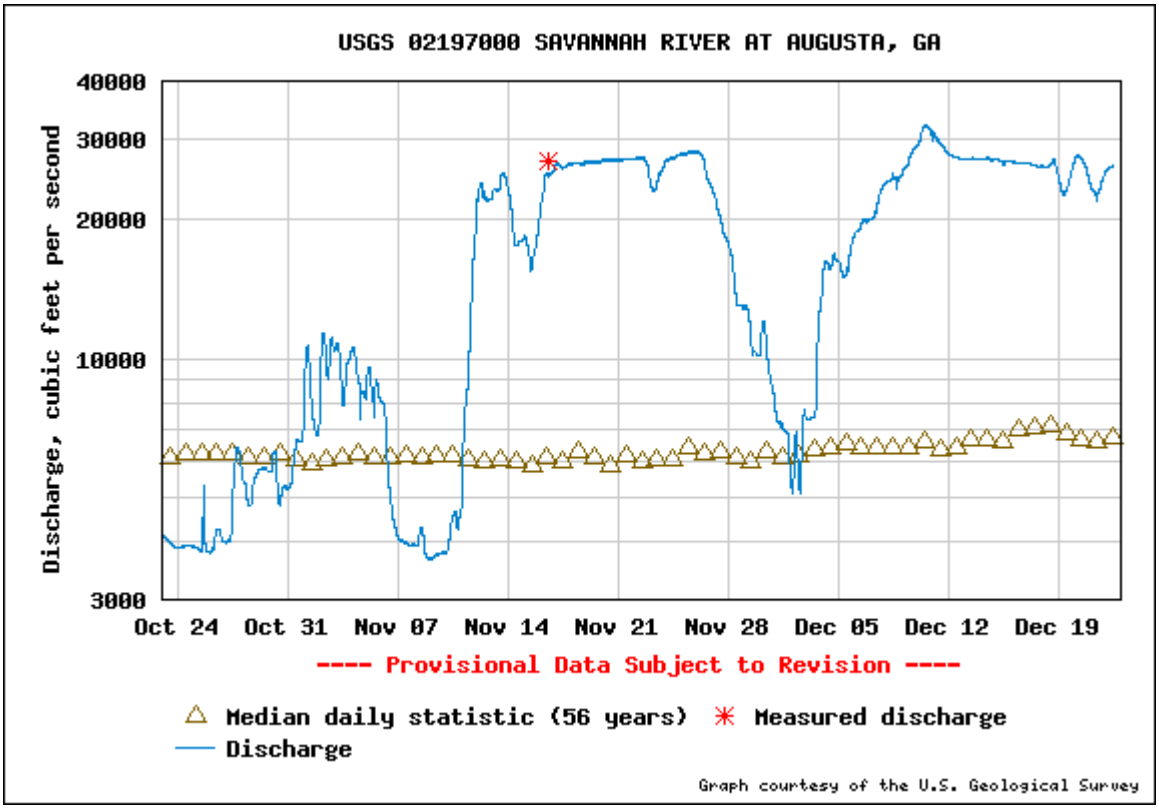

Figure 6. USGS flows measured during the beginning of the sampling period.

During November 2009, we experimented with Eckman and Ponar dredges, which are dropped to the bottom of the channel and which have spring-loaded doors that close when a messenger weight is dropped to the sampler. We found that the gravel particles kept the doors from closing completely, and a large portion of the fine sediment was lost during retrieval. We then experimented with and refined a weighted bucket dredge that could be dragged across the channel bottom and retrieved without loss of fines (Figure 7). A local machine shop built three of the 15 cm diameter bucket dredges for the project. One of the bucket dredges was built with extra weight for use during the higher flows. The bucket dredges produced a composite sample from approximately the top 6 cm of the bar material (Figure 8).

Figure 7. Regular (left) and heavy (right) bucket dredges used for sampling the gravel bars.

Figure 8. Track left by bucket dredge after sampling a transect during wadeable conditions.

We used a 14-foot jon boat with a 4HP outboard to deploy the bucket dredge while motoring over the bar. On December 14th, we used the boat and bucket dredge for the first time in the field, and developed a technique for successfully sampling the bar. The sampling protocol involved dragging the bucket auger from upstream to downstream while letting the current carry the boat. Multiple transects were run to collect a composite sample encompassing the entire bar. Each composite sample was approximately 18 Liters in volume. The average and median dry sample masses were 18 and 16 Kg, respectively.

We used Google Earth images to locate the bar relative to features on the northern stream bank. In early January 2010, we placed markers on the streambank within the park so that the limits of the bar could be identified from the boat even when the bar was deeply submerged. We used these markers as guides for subsequent high water sampling. When flows later dropped below about 6200 cfs and the bar became wadeable again, we simply walked transects over the bar dragging the bucket dredge behind us (Figure 9).

Figure 9. Dragging the bucket dredge over the upper bar during wadeable conditions.

Sample Processing

Samples were returned to University of Georgia where the free water was slowly drained off. The remainder of the sample was spread on a plastic tarp and left to dry for a week or more (Figure 10) in the Hydrology Barn of the Warnell School of Forestry and Natural Resources. After drying, the sample was sieved through a large 2mm sieve to separate the sand and gravel fractions.

The sand fraction was further sieved through 250 and 500 micron sieves. The gravel was then sorted into 2-4mm, 4-8mm, 8-16mm, 16-32mm, 32-64mm, and >64mm fractions. Each fraction was then weighed on an OHAUS ES Series 6Kg scale, and the relative fractions of each category were computed. These data were used to develop particle size distributions and to calculate the sand fraction and the median particle diameter for each sample.

Figure 9. Google Earth image of the lower bar taken October 6, 2010 and showing the tracks of the bucket dredge made during transect sampling.

Figure 10. Gravel sample drying on a plastic tarp. Sample bucket and large 2mm sieve also shown.

