A compendium of Savannah River studies conducted by the U.S. Fish and Wildlife Service intended to inform flow management

A report to the U.S. Army Corps of Engineers

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Executive Summary

Several abnormally dry periods over the past decade have raised both awareness and concern regarding the effects of flow management on reservoir levels and natural resources in the lower Savannah River. Water management at Hartwell, Russell, and Thurmond reservoirs is of significant interest to natural resource managers because discharge plays a principal role in the structure and function of riverine, backwater, and estuary habitats. Because of record droughts and recurring low basin inflows, the U.S. Army Corps of Engineers (Corps) and partners initiated a Comprehensive Study to evaluate the minimum environmentally acceptable releases at Thurmond Dam during drought. In anticipation of 1) the Comprehensive Study and 2) the emerging opportunity to quantify drought effects, the Corps partnered with the U.S. Fish and Wildlife Service (USFWS) to fund multiple research initiatives in the Savannah River, floodplain, and estuary with a specific emphasis on linking flow magnitudes to ecological responses.

This compendium of studies is a product of the coordination between the Corps and USFWS. Several of the studies undertaken in this project were identified as critical research needs in the 2003 Savannah River Ecosystem Flows Workshop. Specifically, we evaluated river and oxbow hydrology during extreme low flows as a function of Thurmond Dam discharge during drought. Using hydrological information collected throughout these areas, we quantified the amount of mussel habitat gained or lost as a function of discharge change. Effects of discharge on gravel bar habitats used by spawning suckers were evaluated. Discharge fluctuations resulted in inaccurate gage readings and attempts were made to more accurately describe hydrology near gravel bars. We evaluated oxbow and cutoff connectivity to the river, and effects of discharge on angler access to these areas. Salinities at multiple locations in the estuary as a function of discharge were a principal concern to USFWS, and were also evaluated.

In summary, five separate studies were conducted in a manner that facilitates evaluation of low flow effects on natural resources. We identify additional research needs, and anticipate the use of these studies in the Comprehensive Study and forthcoming workshop to revise the 2003 Savannah River Ecosystem Flow recommendations. Studies are arranged in upstream-downstream order and suggested citations are provided on the title page of each chapter.

The submission of this report fulfills requirements under MIPR# W33SJG22422117 and MIPR# W26HM422423591.

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Part I: A hydrological foundation for evaluating effects of low flows on river and oxbow habitats and biota

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Summary

Stage discharge relationships are fundamental components of assessing effects of discharge changes on habitat. Because of the potential for the stage discharge relationship to vary among site in over 200 miles of the lower Savannah River, we developed stage discharge relationships for 15 sites. These relationships are intended for use in low flow habitat studies throughout the lower Savannah River. Because the study intent is to inform Thurmond Dam operations, we related discharge and water levels throughout the lower river to Thurmond Dam outflow.

Although stage discharge relationships had similar patterns among sites, differences are likely great enough to affect analysis of habitat effects. The strength of the relationship between Thurmond Dam outflow and USGS gage data weakens in a downriver direction, indicating that other factors including flow attenuation and accretion also contribute to hourly discharge estimates downriver.

United States Geological Survey (USGS) discharge measurements below New Savannah Bluff Lock and Dam show hourly fluctuations of river flows throughout the year. These fluctuations have the potential to affect sucker spawning at the gravel bars. Our discharge measurements using an acoustic Doppler current profiler show that the gage estimates often overpredict actual discharge, depending on the discharge rise and fall rates. After adjusting USGS gage estimates for the effect of fall rate, we found that discharge at the upper gravel bar has a greater range of variation than previously realized and estimated by the USGS gage. Discharge at the upper gravel bar often fell below 3,000 cfs during the spawning season for Robust Redhorse and associated gravel spawning species, and fell as low as 1,949 cfs. These adjusted data are consistent with our field observations. We recommend that these flow fluctuations be investigated and their sources determined so that better flow and habitat recommendations can be developed.

Methodology

We selected 18 sites that coincided with fish and mussel surveys, particularly those sites that contained either a high diversity of species or presence of rare species (Table 1). This strategy enabled us to make direct comparisons between hydrology and expected biological response. This approach also resulted in the dispersion of sites throughout the river, enabling us to develop stage-discharge relationships for estimation of surface water connectivity thresholds and angler access from the river into natural oxbows, meander cutoffs, and sloughs.

Water level data were collected using HOBO Water Level pressure transducers (U20-001-01) attached to t-posts that were vertically driven into the river bed sediments along channel margins. A benchmark was deployed at each site so that we could verify that the water level logger had not vertically moved during deployment and that water level logger elevation changes that occurred following logger offload and redeployment could be compensated. Three additional loggers (downstream from New Savannah Bluff Lock and Dam, Cohen’s Bluff Landing, and downstream from Ebenezer Landing) were deployed above water to compensate water level logger data for air barometric pressure changes.

We developed stage-discharge relationships between FWS survey locations and the nearest USGS discharge gages. Two datasets were used to develop stage-discharge relationships: sites with water level data collected in 2011 and a second set of sites established in 2012. In 2011, a moderate flow event in July affected the stage discharge relationship at Burton’s Ferry gage. USGS prorated their data to account for drift between field measurements. This prorating method resulted in poor correlations between our water level measurements and USGS prorated data. However, USGS data starting October 19, 2011 at 08:45 was not prorated because their field measurements indicated that the gage was on the original rating curve. Thus, stage discharge relationships were developed using the October 19, - November 30, 2011 period (discharge ranged between 4,468-4,885 cfs) when USGS employed the stable rating curve, thereby analyzing correlations between our water level measurements and gage readings with greater confidence.

Water travel times from the gage to the water level loggers were calculated and the discharge data were offset by the travel time to correctly relate river stage to discharge observed at the nearest USGS gage. Water travel time was determined by using repeated correlations between the site's stage data and the USGS discharge data. Each time a correlation was run, it was run on the same stage discharge dataset, but it was offset by one time interval (15 minutes or 1 hour, depending on the USGS gage) from the prior correlation. The highest correlation coefficient was used to identify the appropriate water travel time, correctly offset the discharge data, and calculate stage-discharge relationships.

The stage discharge relationship was developed using a single best-fit line. Although better and more sophisticated methods of developing stage-discharge relationships should be employed (e.g. LOESS fit functions), preliminary analyses showed that this approach fit low discharge data well.

So that our results from these studies can be related to reservoir operations, we related average daily flows observed at USGS gages in the lower river to Thurmond Dam outflow. We focused on the period between July 1, 2012 and December 31, 2012 because it encompassed a range of low flows observed in recent droughts. Water travel time was calculated and data offsets were made as described previously. A correlation matrix was used to evaluate relationships among Thurmond Dam outflow, Savannah River at Augusta (USGS # 02197000), Savannah River at Burton’s Ferry (USGS # 02197500), and the Savannah River at Clyo (USGS # 02198500). Linear regression was used to develop the relationship between Thurmond Dam outflow and USGS discharge gages. USGS data were also expressed as a percentage of Thurmond Dam outflow to illustrate the contribution of Thurmond outflow to discharge in the lower river.

Discharge below New Savannah Bluff Lock and Dam (NSBL&D) was measured on multiple occasions using an Acoustic Doppler Current Profiler (ADCP; Teledyne RD Instruments TRDI Rio Grande system; 1.200 MHz). Comparisons were made with USGS discharge estimates (USGS # 02197000; Table 1). Because of discrepancies between the ADCP and gage estimates during periods of unstable discharge, we evaluated the effect of rise and fall rates over the prior two hour period using best-fit lines and regressions. Using this relationship, we adjusted USGS discharge estimates to more accurately reflect discharge at the upper gravel bar during the 2013 spawning season for suckers. To assess whether non-adjusted or adjusted USGS estimates improved predictions of water surface elevation at the lower gravel bar, we compared correlation coefficients (with the appropriate time lag) with water level elevations from the water level logger deployed at the lower gravel bar.

Results

Of the 18 sites with water level loggers, we analyzed data at 16 sites. High water levels prevented offload at two sites, and one logger may have been stolen. Water travel times between USGS gages and sites (Figure 2) were calculated (Table 2). Stage-discharge relationships were developed using the Clyo gage at four sites (Figure 3), the Burton's Ferry gage at 10 sites (Figure 4), and the Savannah River at Augusta gage at one site (Figure 5). The relationship between stage and USGS discharge was significant, and all regression coefficients were greater than 0.93.

Water travel time using average daily discharge from Thurmond Dam was 0 days to the Savannah River at Augusta gage, 1 day to the Burton' s Ferry gage, and 2 days to Clyo gage. USGS discharge data from three gages and Thurmond Dam outflow were correlated, although relationship strength decreased as distance between gages increased (Table 3). Significance levels of correlations could not be calculated because of the Excel statistical package limitations.

Discharge at USGS gages predicted from Thurmond Dam outflow after compensating for water travel time generally increased in a downstream direction (Figure 6). Regressions analysis showed that hourly Thurmond Dam outflow was a significant predictor of Savannah River at Augusta discharge (R^2= 0.40, $F_{1,183}$=123.7, p<0.001), Savannah River at Burton's Ferry discharge (R^2= 0.25, $F_{1,183}$=61.3, p<0.001), and Savannah River at Clyo discharge (R^2= 0.19, $F_{1,183}$=43.9, p<0.001; Table 4). On most dates, average daily Thurmond Dam outflow accounted for 70 to 90% of discharge at Burton's Ferry (Figure 7).

USGS gage discharge estimates below New Savannah Bluff Lock and Dam showed hourly fluctuations during the survey period. Discharge measurements taken using the ADCP showed that the gage often over predicts ADCP (actual) discharge, particularly during the rising or falling limb of the hydrograph (Figure 8). The magnitude of the difference between the USGS estimate and ADCP measurement is partly explained by rise or fall rate over the previous two hours (Figure 9). Because limited data were available for comparisons of rise rates, we quantitatively examined only the effects on fall rates. Fall rates account for 83% of the variation in the difference between ADCP measurements and concurrent gage estimates (Figure 10; one outlier removed from analysis: difference -1,800, fall rate -246). Using this relationship to adjust USGS gage data, discharge at the upper gravel bar has a greater range of variation as compared to non-adjusted gage data (Figure 11). These "adjusted" data were not as strongly correlated with water level logger data at the lower gravel bar (10 miles downriver) as the non-adjusted USGS discharge estimates.

Discussion

Stage discharge relationships were developed at 16 sites spanning 145.7 river miles. These relationships should provide a good foundation for evaluating effects of discharge changes on water levels throughout the river, including oxbows, meander cutoffs, and sloughs. The method that we used to develop the stage-discharge relationship, a statistically accurate best-fit line, fit both low and high flows well for the range of flows observed in this study. At some sites, however, the highest flows observed were either under or over predicted by the best fit line. We believe that these stage-discharge relationships are sufficient for our studies because our focus is on low flow effects to habitats. High flow estimates can be improved with better statistical techniques in the future if desired. Similarly, we suggest that high and low discharge estimates for stages that occur beyond the regression line should be treated as rough estimates and should be refined when data become available.

The Savannah River Basin had low basin inflow from July through December 2012. Consequently, Thurmond Dam outflow accounted for a majority (70-90%) of lower river flows. This demonstrates that Thurmond Dam operations have a strong influence on lower river discharge. However, Thurmond Dam outflow accounted for 22 to 48% of the variation in lower river discharges, meaning that other factors also play a role in discharge variation in the lower river. Flow attenuation from Thurmond Dam, water withdrawals and discharges, evapotranspiration, and flow accretion (especially during wetter periods) contribute to discharge variation in the lower river. Collectively, these factors in conjunction with Thurmond Dam releases determine discharge in the lower river. The regressions between Thurmond outflow and each USGS gage demonstrate increasing discharge trends downriver and are useful for making predictions for extreme drought conditions.

Discharge at the upper and lower gravel bars often fluctuates on a sub-hourly time step. Our comparisons of ADCP discharge with gage estimates reveal that the USGS gage frequently overpredicts the actual discharge measured with the ADCP, particularly during the rising and falling hydrograph limbs. Consequently, during the period that coincides with the sucker spawning season, flow magnitudes were more extreme than estimated by the gage at the upper gravel bar. Predicted discharge using adjusted gage data fell below 3,000 cfs on numerous occasions, and was estimated to have fallen to as low as 1,949 cfs on May 1, 2013. Water surface also fluctuates at the lower gravel. However, discharge fluctuations attenuate somewhat downriver as is evidenced by the fact that adjusted gage data did not improve the correlation with water surface elevations recorded at the lower gravel bar. We speculate that the error in the gage estimates stem from the placement of the gage in a pool, a pool that is less responsive to discharge change than gages placed in more typical runs.

We suspect that water level fluctuations at the gravel bars originate from a combination of water releases from Thurmond Dam, reregulation, and operation of the gates at NSBL&D. On several occasions, gates were observed moving. On these occasions, we observed water level changes at the upper gravel bar, although we lack quantitative information to corroborate those observations. Nevertheless, understanding the causes of water level fluctuations at the gravel bars should remain a priority given the sensitivity of gravel bar habitat area to discharge.

Table 1. Dates, times, and discharges associated with acoustic Doppler current profiler measurements near the upper gravel bar downstream from New Savannah Bluff Lock and Dam.

Date	Time	ADCP Q	USGS Q	USGS discharge 2 hours prior	Stage trend
8/29/2013	1914	10040	11400	10600	rapid rise
8/29/2013	1927	10669	11700	10600	rapid rise
8/29/2013	1302	12446	12200	14000	rapid fall
4/22/2013	1800	4138	4860	5270	moderate fall
8/29/2013	1830	10047	10600	10700	nearly stable/slight fall
4/22/2013	1602	5540	5270	5330	nearly stable/slight fall
4/22/2013	1616	5734	5280	5320	nearly stable/slight fall
4/22/2013	1645	5503	5240	5300	nearly stable/slight fall
4/22/2013	1532	4450	5270	5370	nearly stable/slight fall
5/1/2013	1600	2551	4950	5900	rapid fall
5/1/2013	1612	2605	4870	5750	rapid fall
5/1/2013	1627	2606	4790	5600	rapid fall
8/29/2013	1313	9232	12000	13900	rapid fall
8/29/2013	1329	8964	11900	13700	rapid fall
8/29/2013	1343	7698	11700	13600	rapid fall
4/22/2013	1659	5804	5050	5290	slow fall
4/22/2013	1500	5917	5290	5420	slow fall
4/22/2013	1515	5781	5280	5490	slow fall
8/29/2013	1859	10005	10700	10700	stable

Table 2. Distribution of sites, water travel times between gages and sites, stage-discharge relationships, and regression coefficients of sites.

Site	River Mile	Logger label	Nearest USGS gage	Water travel time (hours)[1]	Analysis constraints	Stage-discharge relationship[2]	R^2
JDW029 Mainstem	41.35	SR1	Clyo	0	Analyzed on minimum daily values due to tidal influences	$y = 1.2681977630E\text{-}25x^{1.4456818859E+01}$	0.97
JDW025	44.86	SR2	Clyo	0	Analyzed on minimum daily values due to tidal influences	$y = 1.1027732089E\text{-}23x^{1.3513362694E+01}$	0.98
WP 078	54.96	SR3	Clyo	4	USGS gage data available on hourly time step	$y = 1.0693389627E+03x - 9.5096509629E+04$	0.99
WP 079/Kennedy Lake	57.24	SR5	Clyo	3	USGS gage data available on hourly time step	$y = 1.0666686356E+03x - 9.9408363326E+04$	0.99
WP 067[3]	59.50	SR6	Clyo				
NatOx7Out	100.18	SR8	Burton's Ferry	11.25	USGS gage data available on quarter hour time step	$y = 4.3857621440E\text{-}23x^{1.3045497478E+01}$	0.99
Site 4	100.30	SR9	Burton's Ferry	9.25	USGS gage data available on quarter hour time step	$y = 7.8549750566E\text{-}21x^{1.2031954359E+01}$	0.99
Site 5[4]	104.15		Burton's Ferry	8.25	USGS gage data available on quarter hour time step	$y = 4.9413710233E\text{-}04e^{1.6612782146E\text{-}01x}$	0.98
WP 071	106.92	SR10	Burton's Ferry	7	USGS gage data available on quarter hour time step	$y = 3.0386681696E\text{-}20x^{1.1931949192E+01}$	1.00
WP 074	109.26	SR11	Burton's Ferry	5	USGS gage data available on quarter hour time step	$y = 4.2253656874E\text{-}22x^{1.2883710615E+01}$	0.99
Little Hell Marl Outcrop	134.56		Burton's Ferry	-8.25	USGS gage data available on quarter hour time step	$y = 9.5652551147E+02x - 8.7121865671E+04$	0.99
Site 6[4]	135.08		Burton's Ferry	-7.5	USGS gage data available on quarter hour time step	$y = 5.1598097215E\text{-}03e^{1.4640756295E\text{-}01x}$	0.95
Site 7[4]	135.64		Burton's Ferry	-7.75	USGS gage data available on quarter hour time step	$y = 4.4223097808E\text{-}03e^{1.4667605576E\text{-}01x}$	0.93
Site 8	137.07	SR12	Burton's Ferry	-8.5	USGS gage data available on quarter hour time step	$y = 1.8058380648E\text{-}03e^{1.4866747281E\text{-}01x}$	0.95
Site 9[4]	138.98		Burton's Ferry	-9.5	USGS gage data available on quarter hour time step	$y = 6.1351477579E\text{-}03e^{1.3755149965E\text{-}01x}$	0.93
Lower Gravel Bar	177.34		NSBL&D	4.5	USGS gage data available on quarter hour time step	$y = 4.2705283012E\text{-}25x^{1.4127380630E+01}$	0.98
Upper Gravel Bar	187.12		NSBL&D	0	USGS gage data available on quarter hour time step; No logger; Relationship is based on seven low flow water surface elevation measurements at the bar	$y = 809.78x - 71643$	0.98

[1]Positive values indicate that the USGS gage is upstream from the site. Therefore, corresponding dates and times of USGS measurements after accounting for water travel time to a study site are earlier than water level measurments at the study site. The converse is true for negative values.

[2]y is discharge in (cfs); x is stage in feet relative to a benchmark at an arbitrarily defined 100' elevation.

[3]Logger and t-post are missing and water levels need to recede to attempt retrieval.

[4]2011 data were used to develop stage-discharge relationships.

Table 3. Pearson correlation coefficients among discharge gages on the Savannah River during drought from July 1, 2012 to December 31, 2013.

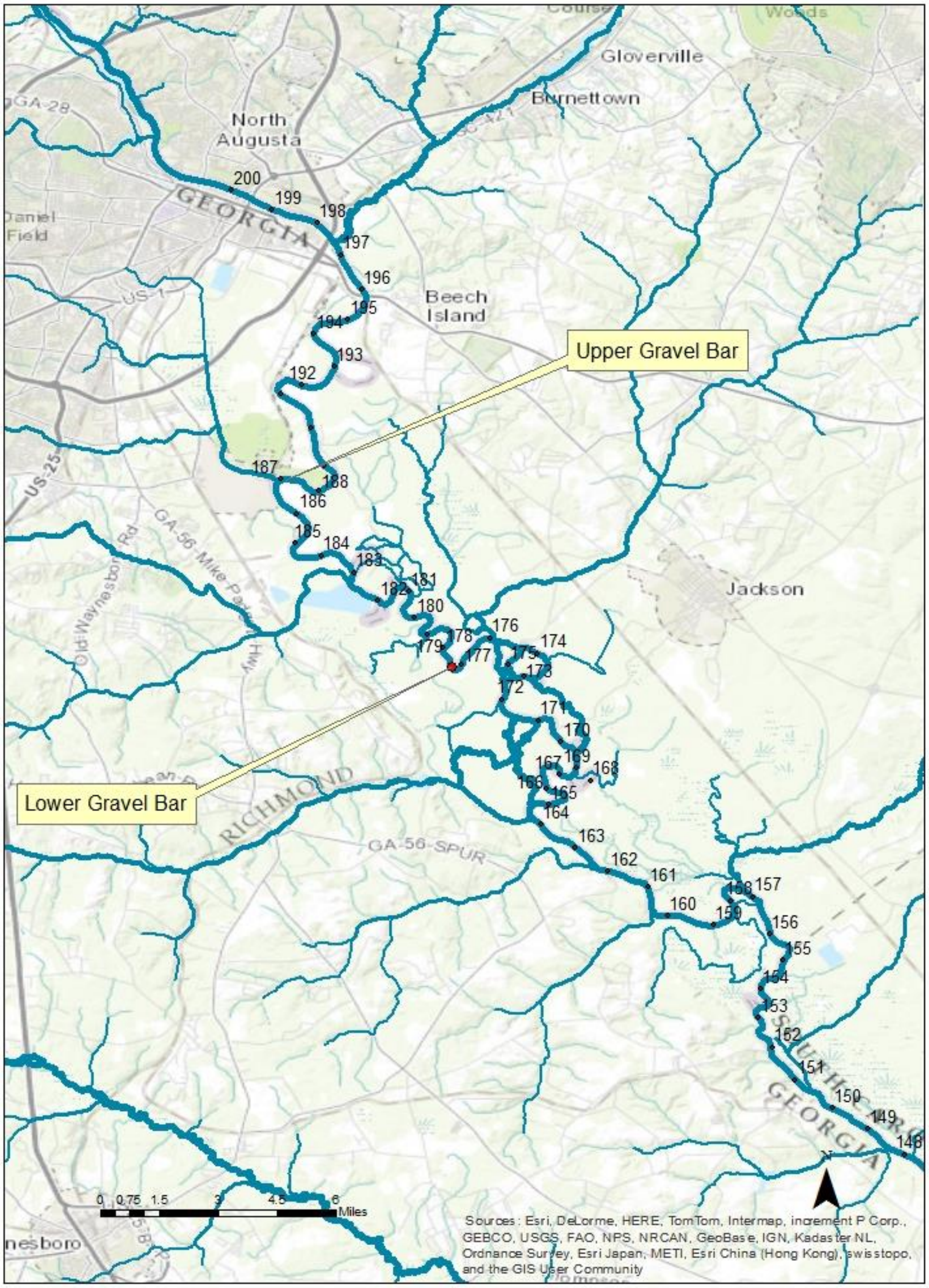
	Thurmond Dam Outflow (cfs)	NSB Discharge (cfs)	Burton's Ferry Discharge (cfs)	Clyo Discharge (cfs)
Thurmond Dam Outflow (cfs)	1.00			
NSB Discharge (cfs)	0.64	1.00		
Burton's Ferry Discharge (cfs)	0.50	0.92	1.00	
Clyo Discharge (cfs)	0.44	0.86	0.96	1.00

Table 4. Discharge at USGS gages as predicted by relationships to Thurmond Dam outflow for discharges often implicated in Drought Contingency Plans and Environmental Assessments.

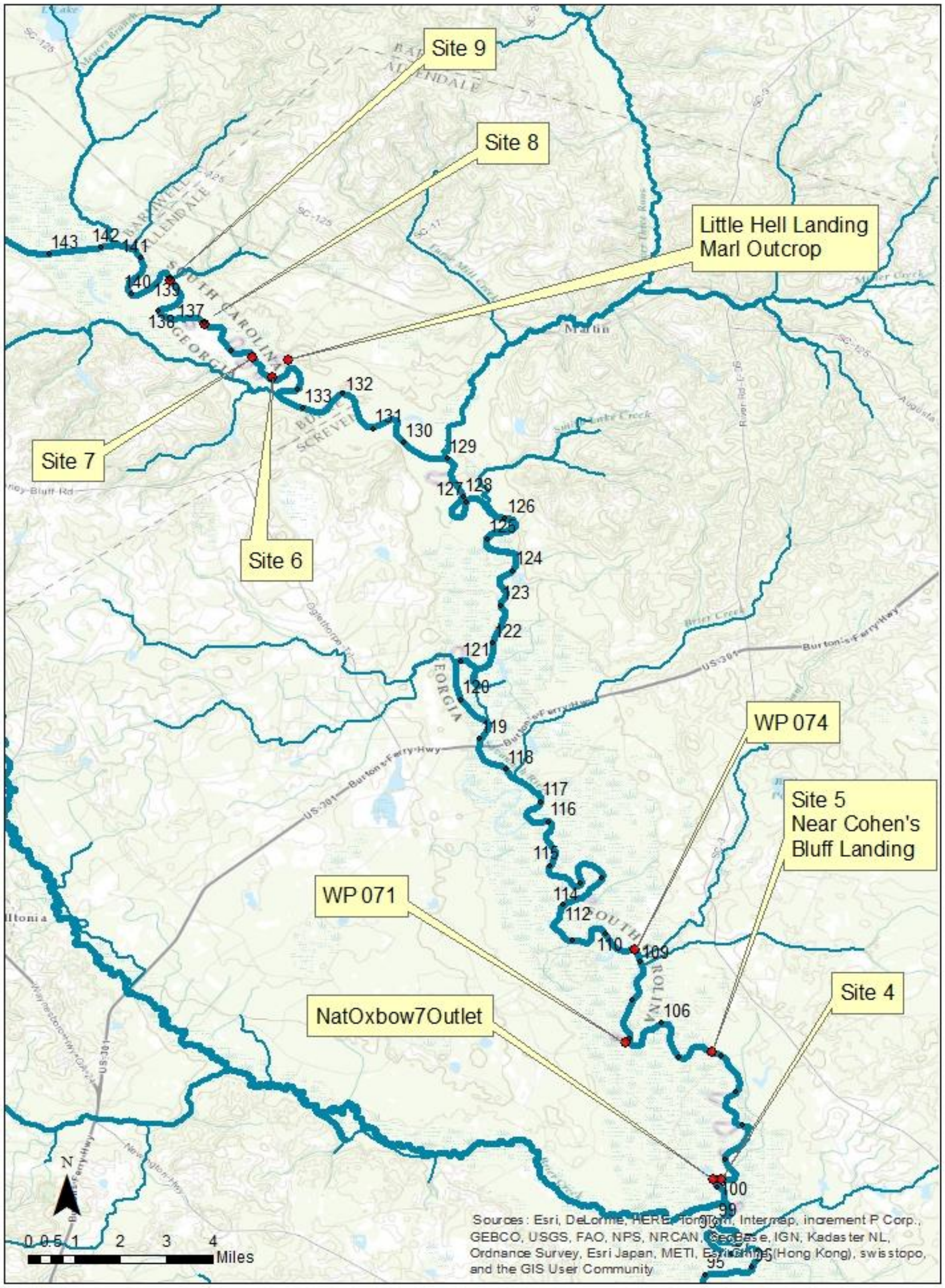
	Savannah River at Augusta gage # 02197000	Savannah River at Burton's Ferry gage # 02197500	Savannah River near Clyo gage # 02198500
Relationship between Thurmond outflow and gage data for July 1, 2012 to Dec 31, 2012	$y = 1.28197586x^{0.98428602}$	$y = 29.03619757x^{0.61576627}$	$y = 41.31025874x^{0.58046658}$
R^2 =	0.48	0.30	0.22
Thurmond Outflow			
5000	5607	5504	5797
4200	4723	4943	5239
4000	4501	4797	5093
3800	4280	4648	4943
3600	4058	4496	4790
3100	3503	4100	4392
2800	3169	3851	4140

Figure 1. Map of water level monitoring locations in the upper (A), middle (B), and lower (C) portions of the lower Savannah River. Small dots and numbers are river miles based on Army Corps of Engineers river mile data.

A)



B)


Site 9
Site 8
Little Hell Landing
Marl Outcrop
Site 7
Site 6
WP 074
Site 5
Near Cohen's
Bluff Landing
WP 071
Site 4
NatOxbow7Outlet
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SOUTH CAROLINA
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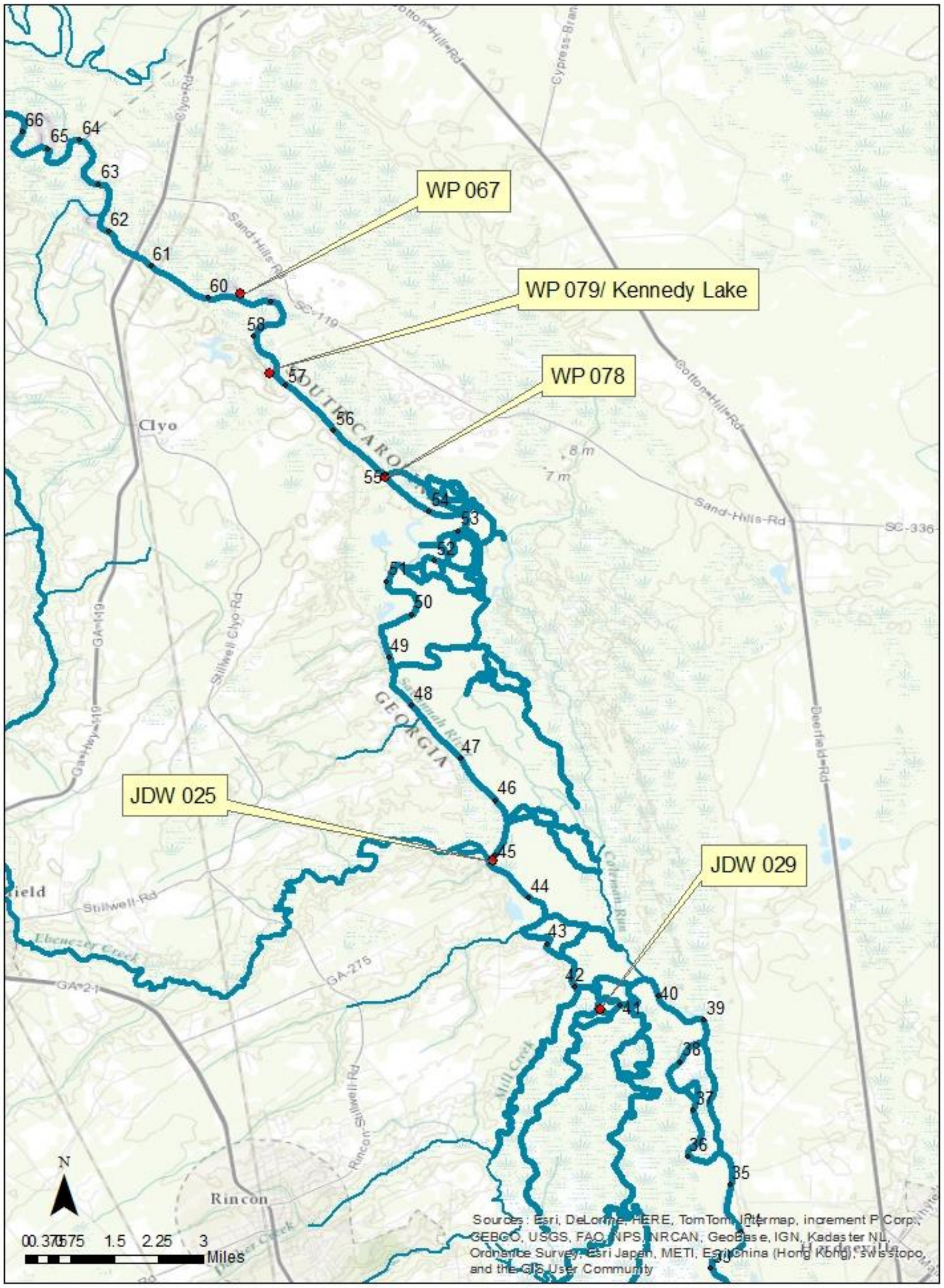
Miles
Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

C)


WP 067
WP 079/ Kennedy Lake
WP 078
JDW 025
JDW 029
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Clyo
Rincon
SOUTH CAROLINA
GEORGIA
Sand-Hills-Rd
Cotton-Hill-Rd
Deerfield-Rd
Stillwell-Rd
Ebenezer Creek
Mill Creek
GA-21
GA-275
SC-119
SC-336
N
0 0.375 0.75 1.5 2.25 3
Miles
Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 2. Example of typical hydrograph (Site 5) depicting the correspondence between water level and discharge at the USGS Burton's Ferry gage after water travel time adjustments were made.

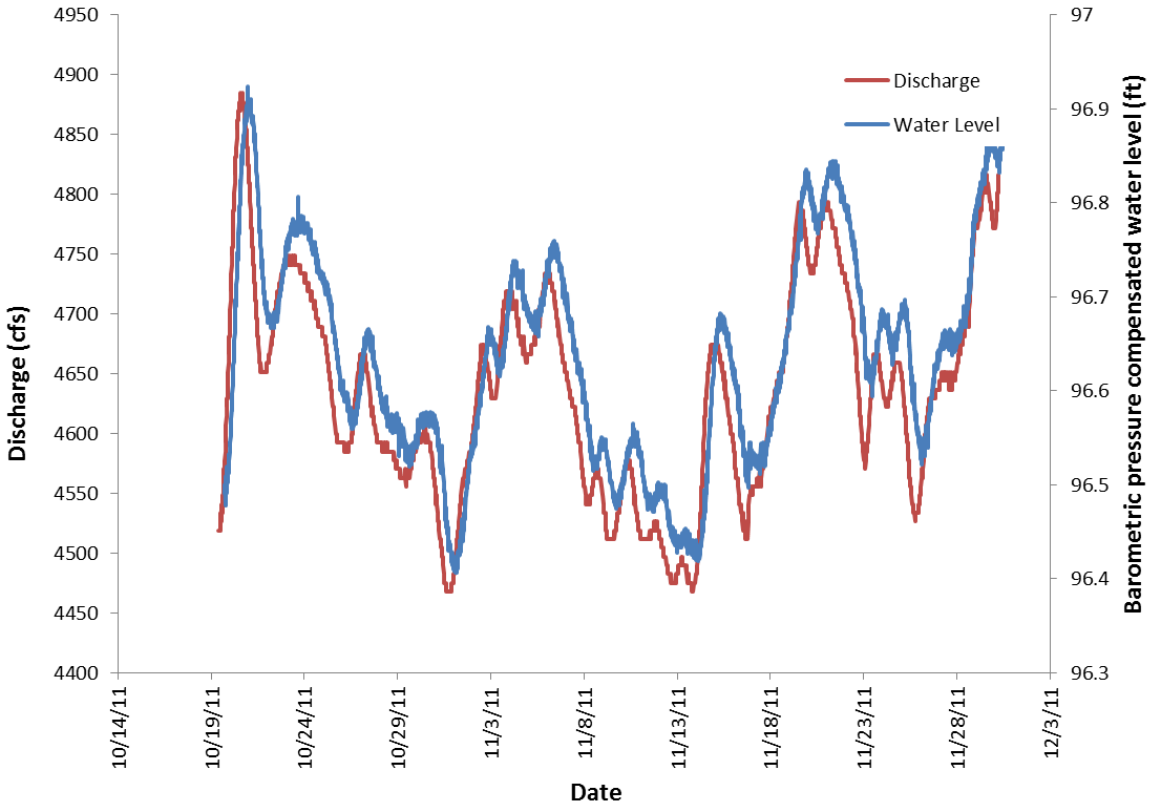


Figure 3. Stage discharge relationships at sites and river miles (RM) monitored by the Fish and Wildlife Service. The nearest USGS discharge gage is the Savannah River at Clyo.

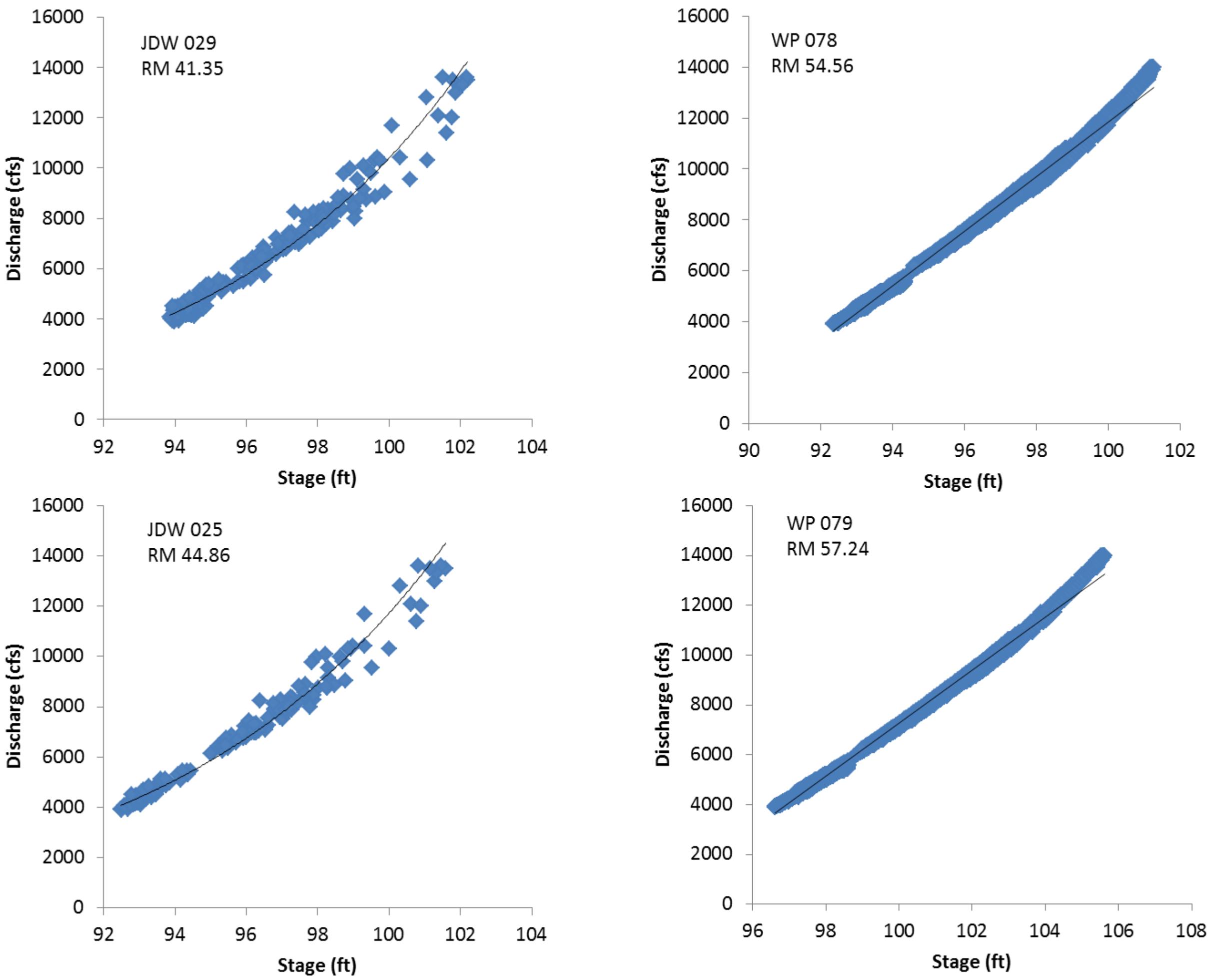


Figure 4. Stage discharge relationships at sites and river miles (RM) monitored by the Fish and Wildlife Service. The nearest USGS discharge gage is the Savannah River at Burton's Ferry.

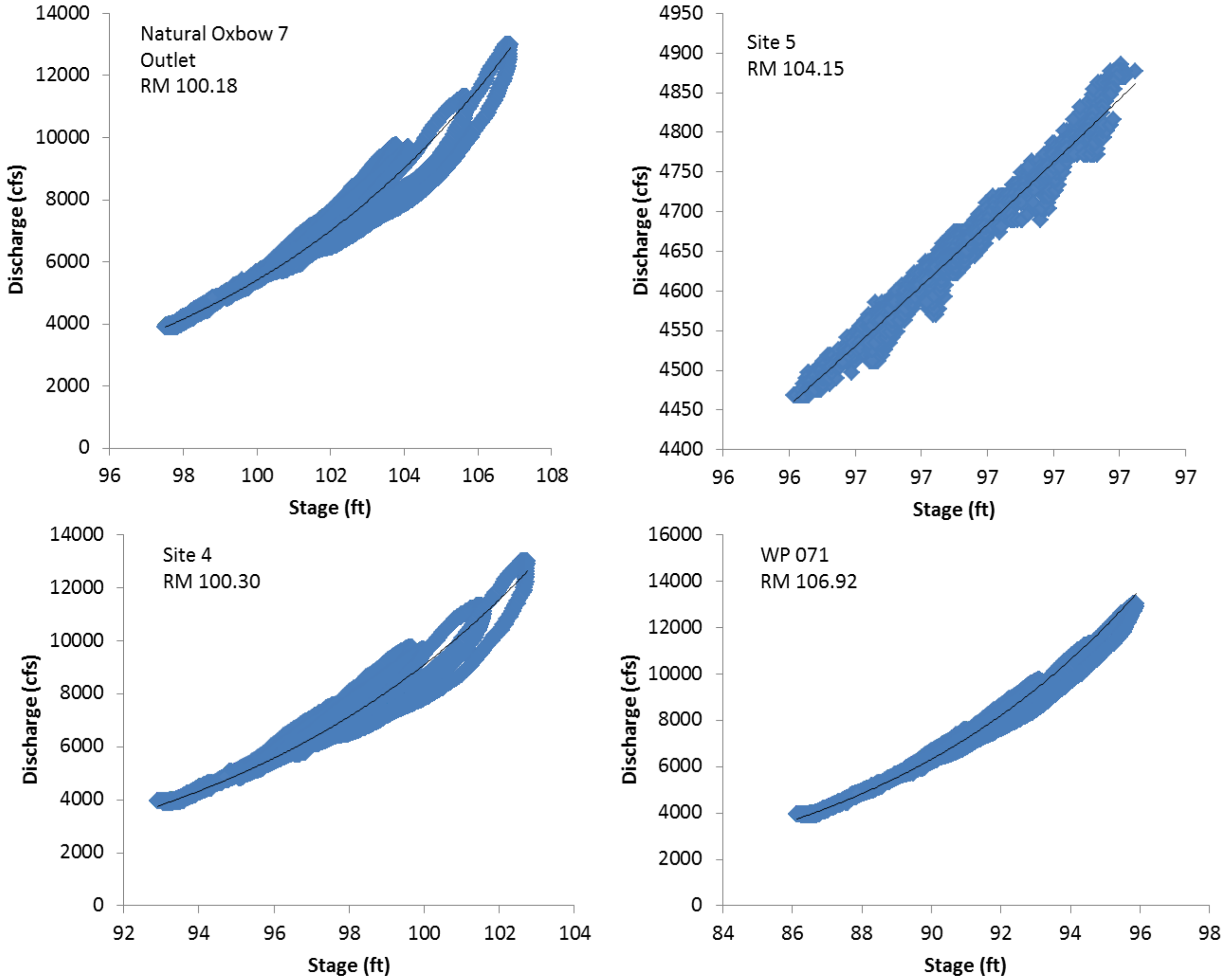


Figure 4 (continued). Stage discharge relationships at sites and river miles (RM) monitored by the Fish and Wildlife Service. The nearest USGS discharge gage is the Savannah River at Burton's Ferry.