Dissolved Oxygen Measurements

On three dates, a narrow optical dissolved oxygen sensor (YSI Optical Dissolved Oxygen 2.5cm diameter probe) was buried in the sediment at the upper bar at various depths, and equilibrium interstitial dissolved oxygen concentrations were measured.

Historical Aerial Photo Analysis of the Upper Bar

We found little documented information about the form and location of the gravel bars, and we wondered how previous navigational dredging might have affected the bars. We searched the historical Richmond County, GA aerial photographs to find evidence of the historical location and form of the Upper Bar. We found a series of photographs dating back to 1937 that include the Lock and Dam area, but all the photographs were taken when flows were too high to see the bar or featured insufficient resolution to observe the bar. The first available imagery that we found showing the bars were Google Earth images from March 12, 1999. The bars have not moved perceptibly since this date.

Results

Both bars usually featured a single-grain layer of armoring gravel on the surface overlying A sand/gravel mix (Figure 11). Both bars featured a mix of coarse sands mixed with well-rounded gravels, mostly in the 8-32mm range (Table 1 and Figure 12). The median particle diameter (D50) rounded to the nearest mm varied temporally from 1mm to 10mm. The sand fraction in the upper bar varied from 30% to 58%, averaging 42%. The lower bar appeared to feature coarser sediments, with sand fractions ranging from 9 to 30% and with higher D50 values. At both bars, fine sands (< 0.25 mm) were a very small fraction of the particle distribution (maximum value 1.5%, usually less than 1%), while medium sands typically comprised about 10% of the samples at the upper bar. No lenses of silt or clay observed on either bar. The percent sand and the median particle diameter (rounded to the nearest mm) were strongly negatively correlated ($r^2 = 0.69$), and the D50 value mostly reflected variance in the amount of sand, as most of the actual gravel occurred in the 8 mm to 32 mm categories.

Figure 11. Single layer of armoring gravel overlying a mix of coarse sands and gravels at the upper bar.

Table 1. Sediment sample fraction less than each listed diameter category.

Diameter (mm)	Upper Bar 12/14/2009	1/8/2010	3/8/2010	4/2/2010	5/14/2010	7/1/2010	8/26/2010	9/30/2010	11/10/2010	11/10/2010	11/10/2010	12/8/2010
<128										1		
<64	1	1	1	1	1	1	1	1	1	0.996	1	1
<32	0.925	0.961	0.973	0.927	0.942	0.938	0.973	0.957	0.948	0.969	0.944	0.960
<16	0.784	0.828	0.802	0.685	0.735	0.798	0.793	0.745	0.679	0.719	0.722	0.745
<8	0.685	0.695	0.630	0.484	0.521	0.622	0.626	0.532	0.478	0.544	0.549	0.533
<4	0.652	0.648	0.544	0.356	0.437	0.531	0.503	0.455	0.343	0.411	0.439	0.380
<2	0.574	0.581	0.451	0.309	0.358	0.449	0.475	0.403	0.305	0.362	0.398	0.344
<0.5	0.108	0.107	0.098	0.065	0.097	0.100	0.120	0.107	0.083	0.081	0.086	0.082
<0.25	0.006	0.008	0.012	0.008	0.012	0.012	0.003	0.011	0.009	0.009	0.009	0.014
D50	1	1	3	7	7	3	4	6	6	7	9	10

Diameter (mm)	Lower Bar 9/30/2010	11/10/2010	12/8/2010
<128			
<64	1	1	1
<32	0.874	0.973	0.944
<16	0.588	0.168	0.631
<8	0.451	0.121	0.463
<4	0.362	0.098	0.366
<2	0.307	0.085	0.309
<0.5	0.071	0.022	0.067
<0.25	0.015	0.004	0.014
D50	12	11	22

By convention in geomorphology and fisheries in the United States, particles less than 2mm diameter are considered fine sediments. Fine sediments can include sands, silts, and clays in order of decreasing size. Sands range from 0.063 mm to 2.0 mm, with further subdivision as follows: fine sands, 0.063 to 0.25 mm, medium sands, 0.25 to 0.5 mm, and coarse sands, from 0.5 to 2.0 mm.

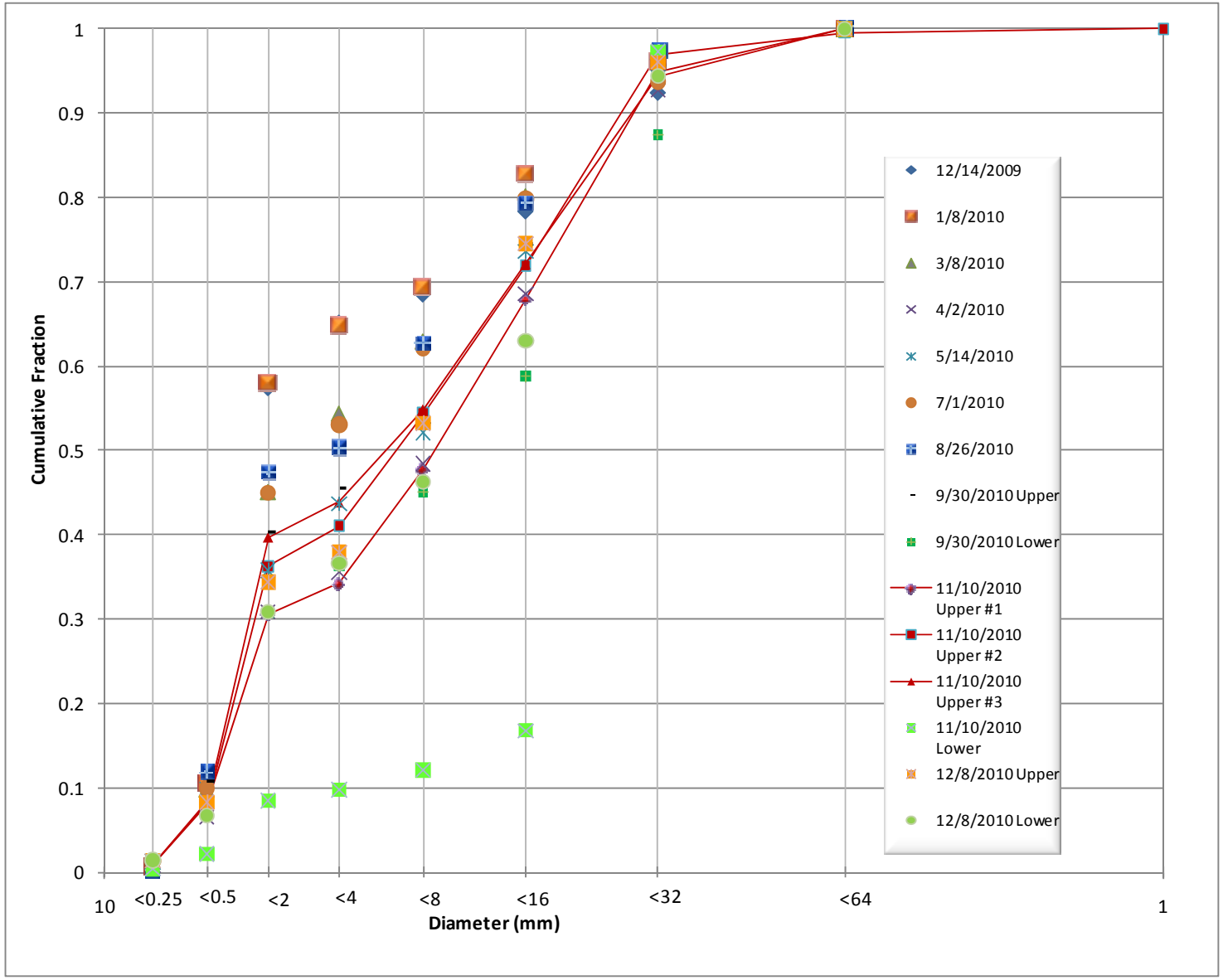

Figure 12. Particle size distributions of all sediment samples taken during the study. Distributions for the replicate samples taken on November 10, 2010 are connected with red lines.

Flows during the study period consisted of over three months of winter high flows ranging from 20,000 to 30,000 cfs starting in mid-November 2009 and ending in late February 2010 (Figure 13). These were followed by a period of generally diminishing flows during Spring 2010 with three pulses of 12,000 to 15,000 cfs. From June 2010 through December 2010, flows generally stayed in the range of 4,000 to 6,000 cfs, with higher flows of 8,000 to 10,000 cfs during high thunderstorm activity in August.

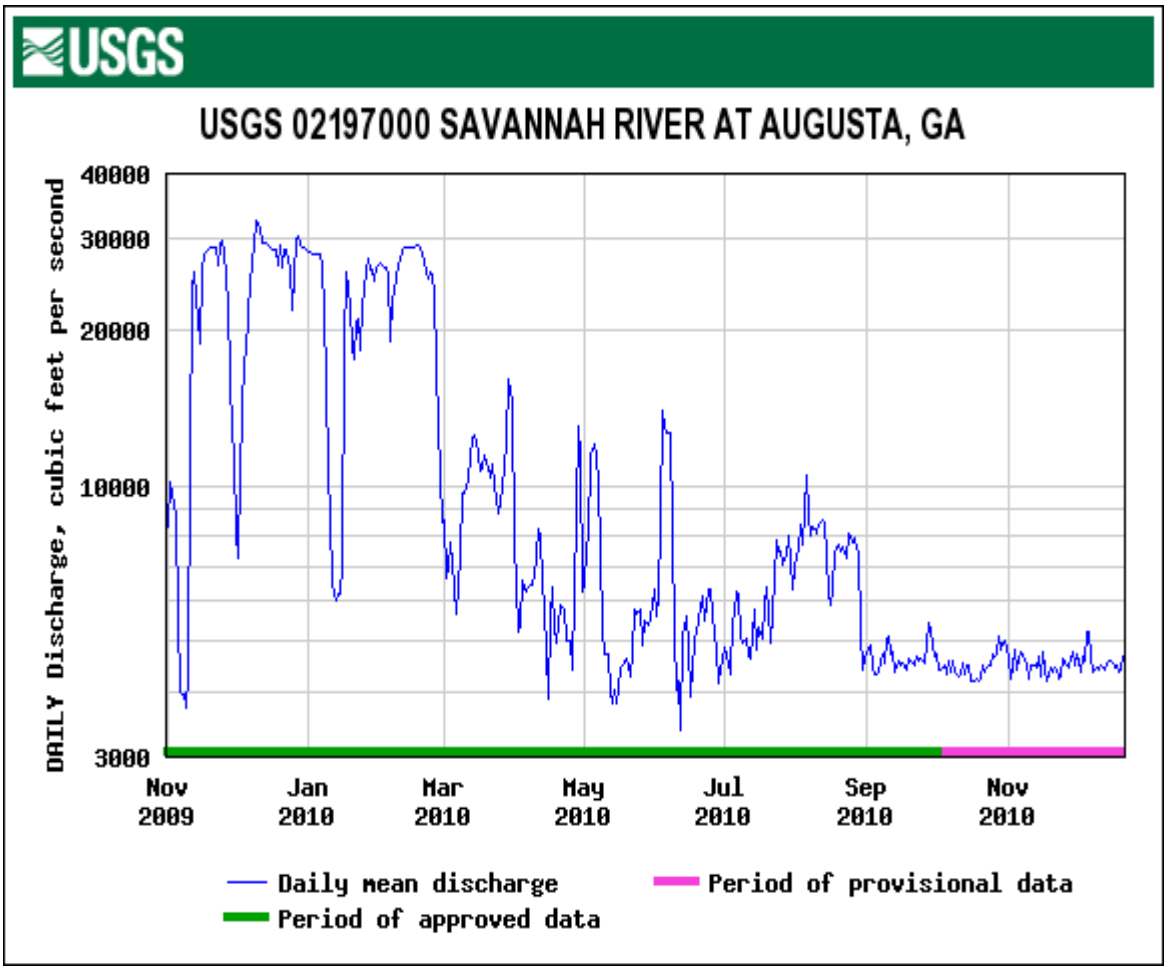

Figure 13. Savannah River at Augusta flows (in cfs) during the study period measured by the USGS.