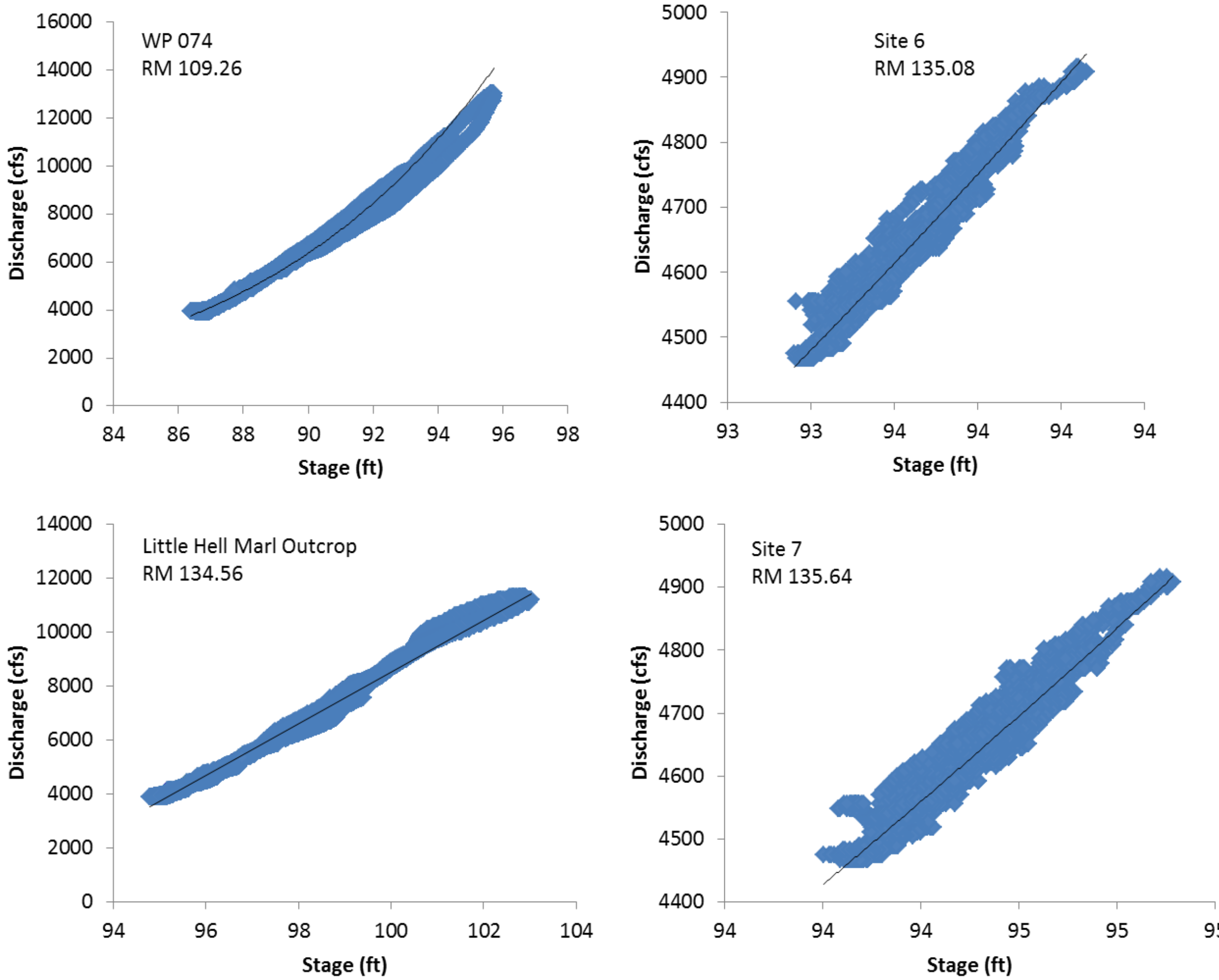
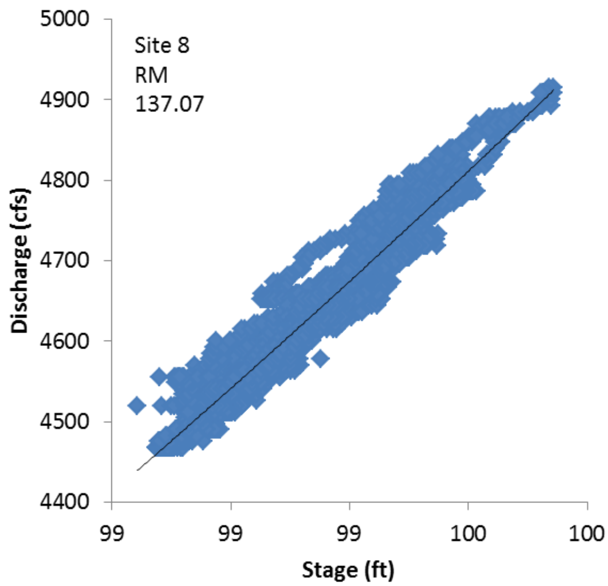


Figure 4 (continued). Stage discharge relationships at sites and river miles (RM) monitored by the Fish and Wildlife Service. The nearest USGS discharge gage is the Savannah River at Burton's Ferry.



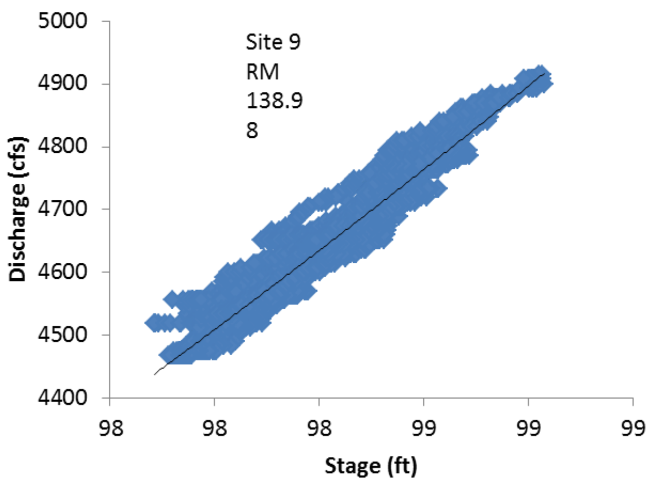


Figure 5. Stage discharge relationships at sites and river miles (RM) monitored by the Fish and Wildlife Service. The nearest USGS discharge gage is the Savannah River at Augusta.

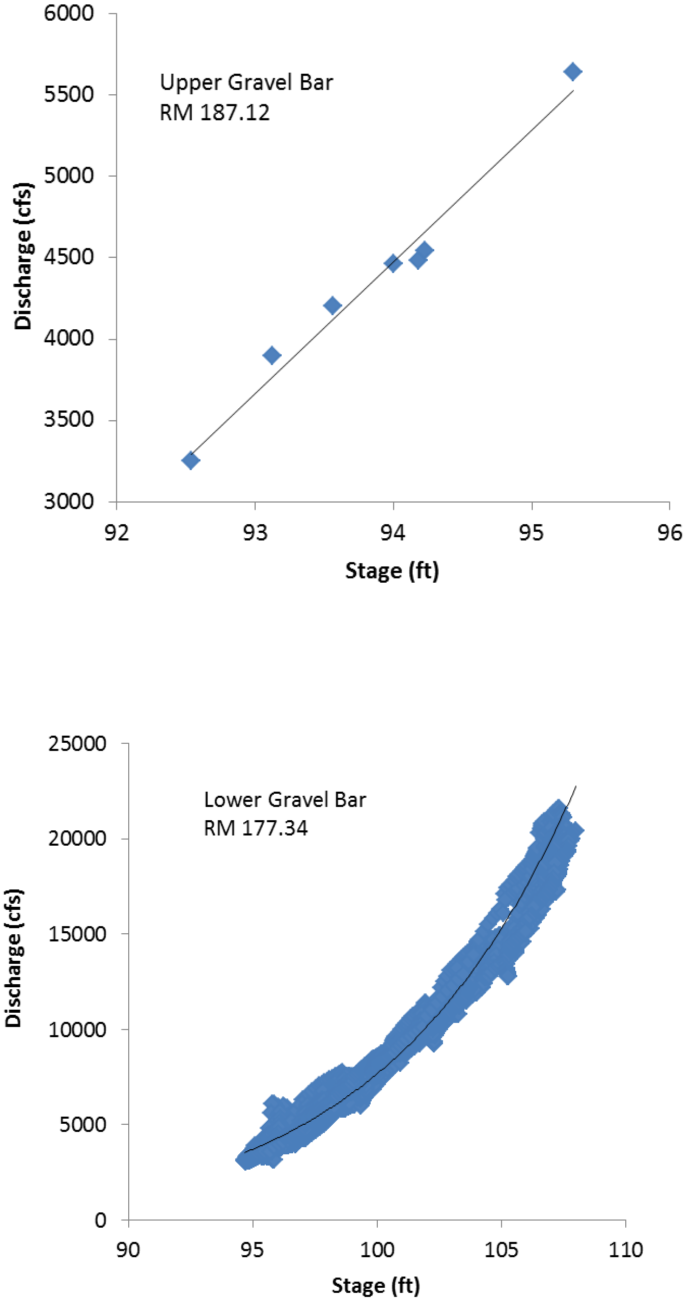


Figure 6. Relationship between Thurmond Dam outflow and discharge at three USGS gages on the Savannah River.

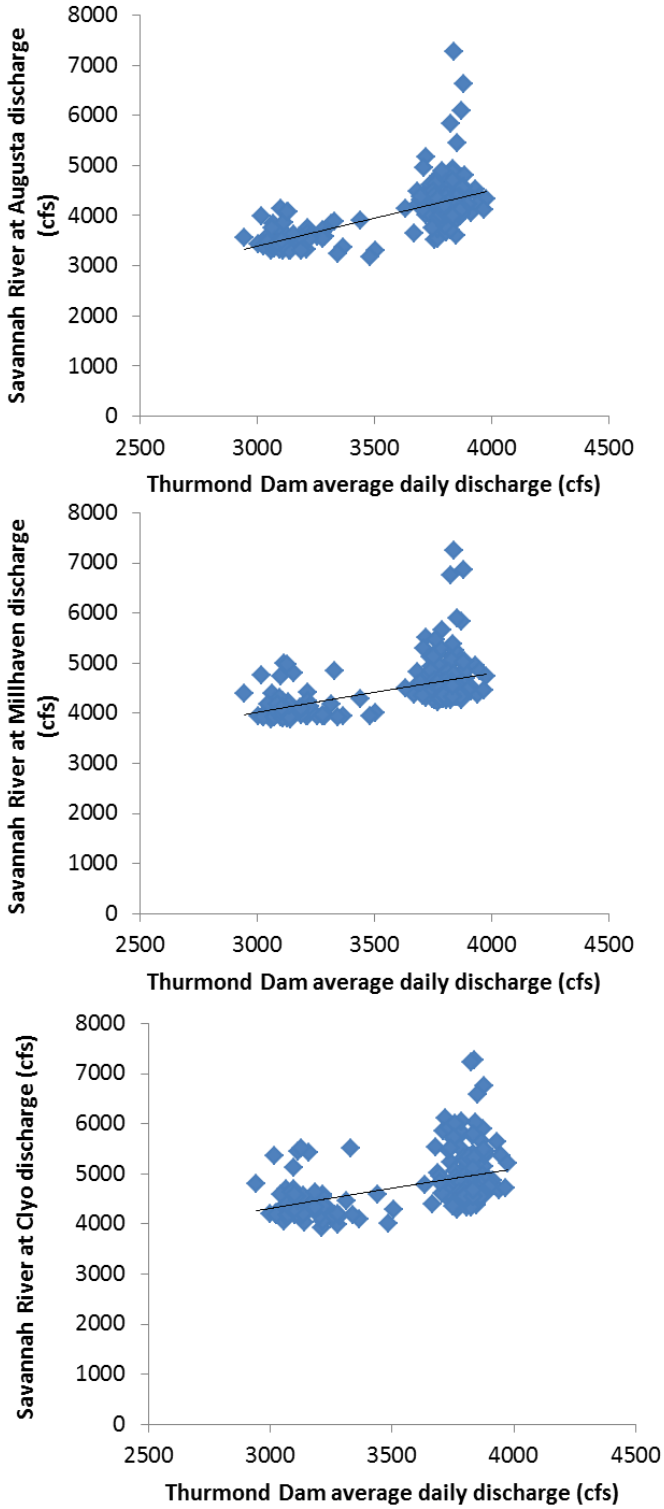


Figure 7. Discharge (A) at the Savannah River at Burton's Ferry gage and percent of Burton's Ferry discharge accounted for by Thurmond Dam outflow (B) from July 1, 2012 to December 31, 2012.

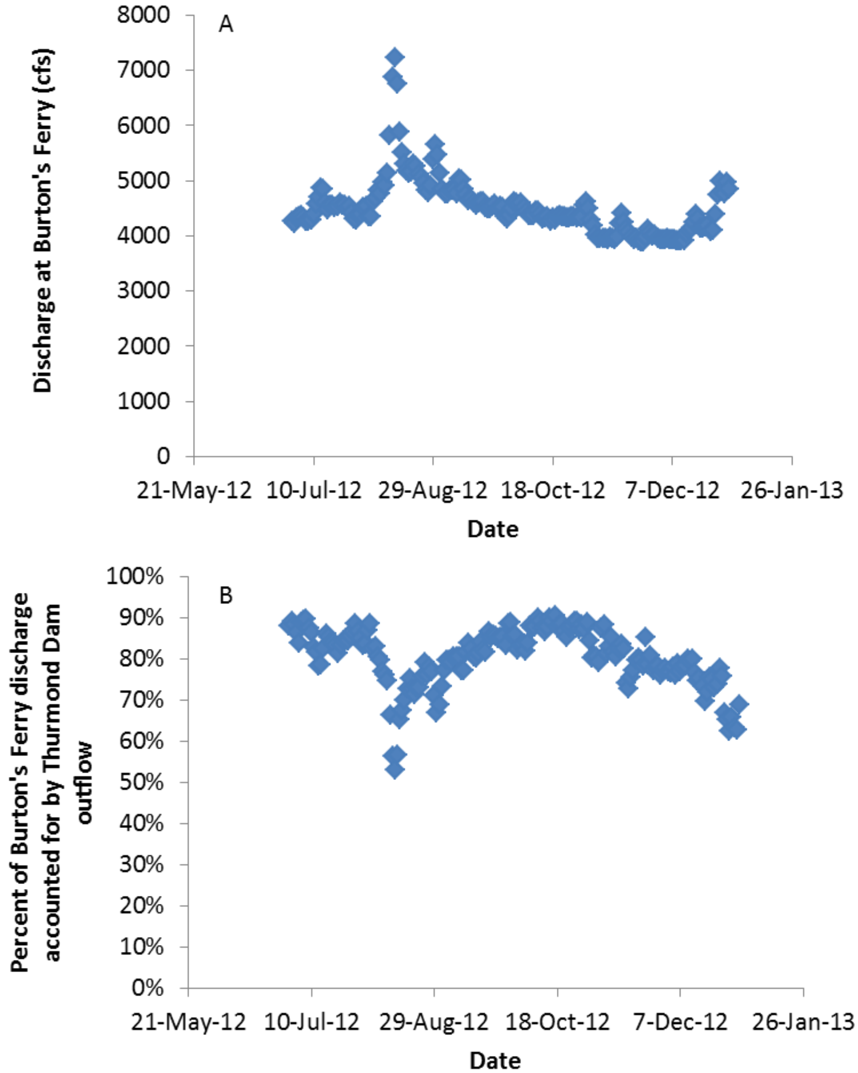


Figure 8. Relationship between actual discharge from acoustic Doppler current profiler (ADCP) and USGS gage estimates at New Savannah Bluff Lock and Dam (USGS # 02197000).

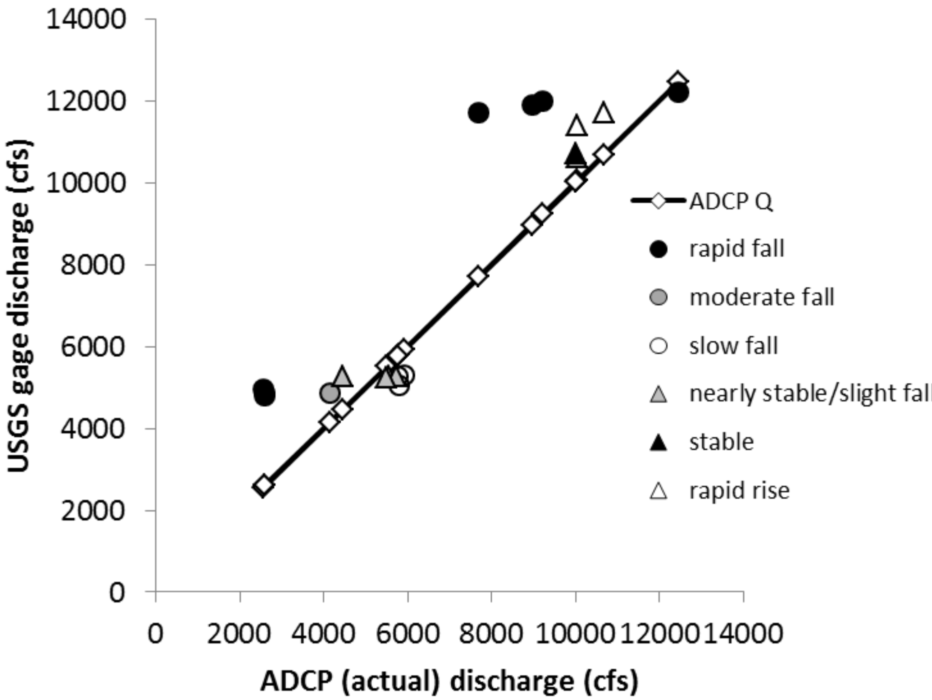


Figure 9. Effects of rise and fall rates on the difference between gage discharge estimates (USGS # 02197000) and actual discharge as measured by ADCP.

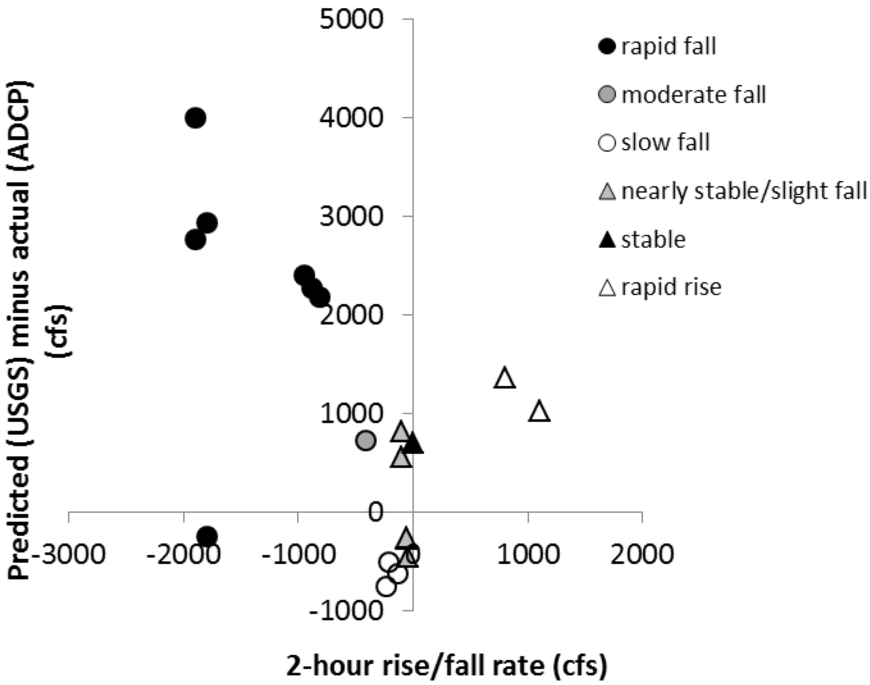


Figure 10. Relationship between fall rates and the difference between gage estimates (USGS # 02197000) and actual discharge as measured by ADCP.

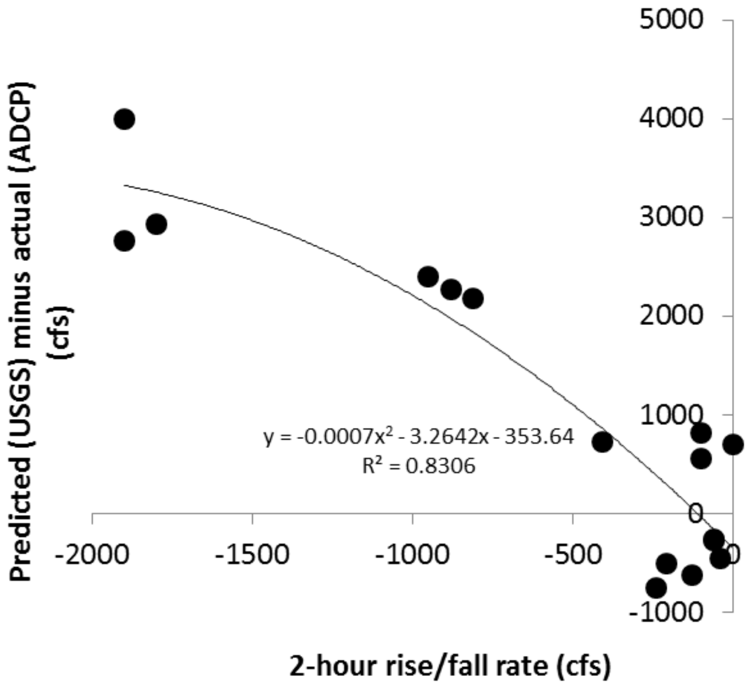
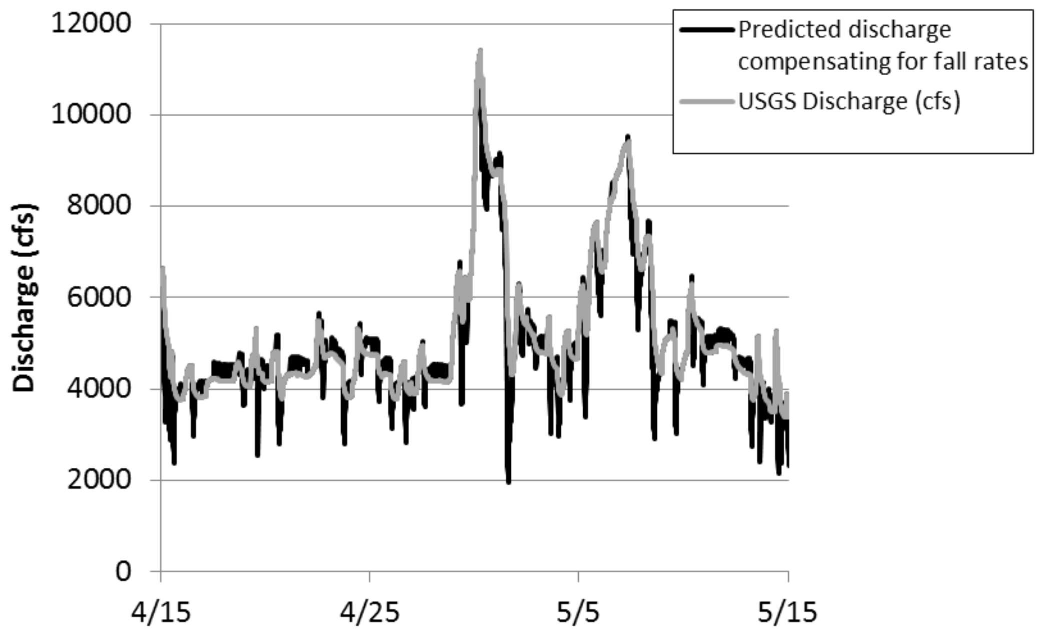


Figure 11. Comparison of discharge estimated by the Savannah River at Augusta gage (USGS # 02197000) and USGS discharge data that were adjusted for fall rate effects.



Part II. Evaluation of low discharge effects on Savannah River mid-channel gravel bars, with an emphasis on habitat suitability for spawning Robust Redhorse (*Moxostoma robustum*)

A report to the
U.S. Army Corps of Engineers
Savannah District

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Summary

Mid-channel gravel bars are an important yet limited habitat feature in the Savannah River. We investigated the two bars near New Savannah Bluff Lock & Dam (NSBL&D) Savannah RM 187.1 and RM 177.4. These stream bed features are key elements of the transition from the rocky shoals along the Fall Line, as the Savannah River flows into the lower gradient meanders of the coastal plain. These central gravel bars have been identified as spawning sites for the Candidate species, Robust Redhorse (*Moxostoma robustum*) a large, riverine sucker (Catostomidae) that spawns in spring during a two-week period when water temperatures are between 20–24°C. The best spawning areas are on the upstream top, flatter portions of each gravel bar, which are inundated at discharges >7,000 cfs .

We measured habitat conditions at the gravel bars during lower, drought response flows, between 3,000 and 5,000 cfs, as well as higher flows. We collected depth, current velocity, and substrate data at multiple flow levels, using multiple methods, including direct and acoustic measurements. At lower flows, velocity and depth were not suitable for spawning Robust Redhorse. The gravel bars are composed of large, medium, and pea-sized gravel substrates, along with silt, sand, and coarse sand. At discharge levels below 7,000 cfs, depth and velocity were insufficient in much of the gravel bar habitat to overlap with the spawning substrate requirements of catostomids. We observed daily and hourly fluctuating flows that caused portions of the two central gravel bars to be exposed above the water surface, or reduced to levels unsuitable for fish courtship, and spawning behaviors. Portions of the gravel bars were exposed at low flow levels. Habitat was available at inundated portions of the gravel bars for other species, including small American eels, striped mullet, and abundant larval fishes, as well as wading birds. Both gravel bars were fully inundated at flow levels of 5,680 cfs. Following higher flows, contours were noticeably altered, indicating scour and redistribution. Our results indicate that conditions at these limited flow-sensitive habitats in the Savannah River can exceed the lowest thresholds for suitability for some species, and are much reduced in quality and spatial extent during very low flows. Further, survival of eggs, fry, and larvae of rare fishes may be compromised if flow conditions fall or fluctuate during critical seasons. In general, suitable habitat (depth, velocity, and substrate) for rare sucker spawning is limited in the Savannah River downstream of NSBL&D. Velocity and depths measured at the gravel bars were generally lower at lower discharges. Gravel substrate with adequate depth and velocity conditions was more patchily distributed at lower flows, and was found at the downstream steeper areas of the gravel bars, rather than the upstream, accelerating flatter expanses used for spawning. Low-velocity habitat at gravel bars in the Savannah River was dynamic during the fluctuating, low discharge levels we observed. Though not suitable for spawning, low-velocity habitats may be important for young life stages of Robust Redhorse, other suckers, diadromous fishes, and other priority aquatic biota. The response of larval Robust Redhorse and other larval fishes to changes in habitat velocities and patchiness warrants investigation. Since these life stages may be limited in

their ability to move between low-velocity habitats, or to seek refuge from increasing water velocity, fluctuating flows may have deleterious effects on early life stages. Exposure of redds could increase the likelihood of desiccation of redds, unhatched eggs, or small fry.

Introduction

Mid-channel gravel bars are an important but limited habitat feature in the Savannah River. These few, scattered bed features are key elements of the transition from the rocky shoals along the Fall Line, as the Savannah River flows into the lower gradient meanders of the Coastal Plain. The number of mid-channel gravel bars is very limited in number (n=2), very limited in size, and very important to catostomid spawning. The two gravel bars identified in other studies (Grabowski and Isely 2007; 2008, Jennings et al. 2010, Isely 2010, Jackson and Long 2011), were subject of our investigations during low flow conditions in 2012 – 2013 (Figure 1). Grabowski and Isely (2007) provide a detailed description of each gravel bar.

These central gravel bars have been identified as spawning sites for the Candidate species, Robust Redhorse (*Moxostoma robustum*) a large, riverine sucker that occurs in a limited range in Georgia, South Carolina and North Carolina. This rare fish is found in Upper Coastal Plain and Piedmont rivers along the Atlantic slope drainages from the Pee Dee River in the Carolinas to the Altamaha River system in Georgia. Robust redhorse spawn over loose gravel substrate in moderate to swift current (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. Spawning is similar to other species of *Moxostoma* (Burr and Morris 1977; Healy 2002, Jenkins and Jenkins 1980; Kwak and Skelly 1992) and results in egg burial depth of 2.4 - 5.9 inches for Robust Redhorse (Freeman and Freeman 2001). 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 occurs from the end of April through mid-June in the Oconee River. Robust redhorse eggs hatch in 3.5 days under incubation temperatures of 23°C in laboratory conditions (J. Zelko, 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 (Jennings et al. 1996).

- Upper Gravel Bar - Savannah RM 187.1 Central gravel bar near New Savannah Bluff Lock & Dam (NSBL&D)
- Lower Gravel Bar - Savannah RM 177.4 Central gravel bar at Stingy Venus

The best spawning areas are on the upstream top, flatter portions of each gravel bar, which are inundated at discharges >7,000 cfs (Grabowski and Isely 2007).

The purpose of our study was to quantify the relationships between river flows and habitat for Robust redhorse and associated gravel spawning species for a larger range of low flow conditions than had been measured in previous studies. We estimated physical spawning habitat and were able to make hydraulic measurements at low flows as they occurred during the study period, regardless of the seasonal or thermal characteristics relevant to Robust Redhorse spawning. We did not make direct measures or observations of spawning activity of the target species, since our focus was on the physical habitat at various low flow levels, and spawning occurred in a limited temporal window. These relationships are intended to inform the development of low-flow management alternatives for US Army Corps of Engineers dams on the Savannah River.

Methods

We collected depth, water velocity, and substrate data at multiple flow levels, using various methods depending on water levels.

Bathymetry and substrate data were collected using a MX Echosounder (BioSonics, Inc.; 204.8 kHz,8.4° single beam) and data processing with BioSonics Visual Habitat software on August 29/30, 2013. These data were used to delineate gravel bar boundaries, calculate total gravel bar area in ArcGIS, and develop bathymetric maps.

Surveys were conducted by wading at 3,260 cubic feet per second (cfs) on January 16, 2013 and approximately 4,500 cfs on March 8, 2013 at the Upper Gravel Bar. At the Lower Gravel Bar, wading measurements were collected at approximately 3,300 and 3,380 cfs on December 18 and 19, respectively (Table 1). We collected depth and water velocity data using a handheld velocity meter. At the Upper Gravel Bar, measurements were taken along transects that were perpendicular to a line starting near the top of the gravel bar (N 33.37230, W -81.94431) and extending toward the lock (azimuth 66 degrees). At the Lower Gravel Bar, the line started at N 33.3032, W -81.8816 with a180 degree azimuth. Transects extended to a maximum wadeable depth of approximately 4 feet, a depth that exceeded the maximum known spawning depth of robust redhorse in the Savannah River system. Transects were spaced 40 feet apart, but were occasionally 20 feet apart if changes in water velocity or depth were noticeable. Measurements along each transect were collected every 20 feet, or smaller intervals if there were noticeable changes in water velocity or depth. Sediment was classified using the Wentworth scale at each measurement location.

We collected depth and water velocity data at greater discharges using a boat-mounted Acoustic Doppler Current Profiler (ADCP; Teledyne RD Instruments TRDI Rio Grande system; 1.200 MHz) and a sub-meter-accurate, differentially corrected GPS system (TopCon model GMS-2) to measure water velocities and depths along transects throughout the gravel bar. As much of the wetted width of each transect was sampled as possible. Mean water column velocities (georeferenced) were obtained using Teledyne Instruments WinRiverII software. ADCP measurements used to characterize habitat conditions occurred at 2,780 cfs at the Upper Gravel Bar, and 8,800 cfs at the Lower Gravel Bar. ADCP measurements were made at other flows, but those flows were either outside the range of depths considered suitable for Robust Redhorse spawning, or lacked the coverage necessary to adequately characterize the gravel bar (Table 1). Data from WinRiver II were exported to Microsoft Excel. The exported data included ensemble number, latitude, longitude, beams average depth, and water speed based on bottom tracking (a measure of average water column velocity in an ensemble). In several instances where water depths were too shallow for the instrument to deliver accurate velocity data, we interpolated between points to estimate water velocities.

WinRiver II was used to provide screenshots of cross-sectional velocity profiles for some transects. The portion of each gravel bar that was emersed during multiple site visits was mapped using a Garmin GPSmap76C, and later incorporated into GIS for aerial extent calculations and polygon creation (Table 2).

River stage varied hourly and daily. The purpose of our measurements was to consider habitat conditions at successively lower discharges from J. Strom Thurmond Reservoir, though flow accretion and fluctuations caused by intercedant dams contributed to the observed variation at the gravel bar study sites. Consequently, we used multiple USGS gages to corroborate observations of depths, velocities, and discharge, along with depth measurements by remote, submerged, pressure sensitive data loggers (ONSET Computer Corp, Inc., HOBO U20 Water Level Data Logger). Data from USGS gaging station 02197000 (SAVANNAH RIVER AT AUGUSTA, GA) showed hourly discharge fluctuations that were also observed at both gravel bars, while USGS gaging station 02197500 (SAVANNAH RIVER AT BURTONS FERRY BR NR MILLHAVEN, GA) showed attenuation of hourly fluctuations and general discharge trends. All discharge data presented in this report are from USGS gaging station 02197000. Because of the complicated hydrology and the variety of methods used to derive discharge values in this report, a summary of survey periods and associated discharge measurements by the USGS and FWS are provided (Table 1).

Habitat Suitability Criteria. Habitat suitability criteria (HSC) or indices define the range of conditions that a particular species life stage will inhabit. HSC values are usually expressed in a range from 0 to 1.0, indicating habitat conditions that are unsuitable to optimal, respectively, for a species/life stage. The HSC provide the biological criteria input to consider physical habitat conditions at various flow levels on the species and life stage(s) of interest. We focused on the HSC for spawning Robust Redhorse (*Moxostoma robustum*), a Candidate for listing as an Endangered Species that occurs in the Savannah River, and we relied on suitability criteria proposed by Freeman and Freeman (2001):

Suitable water depth:	0.29 - 1.1 m / 0.95- 3.61 ft
Suitable average water column velocity:	0.26 - 0.67 m/s 0.85 – 2.20 ft/sec
Suitable substrate:	medium - coarse gravel 0.47-1.97 in & <30% sand

The HSC for each life stage of the Robust Redhorse are important determinants in survival and recruitment of this target species. Our measures of depth, velocity, and substrate were used to determine suitability of the gravel bars for spawning only, though we considered the potential for fluctuating flows to affect survival of eggs and larval fishes at the spawning sites (Grabowski and Isely 2006, 2007, Fisk 2010, Fisk et al. 2013, Weyers et al. 2003). Based on the HSC suitability values, we used a select-by-attribute routine (ESRI 2010) to sequentially identify and select locations of suitable (1) depth, (2) velocities, and (3) sediment size. Only locations that simultaneously met all three suitability criteria were considered suitable for Robust Redhorse spawning.

We used gravel elevation measurements collected on the gravel bar in combination with depth suitability criteria to estimate (1) the minimum elevations required to fully inundate each gravel bar, (2) the minimum elevation required to meet minimum spawning depth criteria on top of each gravel bar, and (3) the elevation above which no suitable spawning depths occur on each gravel bar. Elevations were converted to mean sea level so that the USGS gage rating curve could be used to estimate discharge for each elevation. Because we deployed a water level logger at the lower gravel bar, we calculated the time lag between water level measurements at USGS gaging station 02197000, the upper gravel bar, and the lower gravel bar. After accounting for the time lag, we calculated a best fit line between water surface elevation and discharge (Part 1 of this compendium) so that we could calculate the same threshold discharges at each gravel bar.

We estimated the effect of low water levels on the percent of emersed gravel bar habitats using linear regressions between discharge and emersed area polygons. To evaluate how immersed habitat (100- percent emersed) varies as a function of discharge during the 2013 spawning season (approximately April 15 to May 15), we used sub-hourly gage data to predict immersion and calculate exceedance probability plots. The USGS gaging station 02197000 (SAVANNAH RIVER AT AUGUSTA, GA) provided good, direct 15-minute interval measurements of the river stage at the Upper Gravel Bar. However, the USGS gage at NSBL&D did not accurately predict actual discharge (Q) at the Upper Gravel Bar on the receding limb of the hydrograph due to drain-out and refill of the pool area between the gage and the Upper Gravel Bar. Therefore, we used the rate-of-change compensated USGS discharge data to more accurately represent actual discharge for the upper bar (Part 1 of this compendium). Although compensating for rate-of-change accounted for 83% of the variation in the difference between USGS and ADCP measurements, we stress that the compensated discharge data are estimates that require further refinement in order to accurately predict discharge. Compensated data were not used for the lower gravel bar estimates because level logger data at the Lower Gravel Bar show that non-compensated data predict water levels best, probably because the short duration flow fluctuations by the NSBL&D gate attenuate downriver.

Results

Bathymetric maps were generated for the upper (Figure 2) and lower (Figure 3) gravel bars. The upper and lower gravel bars encompassed 1.84 and 1.24 acres, respectively. Large gravel (1-3 inches), medium (0.5-1.0 inches), pea-sized gravel (0.1 - 0.5 inches) and larger substrates were present at the gravel bars, along with silt, sand, and coarse sand. Although there was overlap between depth and velocity readings at the two lowest discharges when wading measurements were made at the upper gravel bar, the lowest discharge had significantly more exposed surface. At the lowest discharge, most suitable velocities at gravel substrates occurred only at the gravel bar margins where depths were deeper than suitable. At slightly higher discharges (4,500 cfs), we measured areas of suitable habitat that had more large gravel and faster water velocity on average (Figure 4; Table 3). At the Lower Gravel Bar, depth and velocity over gravel generally increased with discharge, but suitability could only be assessed at the lowest discharges (Table 4).

Fluctuating flows caused portions of the two central gravel bars to be exposed above the water surface, or reduced to levels unsuitable for fish courtship and spawning behaviors. The extent of upper gravel bar exposure was measured at 3,260 cfs, 4,500 cfs, and 5,100 cfs (Figure 5), but exposure at only the two lowest discharges was measured at the Lower Gravel Bar (Figure 6; Table 4). For the Upper Gravel Bar, we calculated that a minimum discharge of 5,680 cfs is required to fully inundate the gravel bar. For the Lower Gravel Bar, we found that a minimum discharge of 5,596 cfs is required to fully inundate the gravel bar. We used linear regression lines for the upper bar (R^2= 0.97) and lower bar (R^2= 0.83) to estimate percent exposure as a function of discharge:

$$\text{Upper Gravel Bar: } y = -0.0122x + 68.784$$
$$\text{Lower Gravel Bar: } y = -0.0187x + 100.28$$

At discharges between 3,240 and 4,500 cfs, there was an approximate 5.9% (upper bar) and 11.5 % (lower bar) change in percent exposed gravel bar habitat for every 500 cfs, illustrating similar flow-habitat trends but different effect magnitudes (Table 4). Exposure of the Upper Gravel Bar occurs more frequently than the lower bar (Figure 7), but the Lower Gravel Bar is affected proportionally more than upper bar. For example, inundation of 80% of the Lower Gravel Bar was exceeded 66% of the time, whereas inundation of 80% of the Upper Gravel Bar was exceeded 83% of the time (Figure 8). However, the best spawning areas are on the upstream top, flatter portions of each gravel bar, the first areas to be exposed as flows subside.

How much water is too much? Suitable spawning depths on top of the Upper Gravel Bar occur between 100.84 and 103.50 ft, which is equivalent to 6,540 and 9,320 cfs. Discharge above 9,320 cfs results in no suitable spawning depths for robust redhorse.

Suitable spawning depths on top of the Lower Gravel Bar occur between 99.19 and 101.85 ft, which is equivalent to 6,411 and 9,317 cfs. Discharges above 9,317 cfs results in no suitable spawning depths (too deep) for robust redhorse.

In order for these gravel bars to be utilized for spawning, the appropriate depths must occur during spring (Figure 13) when water temperatures are appropriate. Temperatures used by spawning Robust Redhorse ranged from 16-24.6°C at Broad River, Georgia (Straight and Freeman 2013), 17-26.7°C reported by Freeman and Freeman (2001), similar to the range (17.5-22.1 °C) reported by Fisk (2010) in the Pee Dee River.

In general, at discharge levels below 7,000 cfs, suitable depth and velocity were available at limited areas. Suitable depths and velocities in much of the Upper Gravel Bar did not co-occur with the spawning sediment requirements of Robust Redhorse and other catostomids, and was limited at progressively lower discharges (Figure 9, Figure 10). ADCP water velocity data for both gravel bars showed a high degree of spatial variation, with greater velocities consistently occurring in shallower portions of transects and of bars (Figure 12 and 13). Because of variation between transects, we were not able to compare suitable habitat calculations for the Lower Gravel Bar. However, we retained the data for presently unforeseen future purposes.

We observed that at flow levels greater than approximately 5,680 cfs, both gravel bars were fully inundated (Figure 11). Following higher flows, gravel bar contours were noticeably altered.

Conclusions and Implications for Water Management

Habitat conditions at the two gravel bars limit the suitability for some species and life stages at drought flows. In general, the most contiguous, suitable habitats appear at increasing (to a point) flow levels. Grabowski and Isely (2007) found that Robust Redhorse was vulnerable to fluctuations in water levels at these gravel bars at the Savannah River, and observed nest dewatering and spawning habitat degradation in 2004. Isely (2010) noted that relatively minor changes in discharge exposed large areas of gravel. Fisk et al. 2013 observed redd dewatering at the Pee Dee River, another regulated stream. Declining stage and discharge leads to changes in flow direction and velocities, so that deposition of suspended and bedload materials vary. Although deposition is probably not directly related to discharge rate, decreases in discharge may cause finer materials to drop in slowest areas (i.e. sedimentation). We observed that sedimentation patterns were generally variable within and between the gravel bar sites. Sediments at the Lower Gravel Bar were noticeably finer (more sand) than those at the upper gravel bar. Future work should evaluate bedload transport and sources of gravel materials.

Our results indicate that conditions at these limited flow-sensitive habitats in the Savannah River can exceed the lowest thresholds for suitability for a focal species, the Robust Redhorse, and are much reduced in quality and spatial extent during very low flows. Further, survival of eggs, fry, and larvae of both rare and common fishes may be compromised if flow conditions fall or fluctuate during critical seasons. Conversely, conditions can exceed the highest depth thresholds for suitability for Robust Redhorse at flows less than 2,780 cfs, and greater than 9,320 cfs.

Gravel bar habitats are limited. In general, the Savannah River downstream of NSBL&D is dominated by sandy substrates, and the two central gravel bars are anomalies. Only two central gravel bars have been located. Bars form as a response to the interactions of stream flow moving over a mobile sediment bed. Knowledge of the fluvial conditions required for bar formation, maintenance, and retention is essential to understanding gravel bar occurrence in the Savannah River. Bars provide important structure of riffle-pool sequences in alluvial channels (especially artificially straightened channels with low relief) and are storage sites for mobile sediment. The two central gravel bars are unique in the Savannah River because they occur in an area that is otherwise a meandering (though truncated by prior channel alterations), sand- bed stream at a transition area below the Fall Line. The future of these gravel bars is uncertain, even with continued, similar flow conditions, since gravel supply is likely limited due to the interrupted bedload transport caused by dams.