During the winter high flow period, the sand fraction was higher and the median particle diameter (D50) was lower at the upper bar (Figures 14 and 15). It appears that the winter high flows transport sands from upriver which are carried over the bar during high flows, thus samples taken during that period are affected by the mobile sands, causing higher percent sand and lower D50 values. During subsequent medium and low flows, the sands are carried from the surface, leaving the armoring gravel layer over the sand/gravel mix. Once the winter high flows subside, particle size variation seemed to be mostly random with little consistent variation with recent flow levels. Samples taken just after two spring pulses featured less sand and higher D50 than the previous samples, suggesting that maybe the pulses were helpful in flushing sand from the bar, but the next sample followed a June pulse and the response was reversed, even though turbidity levels were similar to the previous pulse in May. The sand percentages and D50s after the first two spring pulses also weren't different from those seen later in the year during a long period of low flows.

The three replicate samples collected at the upper bar on November 10, 2010 ranged from 31 to 40% sand and 6 to 9mm D50, indicating that a significant amount of variation is possible just from sampling different transects across the bar. Thus small differences in percent sand or D50 should not be considered important.

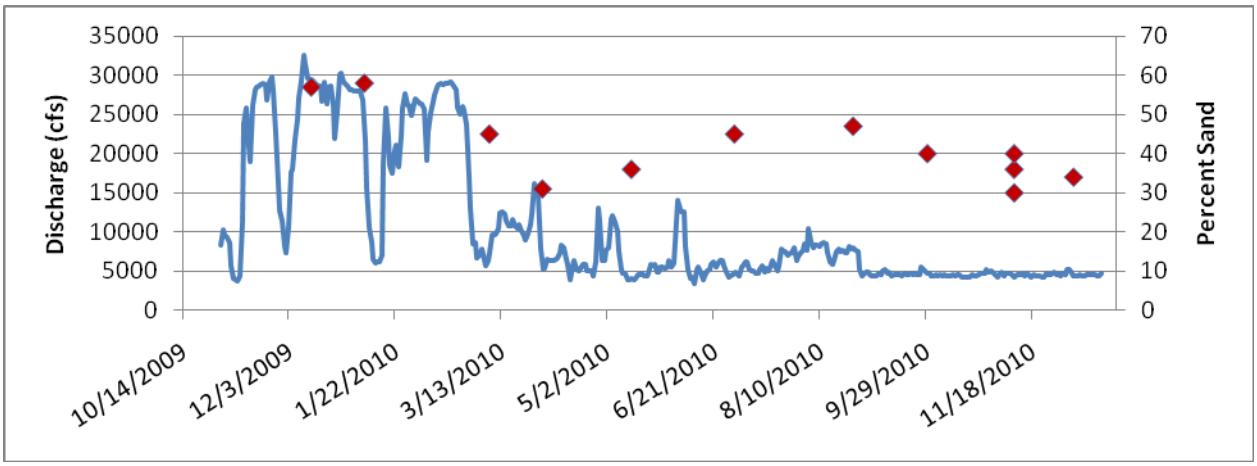

Figure 14. Time series of percent sand measured at the upper bar shown with Savannah River at Augusta flows for the same time period. Red diamonds show percent sand (right axis) and the continuous line shows discharge (left axis).

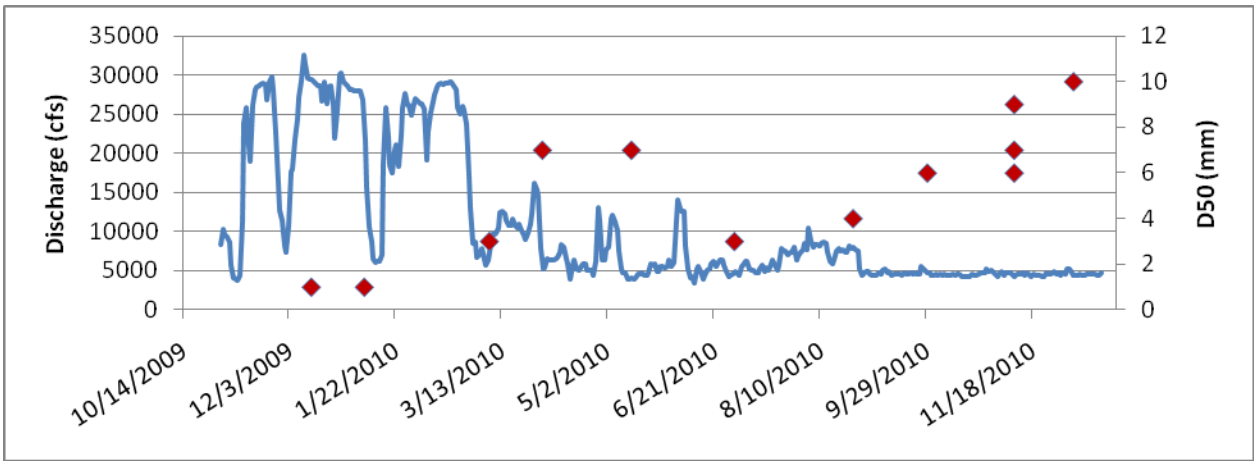

Figure 15. Time series of median particle diameter in mm (D50) measured at the upper bar shown with Savannah River at Augusta flows for the same time period. Red diamonds show median particle diameter (right axis) and the continuous line shows discharge (left axis).

The morphology of the sand bars indicates that surface pebble counts are of little value for assessing spawning habitat quality, as the sands are winnowed from the surface soon after the winter flows subside, leaving a fairly uniform single-grain lens of gravel over the sand/gravel mix.

During wadeable flow conditions, bedload movement was not observed on the gravel bar. There are small places on the point of the bar where the flow diverges and velocities are low where there are sand deposits which show some movement, but the gravel-covered areas of the bar do not exhibit bedload movement at flows less than 7000 cfs. At flows that cause bedload movement over the bar, depths and velocities are high enough that a large boat with a crane strong enough to support a 30Kg BL-84 bedload sampler would be necessary. During the summer and fall, macrophytic algae

was observed growing on the submerged areas of both bars, which would increase the flow necessary to initiate sediment movement within the bar. Macrophytic algae growth was thick and widespread in the river downstream of the Augusta industrial area during the final sampling of December 2010.

The USGS began monitoring water temperatures and turbidity at the Savannah River at Augusta gage beginning April 21, 2010. Daily average water temperatures showed significant seasonal variation over the study period, with summer average daily temperatures around 23°C and winter daily water temperatures below 10 ^{o}C (Figure 16). Most interesting and relevant to management are the drops in water temperatures that occur during high spring flow pulses reflecting the effect of hypolimnetic releases from Lake Thurmond. The pulse that peaked on June 4, 2010 resulted in water temperatures below Robust redhorse spawning temperatures. Daily average turbidity was generally low during most of the study period with most measurements below 10 NTU. High turbidity levels occurred during the spring pulses with daily average levels reaching 23 NTU. The water quality measurements show that spring pulses released from Lake Thurmond are associated with low water temperatures and elevated turbidity levels. Since water released from the dam features low turbidity levels, the high flows during the pulses must entrain and mobilize fine sediments between the dam and the Savannah River at Augusta gage.

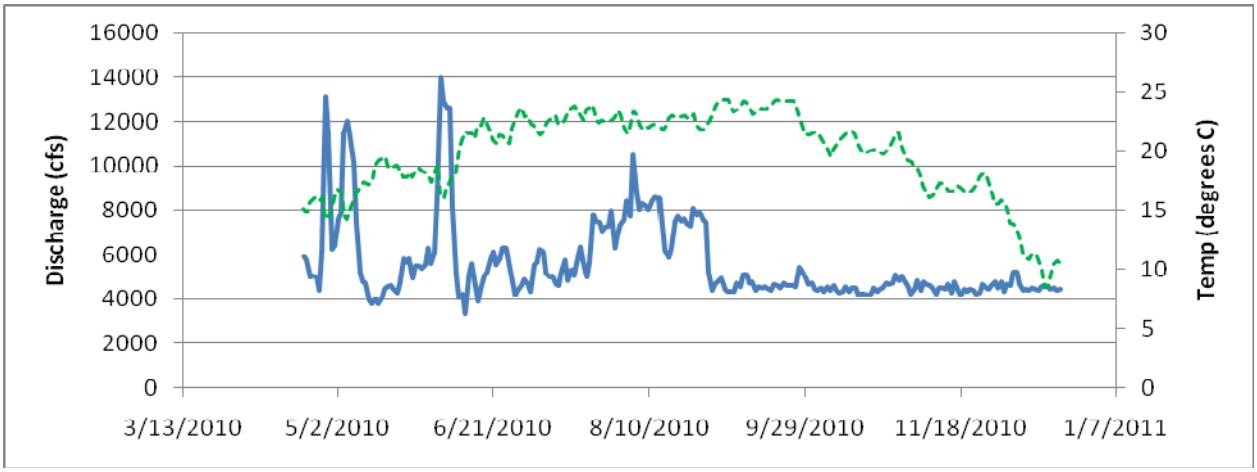

Figure 16. Daily average water temperatures and flows at the Savannah River at Augusta gage. The dashed green line shows average daily water temperature (right axis) and the continuous blue line shows discharge (left axis).

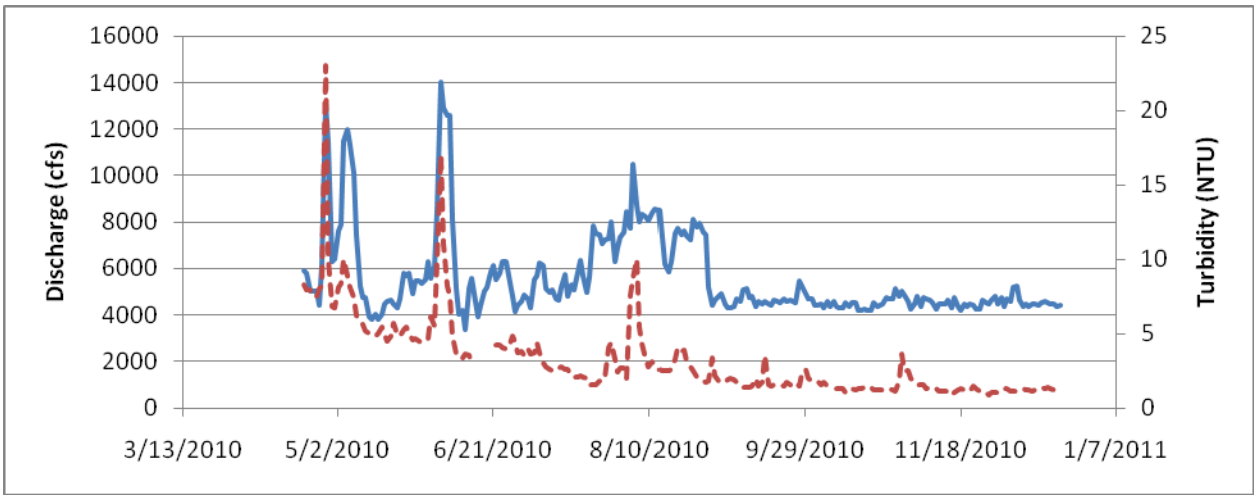

Figure 17. Daily average turbidities and flows at the Savannah River at Augusta gage. The dashed red line shows average daily water temperature (right axis) and the continuous blue line shows discharge (left axis).