Suitable habitat (depth, velocity, substrate) for rare sucker spawning is limited in the Savannah River downstream of New Savannah Bluff Lock & Dam. Velocity and depths measured at the gravel bars were generally lower at lower flow levels. Gravel substrate with adequate depth and velocity conditions was more patchily distributed at lower flows, and was found at the downstream steeper areas of the gravel bars, rather than the upstream, flatter expanses used for spawning. Spawning observations at Pee Dee River (Fisk 2010, Fisk et al. 2013) were supplemented with habitat availability data, to infer habitat *preference*. The depth and velocity preferences measured on the Pee Dee River were slightly higher than the Freeman and Freeman (2001) values because of the habitat availability weighting techniques used. Generally, observations of spawning habitat across the range of Robust Redhorse, in regulated and unregulated streams, all point to higher velocities and deeper spawning sites than we measured at NSBL&D.

Large contiguous portions of the two central gravel bars were emersed at low flows, rendering those areas unsuitable for survival of early life stages. Additional sources of mortality may stem from fluctuating flows. Though we measured habitat conditions during multiple drought flow levels from J. Strom Thurmond Dam, fluctuating flows at intercedent dams allowed us to make additional observations at even lower flow conditions. Between survey dates, fluctuating flows appeared to have transported and redistributed fine particles. Mobilization of these particles could reduce survival of eggs and larvae in redds (Fisk et al. 2013), even if the redds were not dewatered. Robust redhorse egg and larvae mortality experiments indicate a high degree of mortality (>92%) when fine sediment is > 25% (Jennings et al., 2010), meaning that flow fluctuations observed in the Savannah River also may be indirectly contributing to mortality through mobilization of fine sediment.

Gravel bars are dynamic, moving, and may become more limited depending on bedload supply, transport conditions, and local currents. We are concerned about the long-term maintenance of these two key locations in the Savannah River because of what appears to be very limited bedload of gravel recruited into the river reach. The central gravel bars are hydraulically unique in their placement- both are downstream of hydraulic deflectors without an obvious source of recruitment. We recommend targeted efforts to identify sources and rates of movement of gravel-size particles recruiting or persisting at the two sites. Determining the particular hydraulics that favor maintenance of these dynamic habitats, and evaluating the potential to augment the sediment supply to these sites, or to create additional sites warrants further investigation. Furthermore, future changes in flow direction and diversion at NSBL&D (i.e., the fish passage structure planned at NSBL&D as mitigation for the SHEP impacts to Shortnose sturgeon habitat) could alter the shape and stability of the upper gravel bar, as well as sediment supply. We are concerned about how these effects will occur, whether they will be monitored as part of that project, and whether mitigation will occur (McManamay et al. 2010) if negative impacts are observed.

<u>Interaction with other Corps projects.</u> In general, mid-channel storage bars form in response to changing sediment transport conditions (Brice 1964). In the Savannah River, these mid-channel gravel bars have apparently persisted for decades, uncharacteristic for natural flow and sediment regimes. At low flows, we observed that the higher part of these bars may emerge as a medial bar. Such bars are referred to as braid bars, distinguished from islands because they are not not exposed at bankfull flows. The gravel/sand bar at RM 177.4 occurs just downstream of a series of pile dikes (wing dams), while the gravel bar at RM 187.1 is downstream of the dam at NSBL&D. These storage bars form downstream of obstructions as non-fluvial element bars. River regulation can affect bed surface and subsurface material due to bed scour or by changing transport rates, along with reduction in the supply of sand and gravel. In the Savannah River, channel steepening, and navigation improvements have altered sediment supply and transport rates. Transport of sediment from tributaries, river banks, and future reconnection of cutoffs can

cause changes to river pattern and morphology. Changes in the pile dikes, NSBL&D or its operation, or natural ageing and downstream migration of these bars may lead to changes in their suitability, and even their distinctness. In sum, consideration of the complex interactions between discharge and sediment transport should remain a priority for gravel bar management and should be factored into consideration in current and future Corps projects on the Savannah River.

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Figure 1. Location of study sites at two mid-channel gravel bars in Savannah River. The Upper Gravel Bar, is located at Savannah RM 187.1, near New Savannah Bluff Lock & Dam, while the Lower Gravel Bar is located at Savannah RM 177.4 near Stingy Venus.

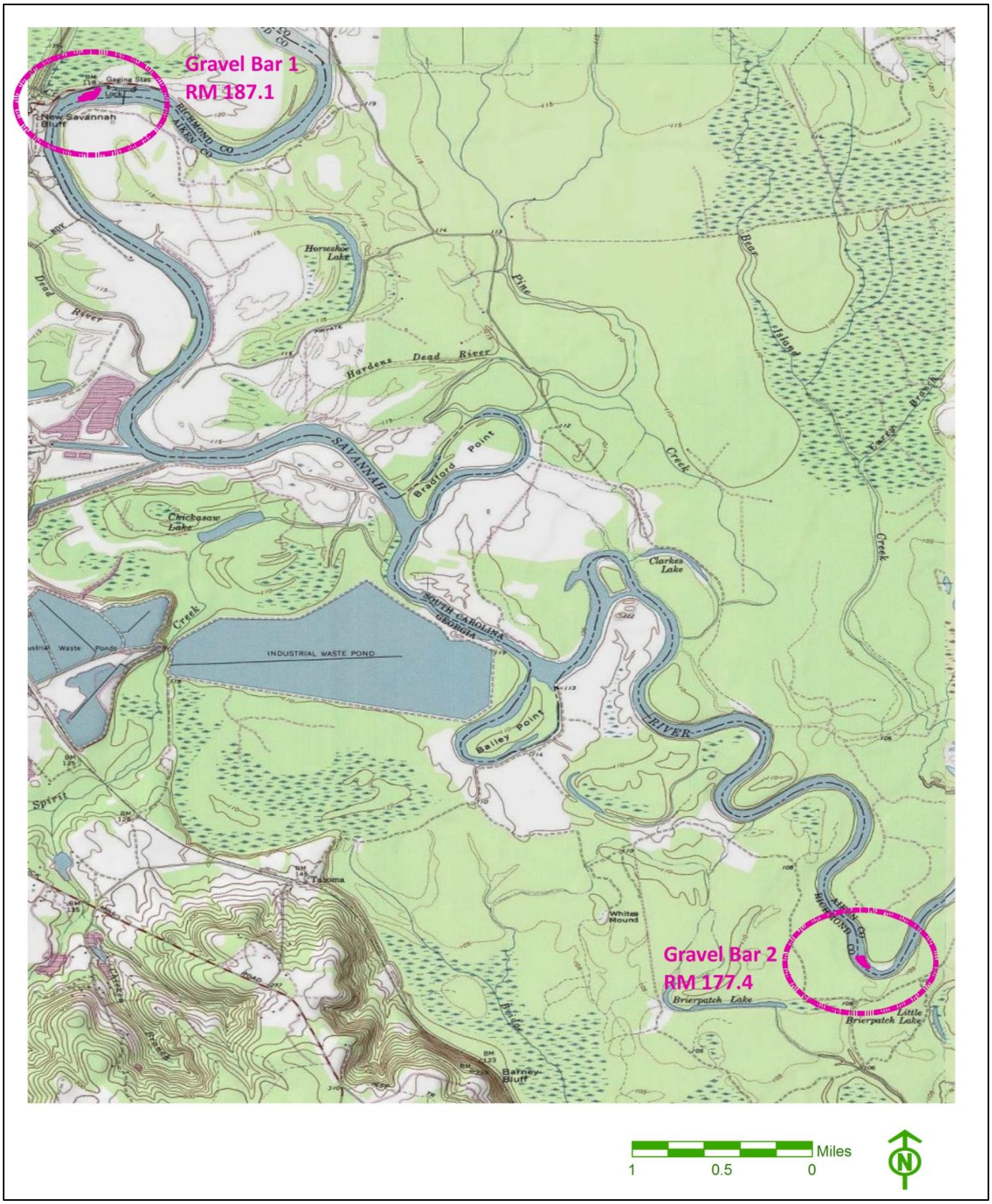


Figure 2. Upper Gravel Bar bathymetry mapped with MXEchosounder. The darker red colors represent the shallowest portions of the gravel bar.

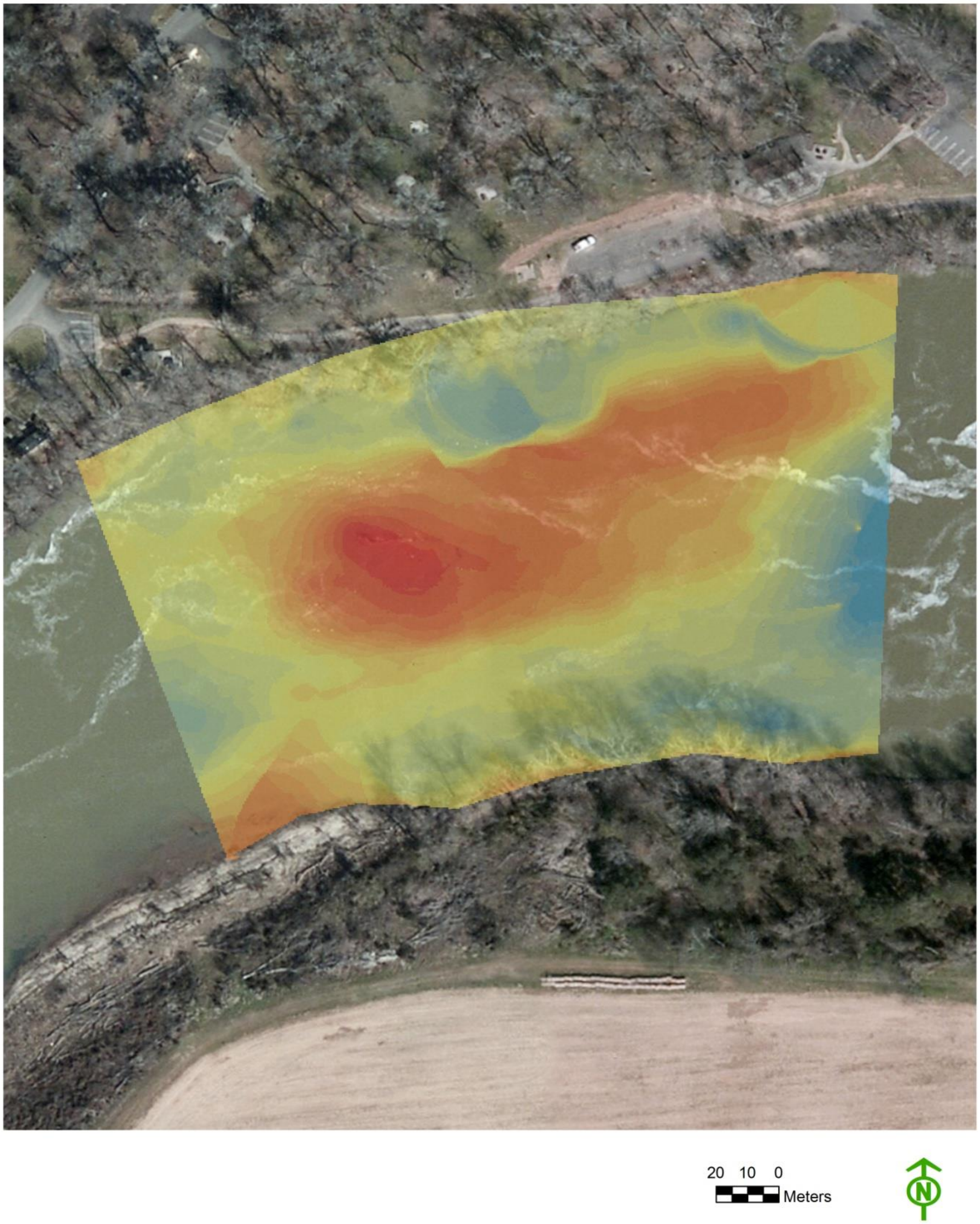


Figure 3. Lower Gravel Bar bathymetry mapped with MXEchosounder. The darker yellow colors represent the shallowest portions of the gravel bar. Note the banding, waved relief across the bar.

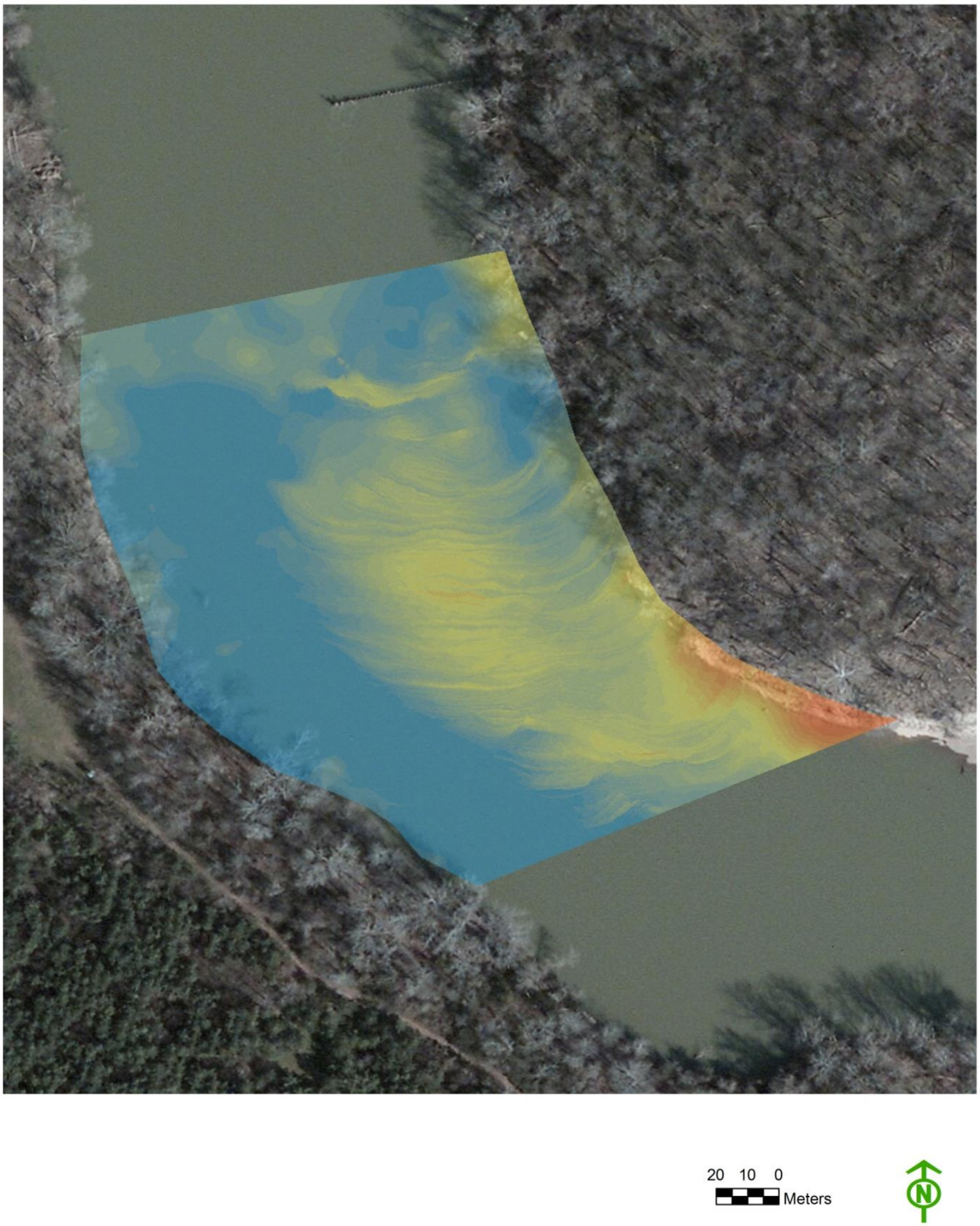


Figure 4. Mean and maximum velocities for three primary sediment classes at locations with suitable depths at the Upper Gravel Bar (Savannah River RM 187.1). At lowest discharges, velocities were scattered, with a wider range.

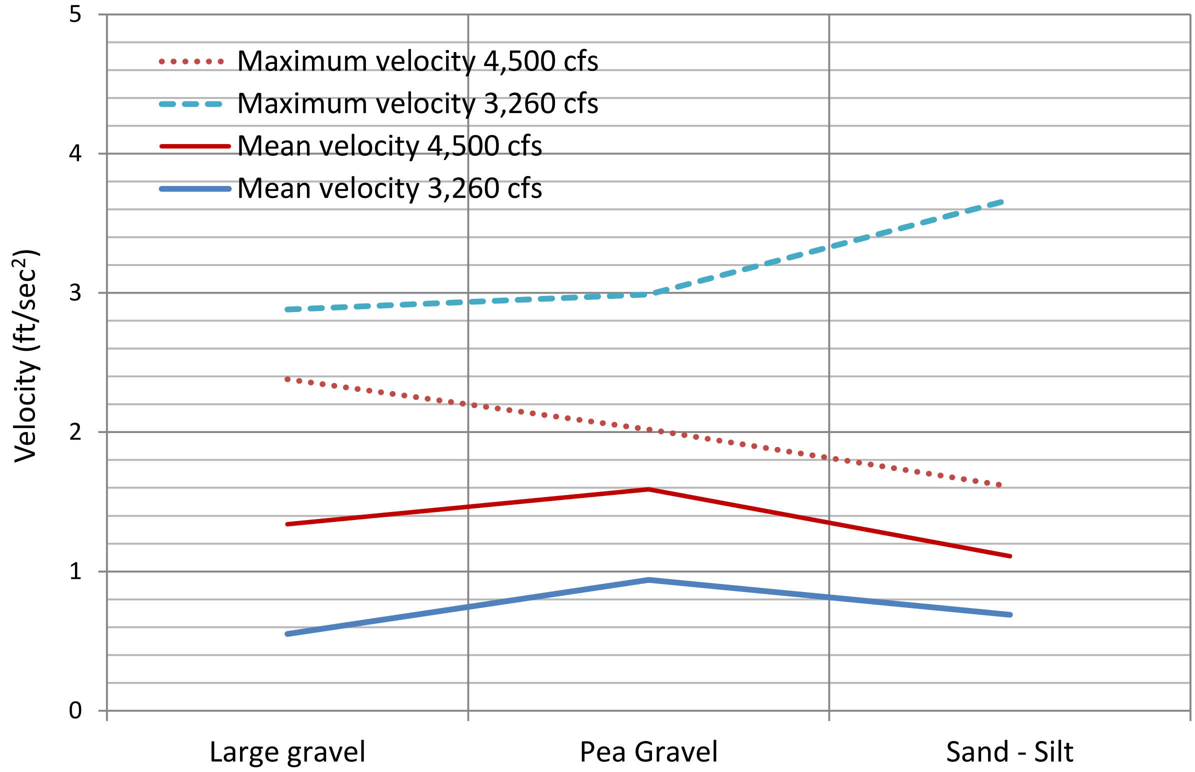


Figure 5. Portions of the Upper Gravel Bar that were exposed at 3,245 cfs (green polygons), 4,720 cfs (yellow polygon), and 5,100 cfs (tan polygon). Exposed portions of the Upper Gravel Bar were not available as aquatic habitat.

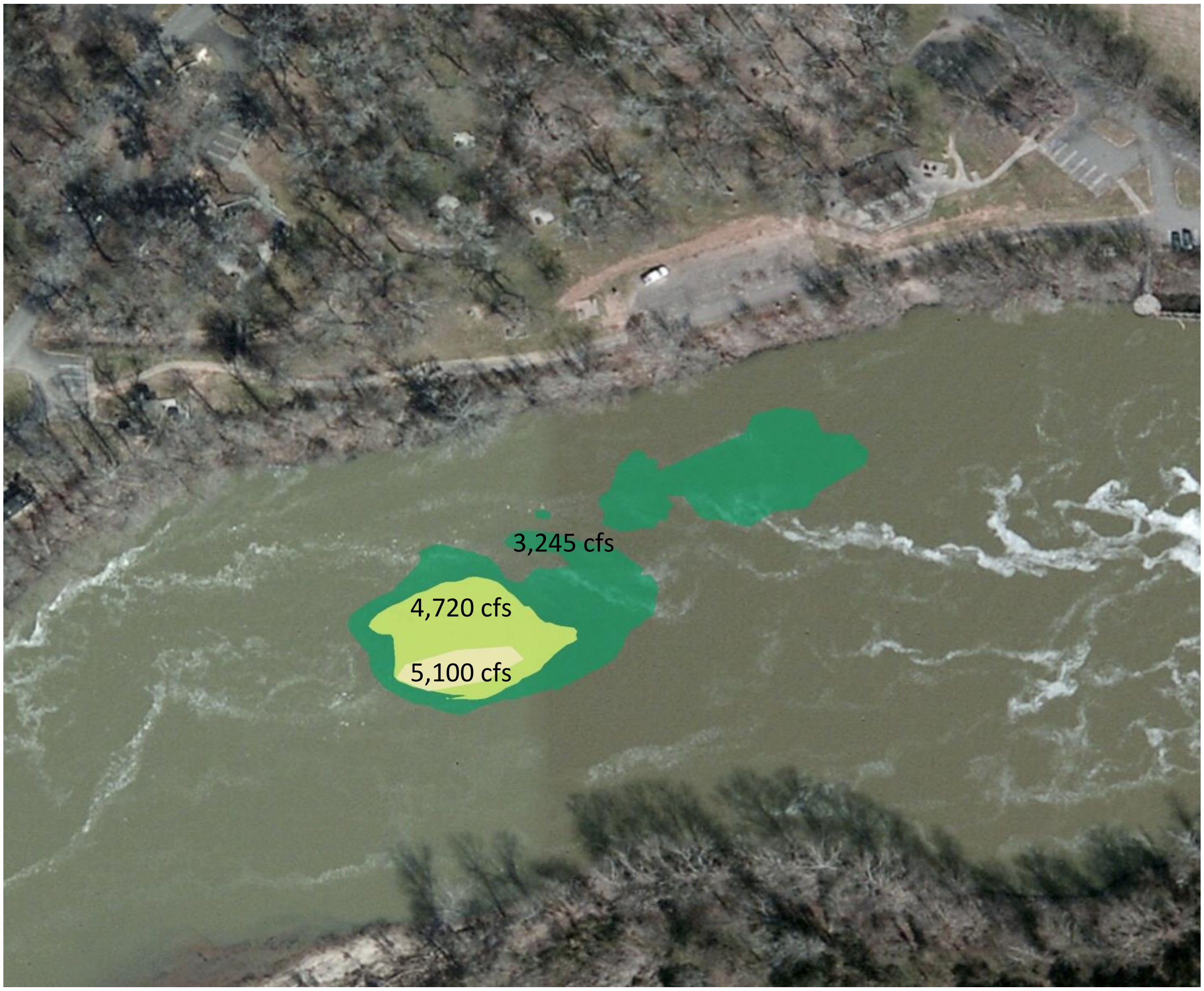
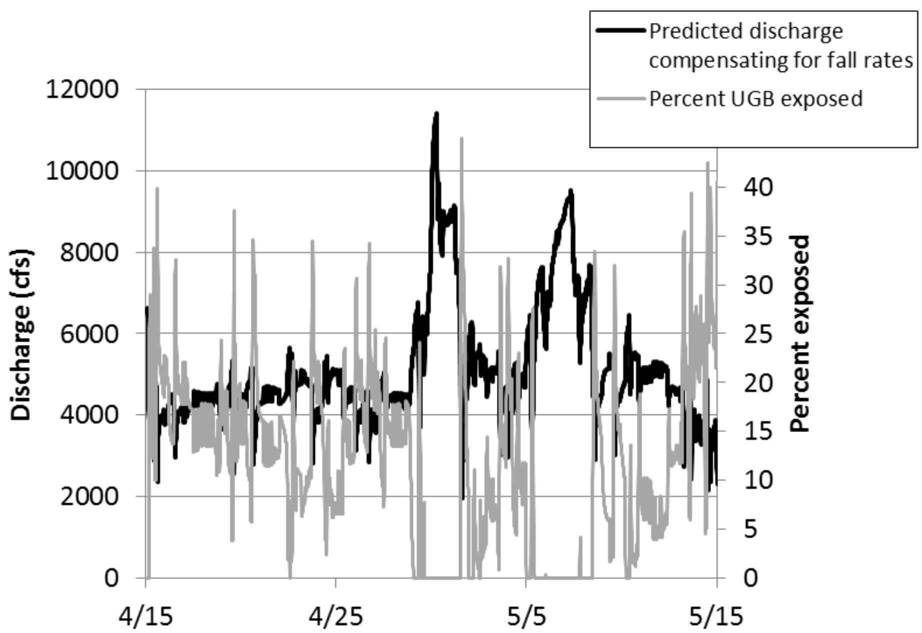


Figure 6. Portions of the Lower Gravel Bar that were exposed at 3,790 cfs (brown polygon), 4,670 cfs (yellow polygon). Exposed portions of the lower gravel bar were not available as aquatic habitat.

Figure 7. Discharge and the percent of the Upper Gravel Bar (A) and Lower Gravel Bar (B) that were exposed during the 2013 spawning season (approximately April 15 to May 15).

A)



B)

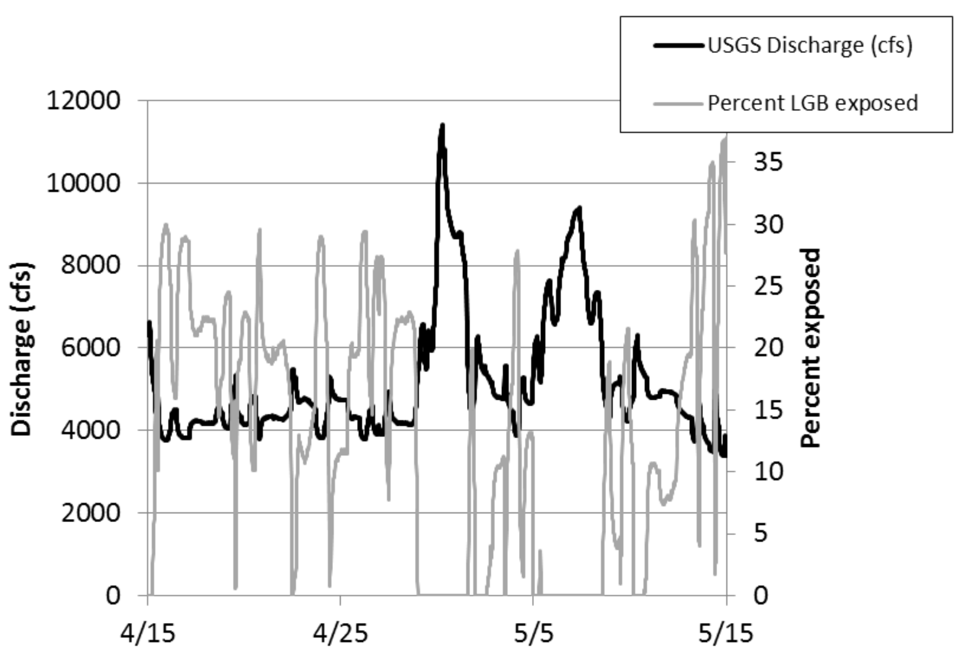


Figure 8. Exceedance probabilities comparing the percent of Upper Gravel Bar and Lower Gravel Bar inundation during the 2013 spawning season (April 15-May 15).

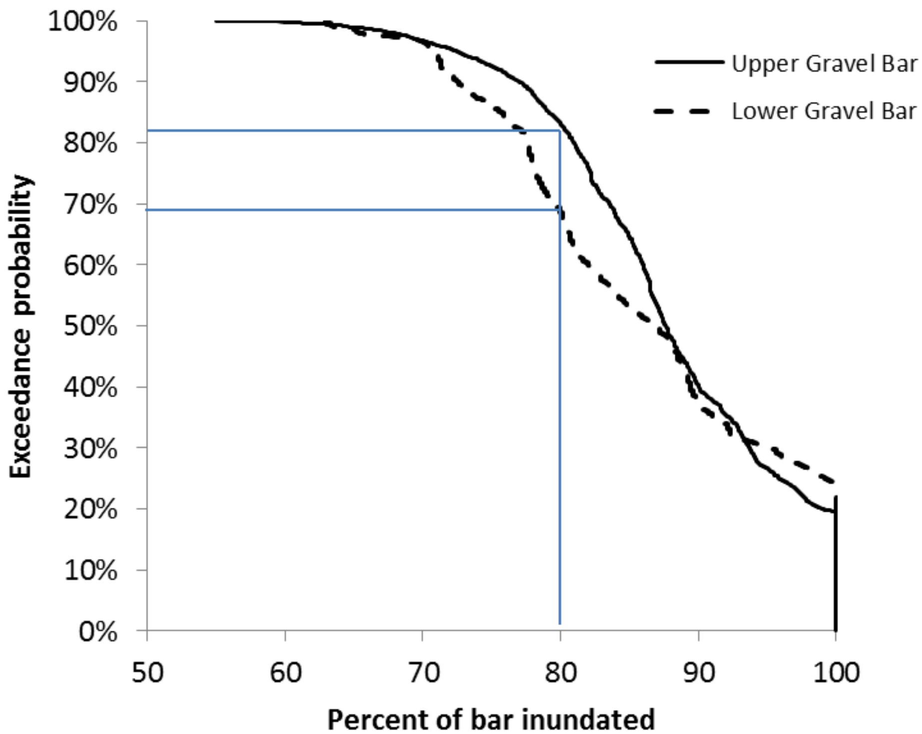


Figure 9. Depths and velocities measured at sampling locations with suitable sediments for Robust Redhorse spawning. The green box delineates the range of preferred spawning habitat depths and velocities. Red squares and blue circles were measurements taken by wading at the Upper Gravel Bar, and at the Lower Gravel Bar, respectively. Values outside of the preferred range were too slow, too shallow, too deep, or both slow and shallow.

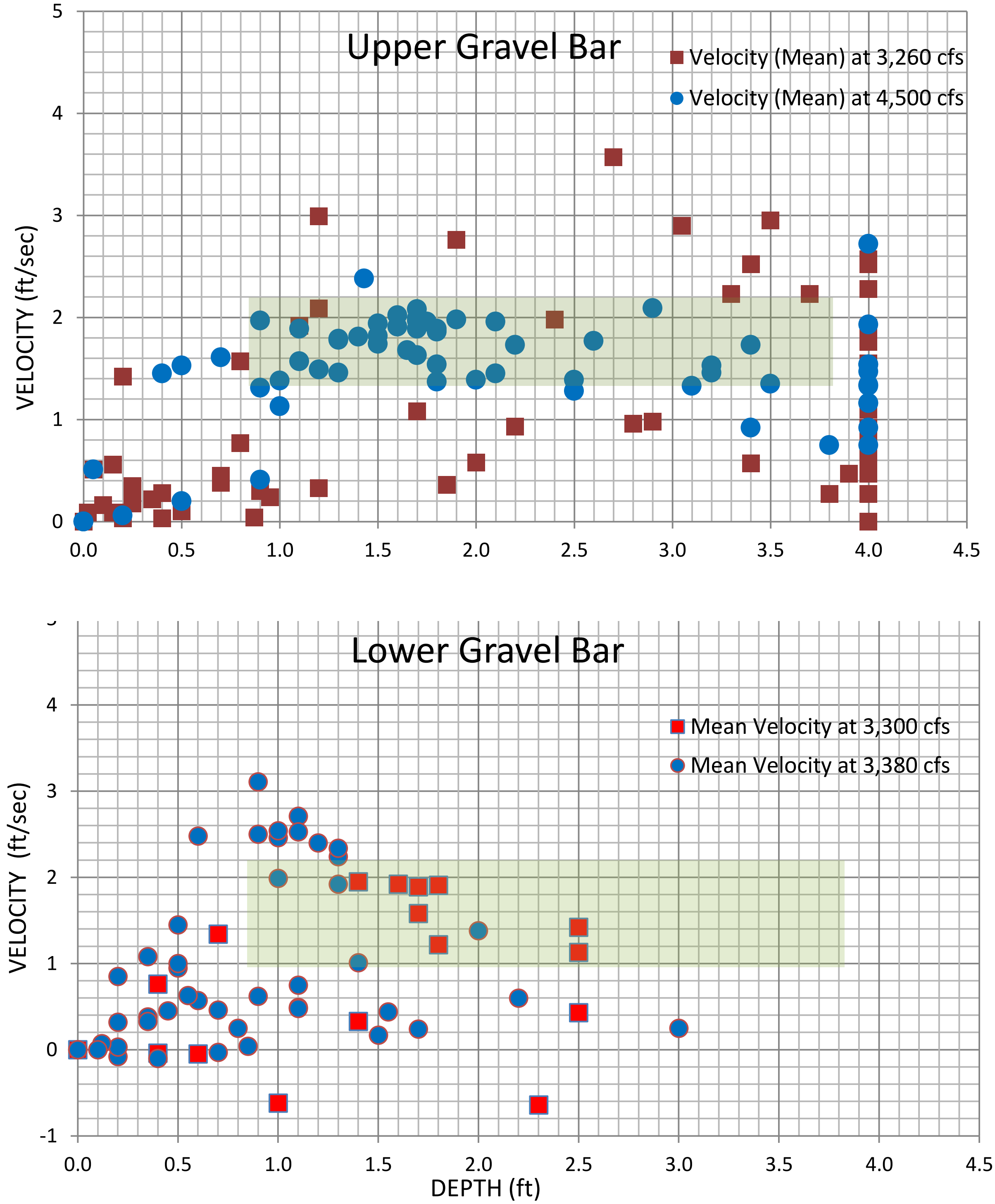


Figure 10. Area suitable for spawning robust redhorse and emersed or flooded as a function of discharge at the Savannah River Upper Gravel Bar (RM 187.1).

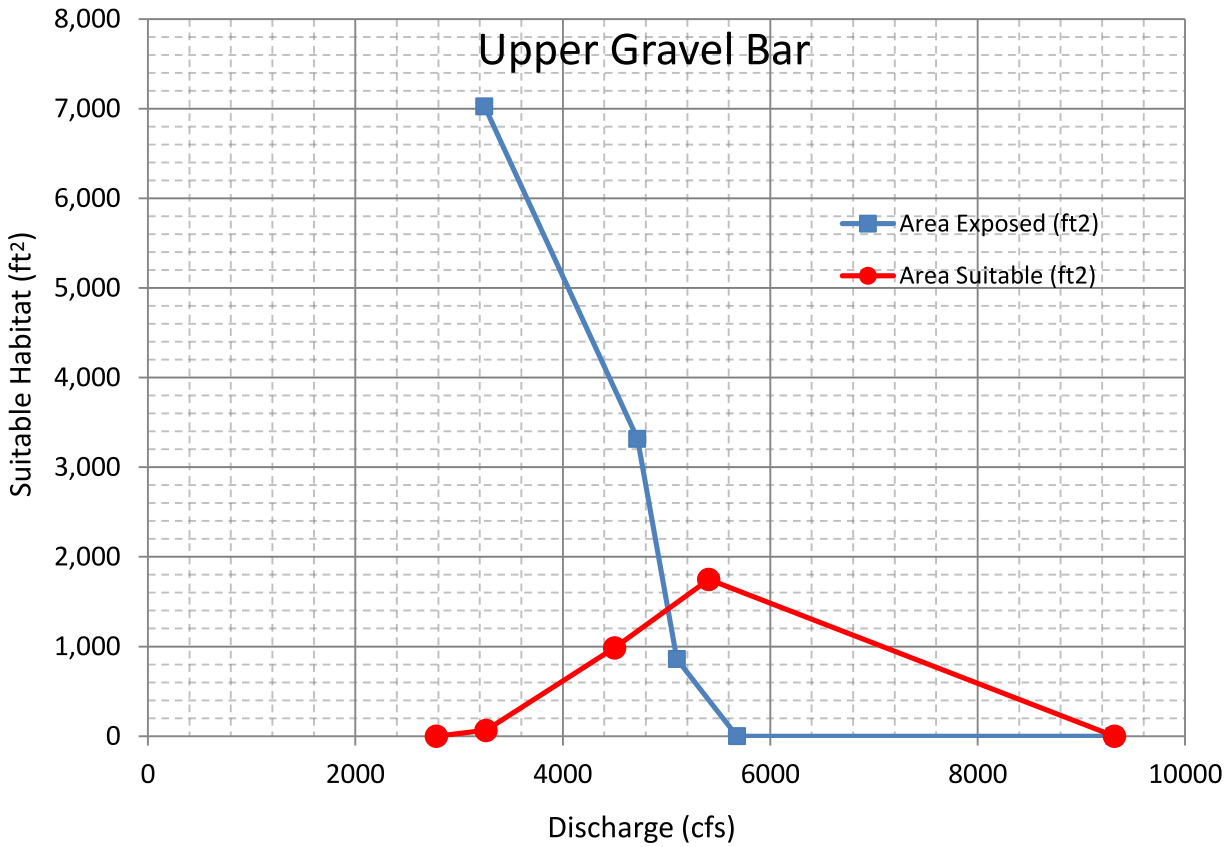
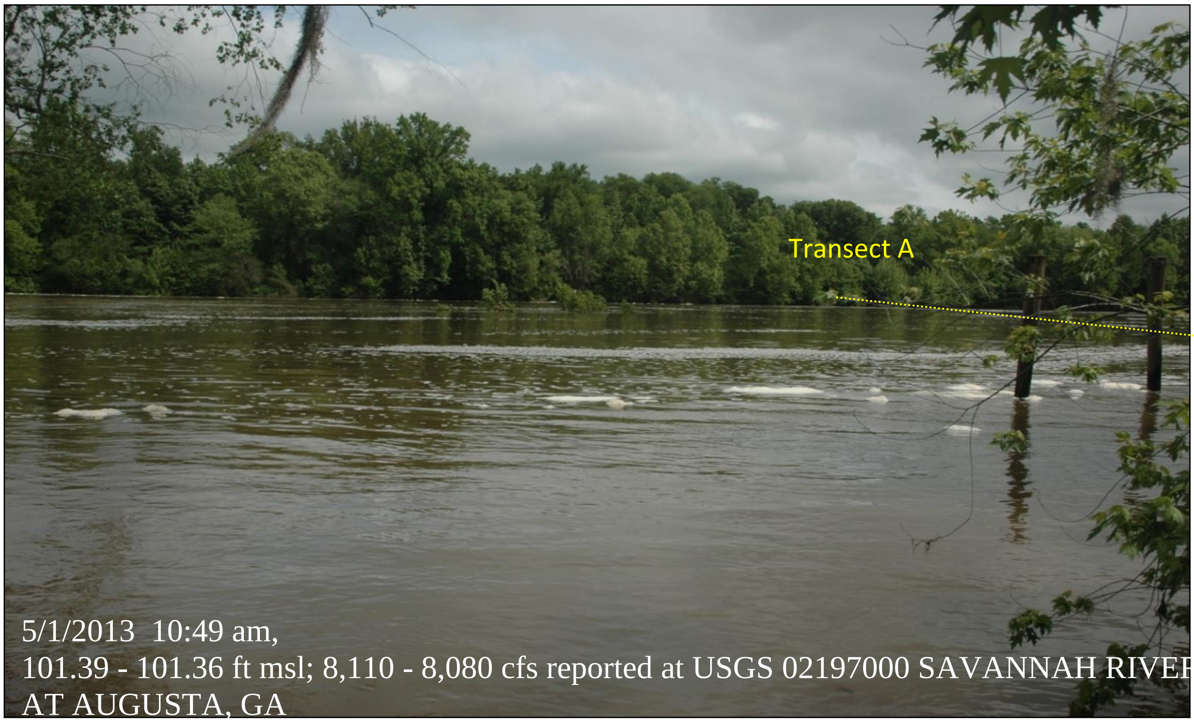


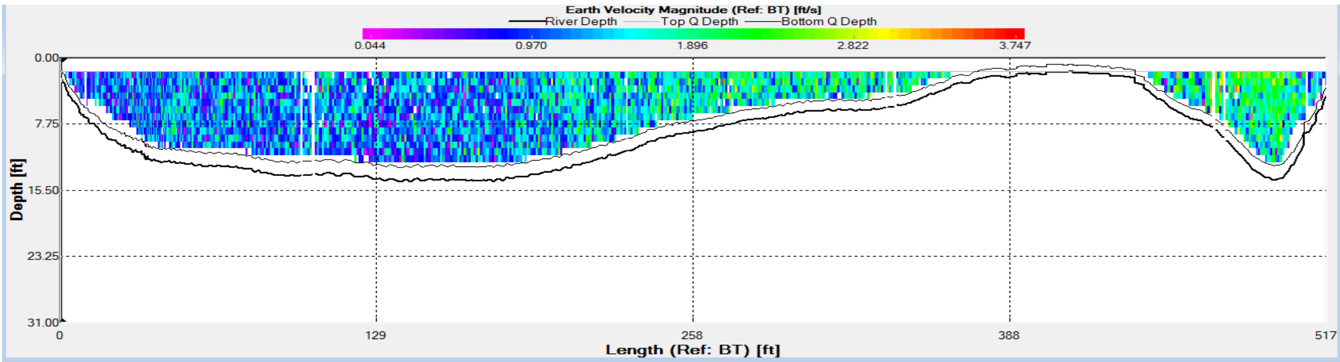
Figure 11. Gravel bar exposure and inundation under variable flow on May 1, 2013. Gates at NSBL&D were observed opening, resulting in the release of accumulated water hyacinth from the forebay. Fluctuating discharges during spawning season may reduce spawning habitat availability, and result in exposure and desiccation of redds, eggs, and fry.



5/1/2013 10:49 am,
101.39 - 101.36 ft msl; 8,110 - 8,080 cfs reported at USGS 02197000 SAVANNAH RIVEF
AT AUGUSTA, GA

5/1/2013 3:24 pm,
98.41 - 98.28 ft msl; 5,350 - 5,250 cfs reported at USGS 02197000 SAVANNAH RIVER A
AUGUSTA, GA

Figure 12. Current profile at across Upper Gravel Bar, Transect A at 5,400 cfs. Areas along survey transects illustrate complex current profiles including where current velocities along the benthic interface were either suitable, marginally suitable, or unsuitable for spawning and early development. The location of Transect A is illustrated on the aerial photograph taken at an unknown discharge greater than 5,400 cfs.