Interstitial dissolved oxygen concentrations differed little from water column measurements (Table 2), indicating good exchange between the river water and the interstitial water.

Table 2. Water column dissolved oxygen concentrations and interstitial dissolved oxygen concentrations at different depths within the sediment.

	Upper Bar			Lower Bar		
Date	Set	Vertical Location	DO (mg/L)	Set	Vertical Location	DO (mg/L)
7/10/2010	A	**Water column**	**8.78**			
		10 cm depth	8.76			
		15 cm depth	8.72			
	B	**Water column**	**8.74**			
		10 cm depth	8.57			
		15 cm depth	8.23			
	C	**Water column**	**8.76**			
		10 cm depth	7.37			
		15 cm depth	8.36			
	D	**Water column**	**8.73**			
		10 cm depth	8.47			
		15 cm depth	8.39			
8/26/2010	A	**Water column**	**8.89**			
		15 cm depth	8.83			
	B	**Water column**	**8.94**			
		19 cm depth	8.7			
9/30/2010	A	**Water column**	8.9	A	**Water column**	**7.62**
		15 cm depth	8.58		15 cm depth	7.53
	B	**Water column**	8.87	B	**Water column**	**7.61**
		15 cm depth	8.66		15 cm depth	7.41
	C	**Water column**	8.85	C	**Water column**	**7.57**
		15 cm depth	8.68		15 cm depth	7.46
	D	**Water column**	8.88	D	**Water column**	**7.59**
		15 cm depth	8.71		15 cm depth	7.54
11/10/2010	A	**Water column**	10.08	A	**Water column**	9.13
		15 cm depth	9.99		15 cm depth	9.12
	B	**Water column**	10.03	B	**Water column**	9.24
		15 cm depth	9.82		15 cm depth	9.27
	C	**Water column**	10.05	C	**Water column**	9.29
		15 cm depth	9.84		15 cm depth	9.12
	D	**Water column**	10.05	D	**Water column**	9.15
		15 cm depth	9.88		15 cm depth	8.86
12/8/2010	A	**Water column**	11.52	A	**Water column**	10.14
		15 cm depth	10.91		15 cm depth	9.94
	B	**Water column**	11.38	B	**Water column**	10.06
		15 cm depth	11.35		15 cm depth	10.17
	C	**Water column**	11.39	C	**Water column**	10.22
		15 cm depth	11.44		15 cm depth	10.18
	D	**Water column**	12.12	D	**Water column**	10.21
		15 cm depth	11.63		15 cm depth	10.55

Discussion and Recommendations

During The Nature Conservancy's 2003 inter-disciplinary process to develop ecosystem flow recommendations for the Savannah River, little was known or documented about Robust redhorse spawning behavior. In the last few years, several journal articles and reports have published valuable life history and spawning information about the Savannah River Robust redhose population, and this information is relevant to managing this population. Key information documented in these papers include the following:

1. Robust redhorse have only been observed spawning at mid-channel gravel bars.
2. In the Savannah River below Augusta, Robust redhorse spawning has been observed on only two gravel bars, the large one just below the New Savannah Bluff Lock and Dam, and a much smaller bar located 16 km down river.
3. Robust redhorse spawning may take place from mid-April to late May, but usually occurs in the first two weeks of May with water temperatures ranging from 17 to 20°C.
4. Spawning aggregations are short-lived, approximately 12 days, and most larvae emerge within two weeks of fertilization, although emergence may take up to 30 days.
5. Levels of fine sediments exceeding 15% may cause entombment problems for larvae. However, the experimental study that quantified these emergence problems did not quantify the size distribution of the sand used in the experiments.
6. Repeated watering and dewatering of the mid-channel gravel bars has been observed during spawning season. Grabowski and Isely (2007b) estimated that a flow of 6870 cfs was necessary to keep the lower bar submerged.

During this study, we also observed repeated dewatering of areas mapped as common spawning locations by Grabowski and Isely (2007b). We estimated that a flow of 6200 cfs was necessary to keep 0.3 meters of water over the top of the upper bar. Because dewatering of redds should be avoided given the demographic issues facing the Robust redhorse, we recommend that a minimum flow of 6200 cfs be maintained during the spawning and larval development period (April 15 through approximately June 7) with some exceptions during drought years. Under current operating guidelines, daily average flows commonly drop below this level during the spawning and larval development period (Figure 13). In the pre-dam period, normal and wet years would typically provide flows exceeding this level during the spawning and larval development period, but flows during dry years might drop to 4,000 cfs during this period (e.g. Figure 18). The 2003 summary report of the ecosystem flow development team (Meyer et al. 2003) did not recognize or specifically address the spawning habitat dewatering issue, probably because insufficient information was available at that time. We recommend reconvening a group of Robust redhorse experts, hydrologists, and USACE personnel to discuss this issue and revise the flow recommendations accordingly.

This study documented that both spawning bars feature a mix of medium and coarse sands (together typically comprising 30 to 58% of the sediment at the upper bar, 9 to30% at the lower bar) and gravels mostly in the 8 to 32mm diameter range. Fine sands comprised a small fraction of the sediment, and silt and clay were inconsequential. These sand fractions were higher than those recommended by Freeman and Freeman (2001) and higher than the problem levels identified by Jennings et al. (2010), but it is not clear that the sand fractions used by Jennings et al. are comparable to those present in the bars, because Jennings et al. (2010) did not provide data on the size distribution of the sands used in their experiments. The sands present on the gravel bar are quite

coarse (Figure 11, Table 1), and it is not known whether these coarse sands constitute an emergence barrier for larval Robust redhorse, particularly after the gravel has been coarsened during the spawning process.

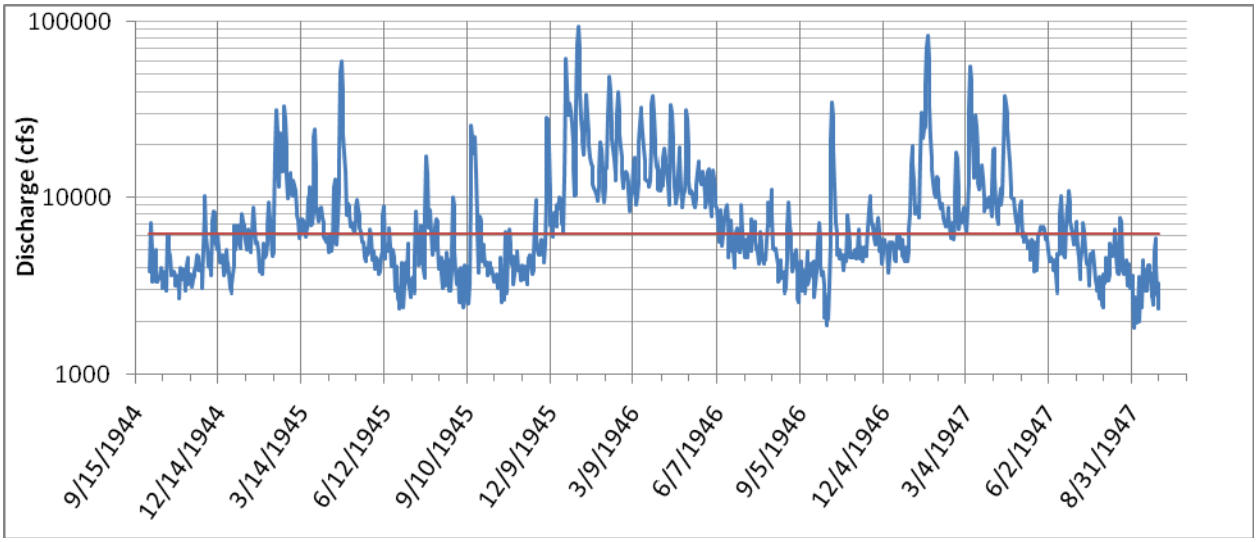

Figure 18. Example pre-dam flows from water years 1945-1947 with the recommended minimum spawning and larval development period (April 15 – approximately June 7) minimum flow of 6200 cfs shown in red.

The time series of flow and sediment size distributions measured here is too short to support confident conclusions about the efficacy of using pulses to clean the gravel bars before the spawning period, but the available data indicate this is not likely to be a useful practice. Rather, the data indicate it would be preferable to drop the winter peak flows as early as possible to allow medium flows to remove the sands carried over the bar during winter high flows. Both bars develop an armoring lens of gravel over the sand/gravel mix during low flows, and it appears that the bars generally become slightly coarser over time during low and medium flow levels.

The surface deposits on these bars do not represent the particle size distribution just a few centimeters below the surface and are thus not good indicators of percent fines in the spawning sediments. Any evaluations of particle size distributions in the spawning gravels should attempt to sample sediments below the surface, ideally in the range of the 6 to 15cm depth documented as egg deposition depths by Freeman and Freeman (2001). The sampling system used here provided a composite of the materials from 0 to 6 cm depth. A heavier drag dredge operated with a small crane from a larger boat would provide better samples, but the amount of sample collected would become a burden for processing and analysis. The samples collected here, averaging 18 Kg, presented a significant challenge for drying, sieving, and gravel classification. Any sampling system used must balance sample depth, spatial coverage, sample size, and the issue of removing gravels from very limited spawning habitat.

Bedload sampling using a Helley-Smith bedload sampler is impractical at these sites. In order to provide information on the timing and relative amounts of sand movement at the bars, we recommend experimentation with deadfall samplers to provide semi-quantitative measures of bedload movement and sand intrusion into gravels and evaluate the relationship between bedload movement and high turbidity periods.

References

Freeman, B.J. and M.C. Freeman. 2001. Criteria for suitable spawning habitat for the Robust redhorse *Moxostoma robustum*. A report to the U.S. Fish and Wildlife Service.

Grabowski, TB. and Isely, J.J. 2007a. Spatial and temporal segregation of spawning habitat by Catastomids in the Savannah River, Georgia and South Carolina, USA. J. Fish Biology 70:782-798.

Grabowski, TB. and Isely, J.J. 2007b. Effects of flow fluctuations on the spawning habitat of a riverine fish. Southeastern Naturalist 6(3)471-478.

Grabowski, TB. and Isely, J.J. 2008. Size of spawning population, residence time, and territory shifts of individuals in the spawning aggregation of a riverine Catostomid. Southeastern Naturalist 7(3):475-482.

Jennings, C.A., E.L. Dilts, J.W. Shelton Jr., and R.C. Peterson. 2010. Fine sediment effects on survival to emergence of Robust redhorse. Environmental Biology of Fish 87:43-53.

Meyer, J., M. Alber, W. Duncan, M. Freeman, C. Hale, R. Jackson, C. Jennings, M. Palta, E. Richardson, R. Sharitz, J. Sheldon, and R. Weyers**.** 2003. Summary Report Supporting the Development of Ecosystem Flow Recommendations for the Savannah River below Thurmond Dam. Nature Conservancy and United States Army Corps of Engineers.

Weyers, R.S., C.A. Jennings, and M.C. Freeman. 2003. Effects of pulsed, high-velocity water flow on larval Robust redhorse and V-lip redhorse. Trans. Amer. Fisheries Soc. 132(1):84-91.