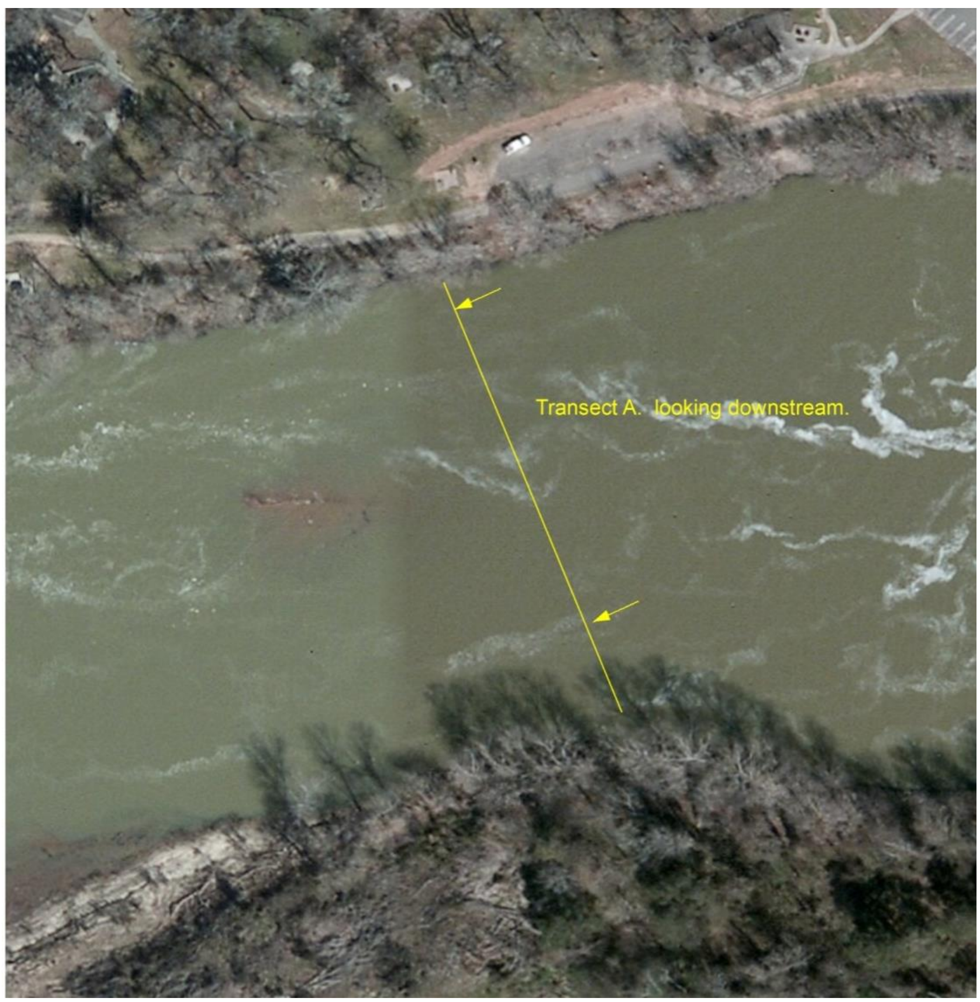


Figure 13. Ship track profile at for transect 008 at the Lower Gravel Bar at 8,918 cfs, on May 1, 2013. The length and direction of the blue lines indicate the magnitude and direction of current velocities in the water column. The higher water velocities across the top of the Lower Gravel Bar provide habitat for spawning catostomids such as the Candidate species Robust Redhorse.

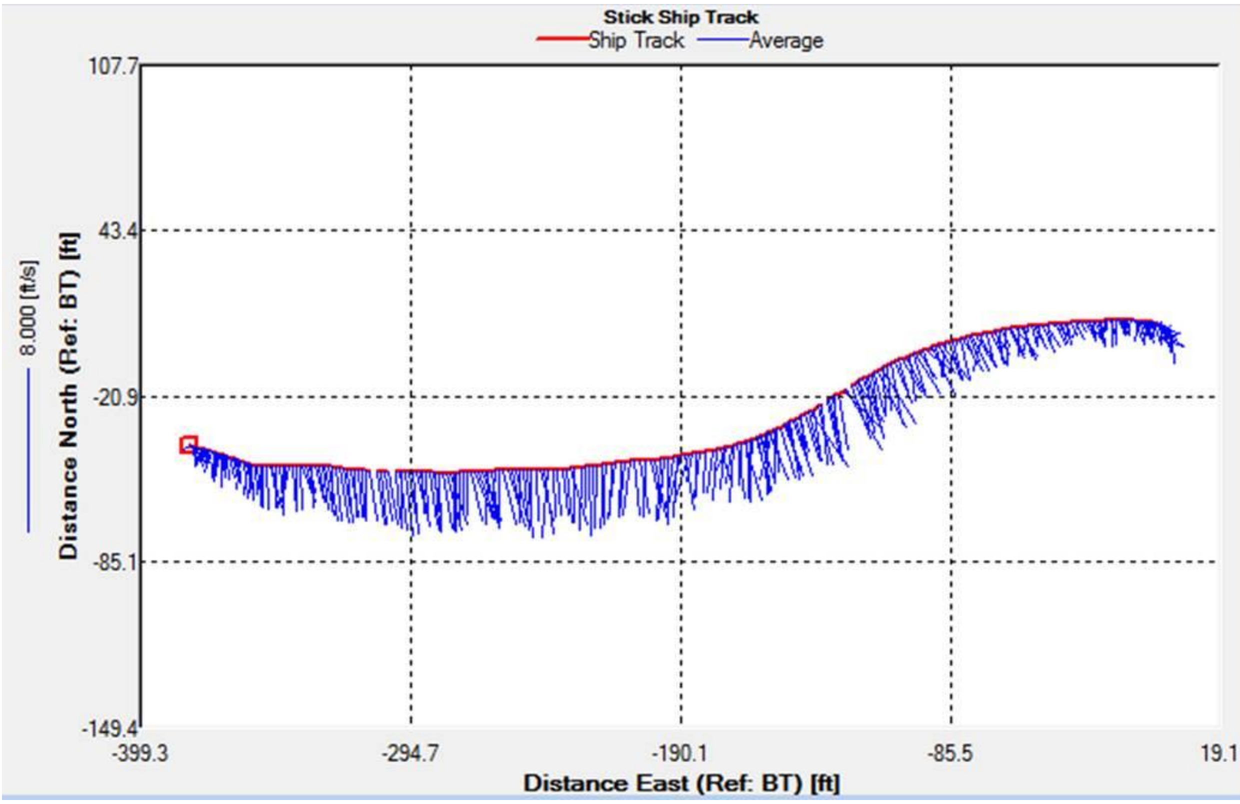


Figure 14. Spring-time flow conditions provide appropriate habitat only between 3,260 – 9,320 cfs at the Upper Gravel Bar and up to 9,317 cfs at the Lower Gravel Bar. Depths across these gravel bars are either too shallow or too deep outside of the range of river flow. These flow conditions must also coincide with appropriate temperatures in late April and May for Robust Redhorse spawning. Temperatures used by spawning Robust Redhorse ranged from 16-24.6°C at Broad River Georgia (Straight and Freeman 2013) , (17-26.7°C) reported by Freeman and Freeman (2001), similar to the range (17.5-22.1 °C) reported by reported by Fisk (2010 in the Pee Dee River.

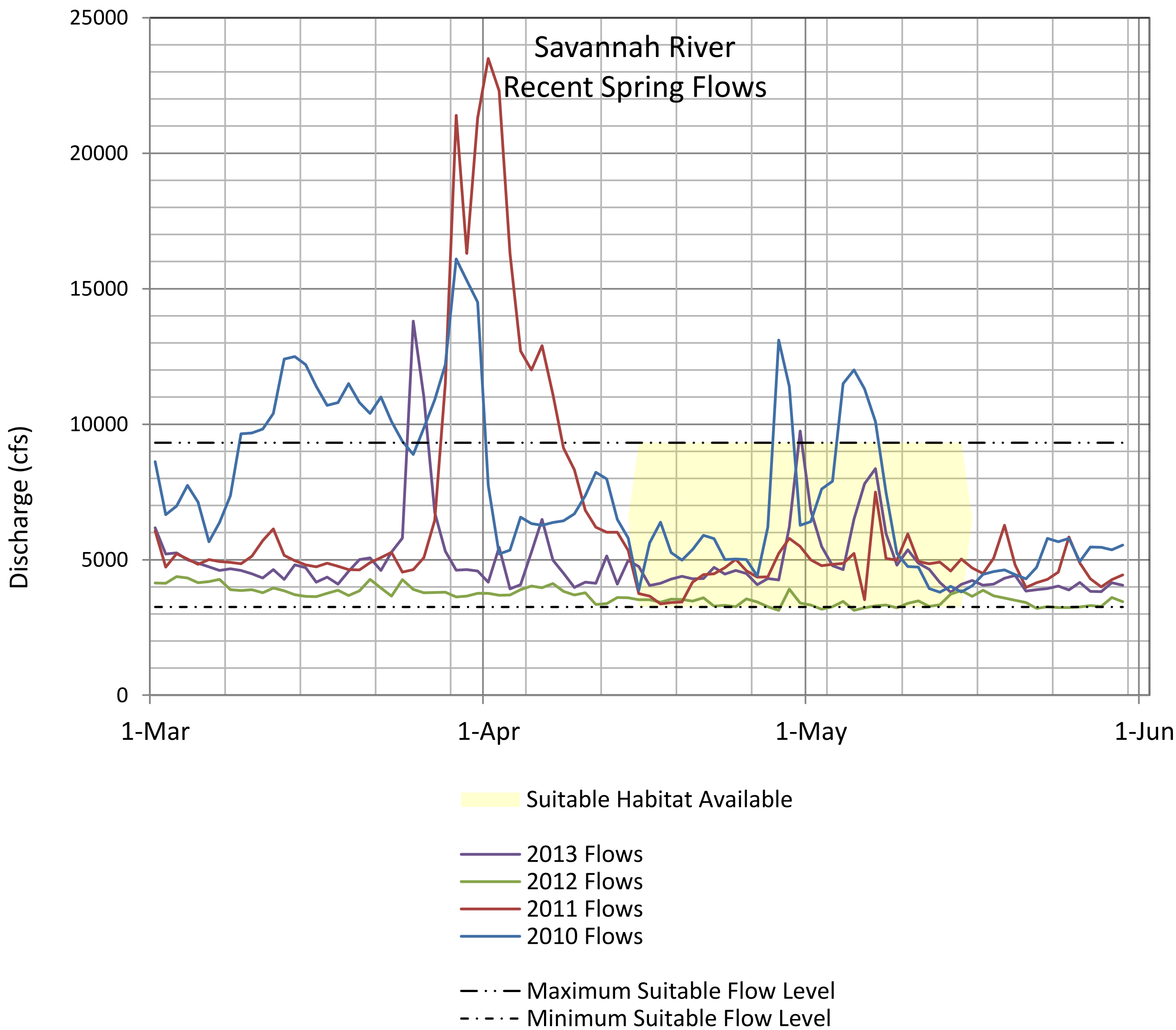


Table 1. Summary of survey dates and times, discharge characteristics, and sampling methodologies used to derive measurements in this report.

	Date	Survey start time	Survey end time	Method	Stage trend	USGS discharge range[1]	ADCP measured range/ number of ADCP measurements	Value used in text and ADCP average
Upper Gravel Bar								
	5/1/2013	1600	1630	ADCP	rapid fall	4950-4790	2551-2990/7	2780
	1/16/2013	1100	1600	Wading	stable	3250-3270		3260
	3/8/2013	1300	1600	Wading	stable	4470-4540		4500
	4/22/2013	1800	1820	ADCP	nearly stable/slight fall	4860-4830	4138/1	Not cited in text; 4138
	4/22/2013	1600	1730	ADCP	nearly stable/slight fall	5270-4940	5503-5804/6	Not cited in text; 5660
	4/22/2013	1445	1545	ADCP	slow fall	5300-5270	4450-5917/5	Not cited in text; 5407
	No survey	-	-	Stage discharge relationship	N/A	5680		5680
	No survey	-	-	Stage discharge relationship	N/A	9320		9320
	8/29/2013	1830	1940	ADCP	stable (slight fall) then rap	10600-11900	9905-10669/9	Not cited in text; 10166
	8/29/2013	1300	1345	ADCP	rapid fall	12200-11700	12446-7698/9	Not cited in text; 9348
Lower Gravel Bar								
	12/18/2012	1400	1630	Wading	slow rise	3230-3380		3300
	12/19/2012	1200	1700	Wading	slow fall/ nearly stable	3430-3330		3380
	-	-	-	Stage discharge relationship	N/A	5596		5596
	5/1/2013	1320	1400	ADCP	rapid fall	8270-8220	8531-8948/9	8800
	5/1/2013	1300	1315	ADCP	rapid fall	8320-8270	9005-8659/5	8800
	-	-	-	Stage discharge relationship	N/A	9317		9317
	8/29/2013	1700	1730	ADCP	rapid fall	12600-12200	11535-12616/7	12036
	8/29/2013	1500	1540	ADCP	slow fall	14200-13900	12877-13731/7	Not cited in text; 13311

Table 2. Survey dates, times, and discharge characteristics during mapping of emersed portions of gravel bars.

	Date	Survey start time	Survey end time	Method	Stage trend	USGS discharge range[1]	Value used in text
Upper Gravel Bar							
	3/8/2013	1639	1639	GPS track	stable	4720	4720
	1/16/2013	1000	1200	GPS track	stable	3240-3250	3245
	5/1/2013			Visual estimate	rapid fall	5100	5100
Lower Gravel Bar							
	11/21/2013	1326	1326	GPS track	slow rise	4670	4670
	12/17/2012	1100	1700	GPS track	stable	3740-3840	3790

[1]4.5 hour lag time between USGS gage at NSBL&D and lower gravel bar applied to reported values.

Table 3. Depth and velocity summary statistics for sediment size classes at the upper gravel bar (RM 187.1) for two low discharges, 4,500 and 3,260 cfs. Suitable sediment size classes for Robust Redhorse spawning include large gravel and pea gravel.

Substrate	Discharge	n	Depth (ft)	Velocity (ft/sec)
	4,500 cfs			
Large gravel		31	0.0-4.0, x̄=1.54 (std dev =1.096)	0.0-2.38, x̄=1.34 (std dev=0.673)
Pea Gravel		31	0.4-4.0, x̄=2.33 (std dev=0.974)	0.75-2.02, x̄=1.59 (std dev=0.317)
Sand - Silt		10	1.8-4.2, x̄=3.35 (std dev=0.876)	0.02-1.61, x̄=1.11 (std dev=0.429)
All substrates		72	0.0-4.2, x̄=2.13 (std dev=1.187)	0-2.38, x̄=1.42 (std dev=0.542)
	3,260 cfs			
Large gravel		21	0.0-4.0, x̄=1.69 (std dev =1.59)	0.0-2.88, x̄=0.55 (std dev =0.834)
Pea Gravel		46	0.0-4.0, x̄=2.12 (std dev=1.557)	0.0-2.99, x̄=0.94 (std dev=0.961)
Sand - Silt		41	1.8-4.0, x̄=1.88 (std dev=1.441)	0.0-3.67, x̄=0.69 (std dev=0.768)
All substrates		108	0.0-4.0, x̄=1.945 (std dev=1.529)	0.0-3.67, x̄=0.74 (std dev=0.885)

Table 4. Gravel bar habitat suitability (depth and velocity) for Robust Redhorse spawning measured at preferred (gravel) substrates at Savannah River. Measurements at the upper gravel bar included sample sizes that allowed plotting of areal estimates of suitable gravel habitats.

Discharge (cfs^a)	**Discharge (cfs)**	**% Exposed**	**Area Exposed (ft^2)**	**% Suitable** (Depth >0.95, Velocity>0.85, Gravel Substrate[b])	**Area Suitable**	**Mean Velocity (ft/sec^2)**	**Mean Depth (ft)**
	Upper Gravel Bar						
NA/2780		-	-	0.0	0.0	1.24	>3.61[c]
3245/3260	3245	28.8	7,028	0.2	66	0.55	1.69
4720/4500	4500	13.5	3,317	4.0	988	1.34	1.54
5100/5407	5250	3.5	860	7.2	1,749	1.63	3.26
5680		0	0	-	-	-	-
9320	9320	0.0	0	0	0	-	-
	Lower Gravel Bar						
3790/3300	3200	34.0	1696	2.8	1,500	0.96	0.85
4670/3380	4500	4.0	218	3.3	1,800	0.95	0.68
5596	5596	0.0	0	-	-	-	-
8800	8800	-	-	-	-	1.71	2.46
9317	9317	0.0	0	0	0	-	-
12036	12500	0.0	0	0	0	2.98	8.37

[a]If two discharge values are presented, gravel bar exposure was mapped at the first reported discharge and suitability was assessed at the second value.
[b] Freeman and Freeman 2001
[c] Deeper than suitable. Although flows were greater, the appropriate velocities were only available at the margins of suitable substrate areas on the gravel bar. There were also areas outside the boundaries of our defined “gravel bar” that were probably within range of suitable criteria for spawning at this discharge. However these were in the main channel, and quickly flooded when water levels increased.

Part III. Effects of discharge changes on freshwater mussels and habitats in the lower Savannah River

A report to the
U.S. Army Corps of Engineers
Savannah District

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Summary

Freshwater mussels are a natural resource in national decline (Williams et al. 1993). Mussels provide a suite of ecosystem services, including the assimilation of wastes and provision of clean water. The lower Savannah River harbors a diversity of mussels, including the Savannah lilliput (*Toxolasma pullus*) and Altamaha arcmussel (*Alasmidonta arcula*; Figure 1). Due to concerns regarding declining populations and reduced range-wide distribution, the Savannah lilliput is listed as “Vulnerable” by IUCN (Cordeiro 2011), “Imperiled” by NatureServe (2013), and critically imperiled-vulnerable (S1/S3) in South Carolina. The Altamaha arcmussel is listed as Endangered by IUCN (Cordeiro 2011) and imperiled by NatureServe (2013). For these reasons, both were petitioned for listing under the Endangered Species Act in 2011 and their status is now under review.

Flow regulation of the Savannah River has the potential to affect mussel habitat and survival. Low flows are likely to reduce habitat amounts along river channel margins, and reduce connectivity to potentially important backwater habitats in cutoffs and oxbows. Fast flow recession rates have the potential to strand the mussels that are unable to track receding water levels, resulting in greater mortality rates. Consequently, multiple Savannah River collaborations have identified “impacts to mussels from low flows” as an important investigation topic. We quantified habitat effects and evaluated biological evidence to evaluate potential impacts during extreme drought.

We found that habitat area for the Savannah lilliput and associated mussels decreases as discharge declines, but the amount of habitat loss depends on site-specific channel margin slope. Although a majority of surveyed habitat in the Savannah River remains submerged when Thurmond Dam releases >3,600 cfs, habitat declines are more pronounced when Thurmond Dam releases flows <3,600 cfs. In habitats that became emersed at one study site, water level decline rates probably exceeded the Savannah lilliput’s ability to track receding water levels resulting in stranding. Stranded Savannah lilliputs, however, survived for prolonged periods buried in sediments. Mussels at another site, however, were unable to bury or move due to the compact nature of marl sediments and variable microtopography. More than half of those mussels showed significant signs of stress or died, demonstrating that both geology and slope play a role in the effects of flow declines on mussel responses. Impacts to mussels during Drought Contingency Plan implementation probably can be minimized by engineering slow flow recession rates and occasional flow pulses to periodically re-inundate dewatered habitat. We recommend that the data accumulated in these habitat studies be used to develop metrics for evaluation and comparison of multiple flow management alternatives that are specific to the Savannah River system.

Methods

We evaluated the effects of discharge changes on mussel habitat using an incremental approach (Stalnaker et al. 1995). Suitable habitat for the Savannah lilliput was determined, bathymetry at representative locations was characterized, and the percent of suitable habitat was calculated as a function of river discharge. The general approach is described in detail below.

Site selection. Mussel surveys were conducted in July 2011 and June 2012 through a collaboration among individuals associated with The Nature Conservancy, US Geological Survey, South Carolina Aquarium, South Carolina Department of Health and Environmental Control, and US Fish and Wildlife Service. An initial suite of sites (100 – 500 meter reaches of river shoreline) was identified that was likely to contain Savannah lilliput and Altamaha arcmussel habitat (Figure 2). Although these surveys were funded separately from this study and reports are pending, we used the data acquired during these surveys to further guide site selection. The subset of sites that contained Savannah lilliput mussels or a large diversity of mussels was incorporated into subsequent habitat mapping (Figure 3). Water depths were recorded for most Savannah lilliputs, and locations of most were denoted in bathymetric surveys. Several Altamaha arcmussels were detected at these sites, but they generally occurred in deeper water compared to the lilliput and their locations were not considered limited by flows. Hence, Altamaha arcmussels were not the focus of this study.

Bathymetric mapping and habitat suitability. Permanent benchmarks were established for each site so that repeated measurements of water level data and bathymetric data along multiple transects could be related. Benchmark locations were recorded with a GPS unit set to record the average of 100 GPS measurements to improve accuracy. Cross-sectional transects (n= 3-5 per site) were placed perpendicular to stream flow throughout the surveyed habitat. Bed and bank elevations were measured relative to the benchmark using a combination of a rotary laser level and water surface measurements. Data from multiple transects were mathematically related in Excel to develop bathymetric maps, calculate the amount of habitat available between map contours, the amount of habitat gained or lost as a consequence of flow change, and the linear distance mussels must travel laterally toward the main channel to remain submerged. We expressed the amount of habitat gained or lost as a percentage of the total amount of habitat available for the site. Lacking detailed habitat suitability indices, we defined the upper limit of available habitat as the transition between root-bound sediments and fine, unvegetated sediments near water's edge. Our collective observations of the Savannah lilliput indicate occurrence in fine sand and silt that can be described as "soupy" due to the lack of compactness and high water content. Because the Savannah lilliput was not observed in coarse sand, the transition from soupy sediments to coarser sediments that generally occurred near the transition from slow to moderate water velocities was identified, and was used to define the lower limit of available habitat. Of the habitat areas sampled for mussels, this habitat area generally corresponded to the locations with the highest abundances of other species.