Appendix – Locations of Catostomid spawning on the two gravel bars as mapped by Grabowski and Isely, 2007a.

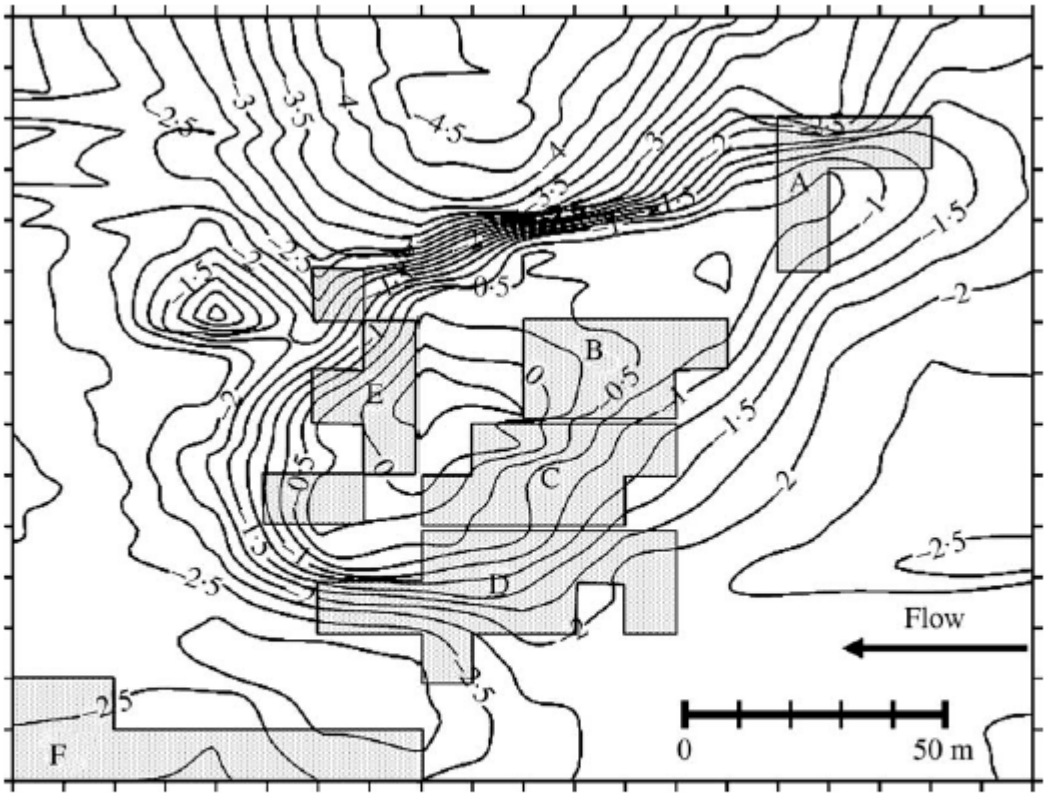

FIG. 1. Bathymetric map of the upper gravel bar at river kilometre 299·4 on the lower Savannah River. Contour lines represent a change in depth of 0·25 m. Depths indicate water depth under low flow conditions (*c.* 85 $m^3 s^{-1}$). The locations where catostomids were observed or captured (zones A–F) are delineated by shaded boxes.

From Grabowski and Isely, 2007a.

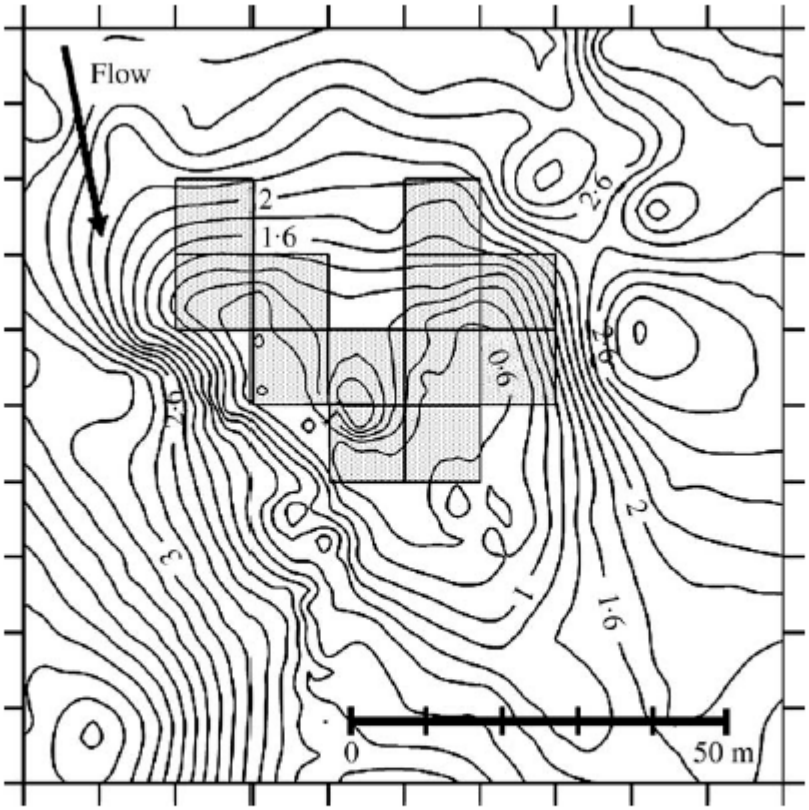

FIG. 2. Bathymetric map of the lower gravel bar at river kilometre 283·7 on the lower Savannah River. Contour lines represent a change in depth of 0·2 m. Depths indicate water depth under average flow conditions (*c.* 200 $m^3 s^{-1}$). The 10 m × 10 m areas in which catostomids were observed or captured are indicated by shaded boxes.

From Grabowski and Isely, 2007a.