Relationship to Thurmond outflow. Although these results are of interest at a site-specific scale, we calculated the cumulative amount of available habitat across sites as a function of discharge change. In order to place the results in a management context, we used the relationships developed in Chapter 1 between Thurmond Dam outflow and USGS gages to predict how dam management changes affect lower river discharge during drought conditions similar to 2012 (Chapter 1 Table 3). The relationships between Thurmond Dam outflow and lower river discharge varies across a range of drought and meteorological conditions. For example, minimum discharge in the lower river (Burton's Ferry gage) during the 2012 drought was 3,300 cfs, but regressions predict that a 3,100 cfs Thurmond Dam outflow (the lowest permitted in the drought plan) should equate to 4,100 cfs. Nevertheless, this method provided a quantitative means of evaluating how dam operations can potentially affect lower river habitats and we acknowledge that habitat losses resulting from low flows could be greater depending on drought conditions.

Mussel response. We calculated the linear distance that mussels must move in order to remain submerged for each bathymetric transect at each site. Average site travel distances were calculated for each incremental 0.5 foot stage change. Similar to the habitat availability analysis, we calculated travel distances as a function of Thurmond Dam outflow and compared sites across a gradient of bathymetric slopes.

Anecdotal mussel tracking

Mussel movement rates and mortality are likely to vary with water level dynamics, bathymetry, and sediment composition. Given the lack of information regarding the relationship between habitat inundation and discharge and the remote locations of lower Savannah River study sites, we did not attempt a rigorous study of mussel population dynamics in response to discharge. However, we conducted pilot studies at three geomorphically diverse locations that could be used to make informed hypotheses regarding effects of discharge change on mussel survivorship and movement rates. Low slope sites are more likely to have more mussel strandings because mussels must move larger distances to track receding water levels as compared to high slope sites. Sites with fine or soupy sediments are suitable for mussel movement in both the horizontal and vertical directions. However, sites dominated by rock could potentially inhibit mussel movement because rock is impermeable to mussel burrowing, and small-scale topographic variation between rocks increases the probability that rock can prevent or delay mussel movement to suitable inundated habitat, leading to low movement rates, greater likelihood of stranding, and higher mortality.

We focused additional detailed observations at several sites. Oxbow H was selected because of the abundance of Savannah lilliputs and because characteristic oxbow habitat features included soupy sediments and low slope bathymetry (Figure 4). BM098 was selected because it was a mainstem site with fine and soupy sediments with low and high slope bathymetry (Figure 5 and

6). A marl rock outcrop at Little Hell Landing was selected because of the abundance of *Elliptio* spp. interspersed throughout topographically variable rocks that were impermeable to mussel burrowing (Figure 7). Sites were surveyed for mussels sporadically, depending on accessibility and proximity to study sites that were part of other field investigations. Bathymetry was characterized and bed slopes calculated. Attempts were made to locate, identify, and track mussels without handling them so as not to influence their behavior. However, some mussels could only be relocated on subsequent visits by using tactile search. Similarly, all Savannah lilliputs identified in Oxbow H were found using tactile searches. In all instances where a mussel was handled, it was replaced at the location and elevation at which it was found. Numbered survey flags were placed approximately one inch from the mussel when located at Oxbow H and BM098. We assumed that the mussels located on subsequent visits at BM098 were recaptures of the same individuals, and in some cases, mussel tracks were evident that showed the path between locations. Numbered markers were placed adjacent to live mussels on the Marl outcrop to facilitate subsequent relocation. *Elliptio* species were usually identified to genus level because species-level identification would have involved handling.

Results

Mainstem habitat availability

For each incremental reduction in river discharge, there is a corresponding reduction in the amount of habitat that is available to the Savannah lilliput and associated mussel species at sites in the vicinity of the USGS Burton's Ferry discharge gage. However, the magnitude of the habitat reduction varies among sites depending on topography and the stage discharge relationship. Sites such as Site 4, Site 7, and Little Hell Confluence lose a majority of the available mussel habitat at comparatively higher discharges (sooner) than other sites. Other sites, such as Site 9, Little Hell Marl Outcrop, and WP 074 retain a larger proportion of their available habitat as discharge declines (Figure 8).

Three sites in the lower river near the USGS Clyo gage could not be assessed due to high water levels during this study. However, based on the two sites with bathymetry data, there were similar trends of decreasing habitat with discharge (Figure 9).

When percent habitat availability is expressed as a function of Thurmond Dam (RM 220.9) outflow, over 80% of mussel habitat in the vicinity of the Burton's Ferry gage (RM 118) remains submerged when discharge releases are $\geq$ 3,600. Habitat availability declines more significantly as discharge declines below 3,600 cfs (Figure 10). Near the Clyo gage (RM 61), over 95% of mussel habitat remains submerged when Thurmond Dam outflow is $\geq$ 3,100 cfs. Habitat availability declines more significantly as discharge declines below 3,100 cfs (Figure 11).

Mainstem mussel movement

The threshold at which usable habitat becomes emersed, and therefore the threshold at which mussels must move in order to remain submerged, varies among sites. Habitats at sites such as BM098 remain submerged until discharge falls below 3,337 cfs at the Burton's Ferry gage. All other sites retain habitat that is otherwise considered usable at discharges above 4,200 cfs (Figure 8), meaning that mussels either detect and move in the direction of (i.e. track) receding water levels or are stranded as water levels decrease. At sites along the mainstem Savannah River, the distances that mussels must move in order to track receding water levels depends on discharge (Figure 10) and is inversely proportional to average site slope (R^2=0.72; Figure 11) – mussels remain submersed with shorter lateral track distances at steeper shoreline areas. On average across sites, however, changes in Thurmond Dam outflow from 4,200 to 3,100 cfs result in mussels having to move a linear distance of 10.4 feet (range 3.1-26.8 feet) to remain submerged.

Mussel condition and location tracking

Mussel tracking: Oxbow H. Three parallel transects were used to characterize the bathymetry of Oxbow H (Figure 13). Average slope ($m = \frac{Distance_{vertical}}{Distance_{horizontal}}$) along the transect from the elevation of the highest occurring Savannah lilliput to the deepest point along the transect was 0.027 ft/ft. Slopes were lower along the channel centerline -0.024 to -0.002 ft/ft. Water levels between mussel survey dates August 30 and November 27, 2012, a period of no surface water connectivity to the mainstem, receded an average of 0.01 ft/day vertically, and a minimum of approximately 0.54 ft/day horizontally. Mussels in Oxbow H were located on August 30, 2012 when oxbow water surface was 96.50 ft, and November 27, 2012 when water surface elevation was 95.58 feet (Figure 14). Most of those located in August (n = 102) occurred at an elevation near 96.5 feet. Although initial locations of these mussels were identified with survey flags for photographic purposes, no attempt was made to track individual mussels because high mussel densities made redetection of individual mussels impossible using our tracking method. Several (n = 6) were found in November during a much less intensive survey that targeted emersed areas. Individuals in the November survey were buried at elevations of approximately 95.2-95.5 feet, elevations that were inundated by groundwater.

Mussel tracking: BM098. Slopes along transects from the highest to the lowest elevation measured during bathymetric surveys at BM098 ranged between -0.17 and -0.12 ft/ft (Figure 15). BM098 was visually examined for stranded and immersed mussels on November 9, 2012 and ten mussels were found and flagged. Attempts to relocate mussels were made on November 11 and 27, however, only six were relocated on the second and two were relocated on the third visit (Figure 16). Most relocated mussels showed relatively little vertical movement throughout the course of the study. However, the linear horizontal speed that relocated Savannah lilliputs moved between site visits ranged between 0.02 and 0.14 ft/day (n = 3 moving Savannah lilliputs). During this period, water level fluctuated between 95.81 and 96.12 ft.

Mussel tracking: Marl outcrop. Bathymetric surveys of the marl outcrop targeted general elevation trends, and did not target the more complex microtopographic elevation differences from the presence of cobble. Slopes that were calculated from bathymetric surveys from the highest to the lowest measured elevation ranged between 0.20 and 0.63 ft/ft (average = 0.39 ft/ft, n = 5 transects). The marl outcrop was visually examined for stranded and immersed mussels on November 20, December 6, and December 14, 2012. Of the n = 75 mussels located during the initial survey, n = 32 (43%) were relocated on the second visit at which time mussel elevation measurements were collected. Some labels weathered or disappeared between site visits. Some mussels were missing from their original location, but the labels remained. On December 14, n = 23 mussels were relocated and classified as live, dead, or stressed (e.g. gaped or snotty appearance; Figure 17). Water levels had exceeded the levels observed on December 14 (95.3 ft) on 83% of days over the prior six months and 40% of the days over the prior two months (Figure 18). Most mussels were located above 95.8 feet, a water level that was exceeded 25% of the time over the prior 6 months, but was never exceeded over the prior two months. Emersed mussels died (22% of relocated mussels), showed significant signs of stress (30%), or survived without obvious stress signs (47%). Coarse marl sediments prevented the vertical movement of mussels. We suspect that some of the missing mussels had been depredated and removed from their original locations because freshly consumed mussel shell fragments were located within the study site but not adjacent to a label.

Discussion

A diverse native freshwater mussel community reside within the Savannah River, oxbows, and cutoffs. The data collected for mussels and mussel habitat at selected sites allow us to make inference into long-term management strategies for the Savannah River. Native freshwater mussels are an important flow-sensitive consideration for management. The data will provide baseline information on potential population effects, mechanisms of drought-habitat effects on local diversity, and help to establish the range of variation for these habitats across the regulated, lower Savannah River. It is our goal that data collected for the mussel community will serve to inform future studies on flow effects on life history and habitat interactions in the Savannah River.

The imperiled Savannah lilliput resides in “soupy” silt with nearly no water velocity and depths between 0 and 2.5 ft – a very specialized habitat. Surveys and associated species identifications showed that the Savannah lilliput and Altamaha arcmussel co-occurs with the barrel floater (*Anodonta couperiana*), delicate spike (*Elliptio arctata*), eastern elliptio (*E. complanata*), Carolina slabshell (*E. congaraea*), Altamaha slabshell (*E. hopetonensis*), variable spike (*E. icterina*), Atlantic spike (*E. producta*), Roanoke slabshell (*E. roanokensis*), *rayed pink fatmucket* (*L. splendida*), yellow lampmussel (*L. cariosa*), eastern floater (*Pyganodon cataracta*), paper pondshell (*Utterbackia imbecillis*), and eastern creekshell (*Villosa delumbis*). However, most of these species, including the Altamaha arcmussel, occurred at a larger range of depths (0.1 to ~10 feet), larger range of water velocities (0 to ~2ft/second), and a larger range of sediment types (silt to coarse sand). Savannah lilliput habitat effects, therefore, also represent effects to portions of habitat for other species that co-occur in shallow water.

River channel margins are subject to periodic inundation and dewatering depending on river hydrological dynamics. In the Savannah River, the amount of habitat available to the Savannah lilliput and associated shallow mussel community generally decreases as river stage declines, with no discernable threshold effect. Among sites, there is considerable variation in the rate of habitat loss, and some sites lose all habitat value at flows < 5,400 cfs. More habitat becomes emersed as discharge declines at low-slope sites compared to high-slope sites. These results demonstrate the influence of reach-scale geomorphology on habitat loss rates.

Multiple studies have shown that mussels horizontally move in response to receding water levels, but some become stranded when recession rates are faster than their ability to move. Movement rates vary widely by species, sediment type, and environmental conditions (Haag 2012), making it difficult to model and to infer mussel responses to stage decline in the Savannah River. However, it is generally assumed that 1) slower river recession rates provide greater opportunities for mussels to retreat into aquatic refugia, and 2) that larger distances that mussels must move to remain submerged will result in a greater number of strandings. In our study, low channel margin slopes result in larger distances that mussels must travel in order to remain submerged as water levels decline. Therefore, these sites may have a higher extirpation risk than high slope sites. Future evaluations of dam operation alternatives could use the bathymetry data that we've compiled in combination with HEC Res-Sim (the Corps' flow modeling software) output to compare mussel movement rates that would be required to remain submerged.

The hypothesized relationship between slope and stranding potential is supported by biological evidence at Oxbow H, a site with slopes that are lower than any measured river channel margin slope. We observed that Savannah lilliputs can move laterally between 0.02 and 0.14 ft/day. If these mussels are similar to other Savannah lilliputs, the water level recession rates at Oxbow H (0.54 ft/day) exceeded their ability to track the receeding water levels. The detection of stranded, buried mussels in Oxbow H supports this hypothesis. Our ability to track mussels was limited and it is uncertain whether they can move faster in response to water level declines. Therefore, studies that identify mussel movement rates and post-stranding survivorship could help to elucidate potential effects of recession rates and prolonged low flows on mussels.

Although slope is a likely correlate with stranding potential, geology is also an important factor (Vannote and Minshall 1982). The marl outcrop at Little Hell Landing had higher slopes than most other surveyed locations, yet 52% of mussels (predominantly *Elliptio* spp.) were stranded and either died or were stressed after prolonged emersion. Microtopographic variation induced by marl cobbles likely inhibited the emigration or vertical movement of these individuals, resulting in a potentially significant impact to the mussel community at the marl outcrop. Albeit marl outcrops are rare in the Savannah River system (the current channel configuration has been modified for navigation), we observed a diverse and abundant mussel community at Little Hell Landing; it is uncertain whether they play a major role in mussel ecology in the Savannah River. Observations at other South Atlantic streams with unaltered river channels also noted the abundance and diversity of mussels at these marl outcrops (The Catena Group 2006, 2011). However, it is unlikely that the high mortality at the marl outcrop is representative of available mussel habitats throughout the Savannah River, but it illustrates the importance of this limited, flow-sensitive habitat.

Mussel tracking surveys at Oxbow H, BM098, and the marl outcrop demonstrate that the interaction between hydrology and geomorphology can exert a strong influence on mussel behavior, stress, and mortality. However, these surveys also demonstrate that some species can respond to changing habitat conditions during dry periods. Some mussels are capable of surviving (at least short-term) prolonged periods of emersion. Survivorship of emersed individuals likely depends on ambient air temperature, shell morphology (some mussels cannot "clam up" to entirely seal the shell), physiology, and depredation rates. Additional studies are necessary to quantify mortality rates in a more comprehensive manner, and to identify species traits that are responsible for differential survival.

Elliptio spp. and Savannah lilliputs at BM098 and Oxbow H either emigrated to inundated habitat, or buried vertically through the soupy fine sediments to the elevation of groundwater. Although our observations of vertical movement to the groundwater level are based on a small number of individuals, it demonstrates that some adult Savannah lilliputs can survive buried for a minimum of 18 days without inundation. Abiotic conditions at the groundwater level are likely to be more favorable for survival because temperatures are less extreme (either hot or cold). Raccoon depredation contributes to higher mortality of Savannah lilliputs in other basins (Hanlon and Levine 2004) and raccoon tracks were frequently observed. Burial may reduce raccoon depredation risk because detection rates are likely to be lower than at the surface. Of the mussels that were buried and tracked over time, most remained below the sediment elevation, and few moved in either the horizontal or vertical directions. They were either stranded and could not move, or once suitable habitat conditions were found, there was no incentive to move. Nevertheless, it is certain that some mussels can survive buried for prolonged periods, but the duration of burrowed mussel survivability is unknown and the proportion of the population that burrows and survives is also unknown. The seasonality of drought, and the burrowing response may further affect growth and reproduction, since burrowed mussels are not able to feed normally or disperse gametes, interact with fish hosts, or discharge larval mussels to appropriately inundated habitats.

Despite the observed strandings throughout the study area, and high mortality at some sites, more than 80% of the total habitat that we measured along mainstem channel margins is available when Thurmond Dam releases more than 3,600 cfs. This demonstrates that typical drought flows > 3,600 cfs are unlikely to have major effects on Savannah lilliput populations and associated shallow-dwelling species. However, flows less than 3,600 cfs have a larger effect on habitat, and should be cautiously considered when evaluating drought management options. To that end, minimization of low-flow impacts to the mussel community may be achieved through the provision of periodic short-term re-inundation during drought conditions in regulated systems like the Savannah River. Periodic re-inundation may facilitate persistence of mussels by either providing them emigration opportunities or by abating stressful abiotic conditions. Inundation of flow-sensitive habitat may be achieved either by additional basin inflow from tributaries below Thurmond Dam, or by flow pulses released from Thurmond Dam. Such pulses are consistent with historical patterns of pre-dam low flows that were occasionally interrupted by precipitation-induced flow pulses.

Acknowledgments

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Figure 1. The Savannah lilliput (left) and Altamaha arcmussel (right) collected in shallow Savannah River channel margins among a diversity of other mussels.

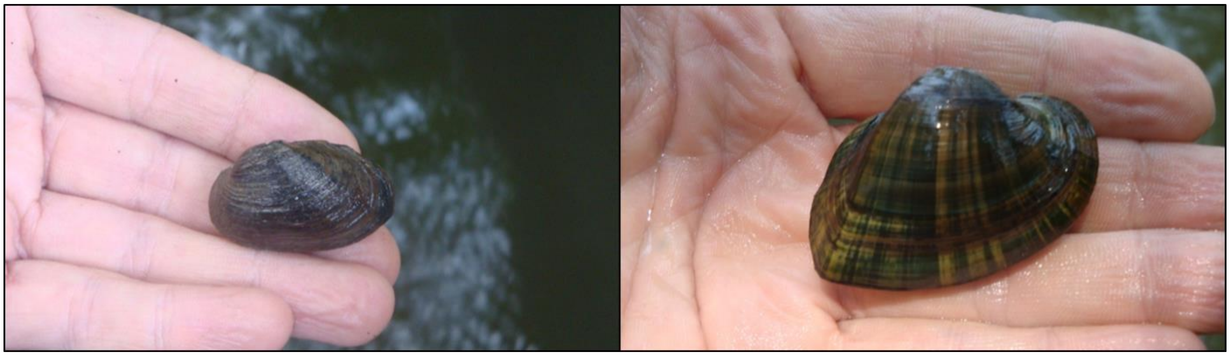
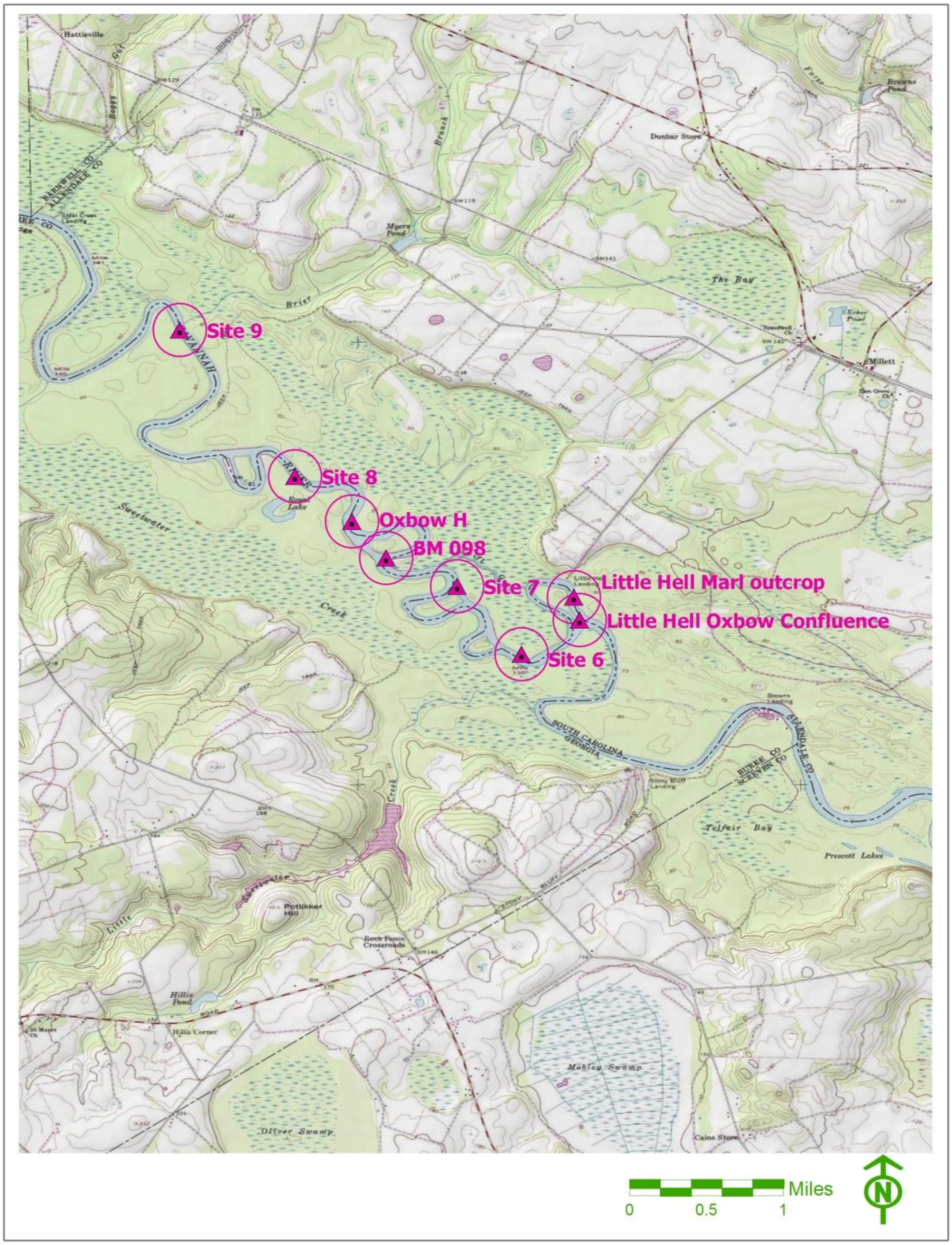
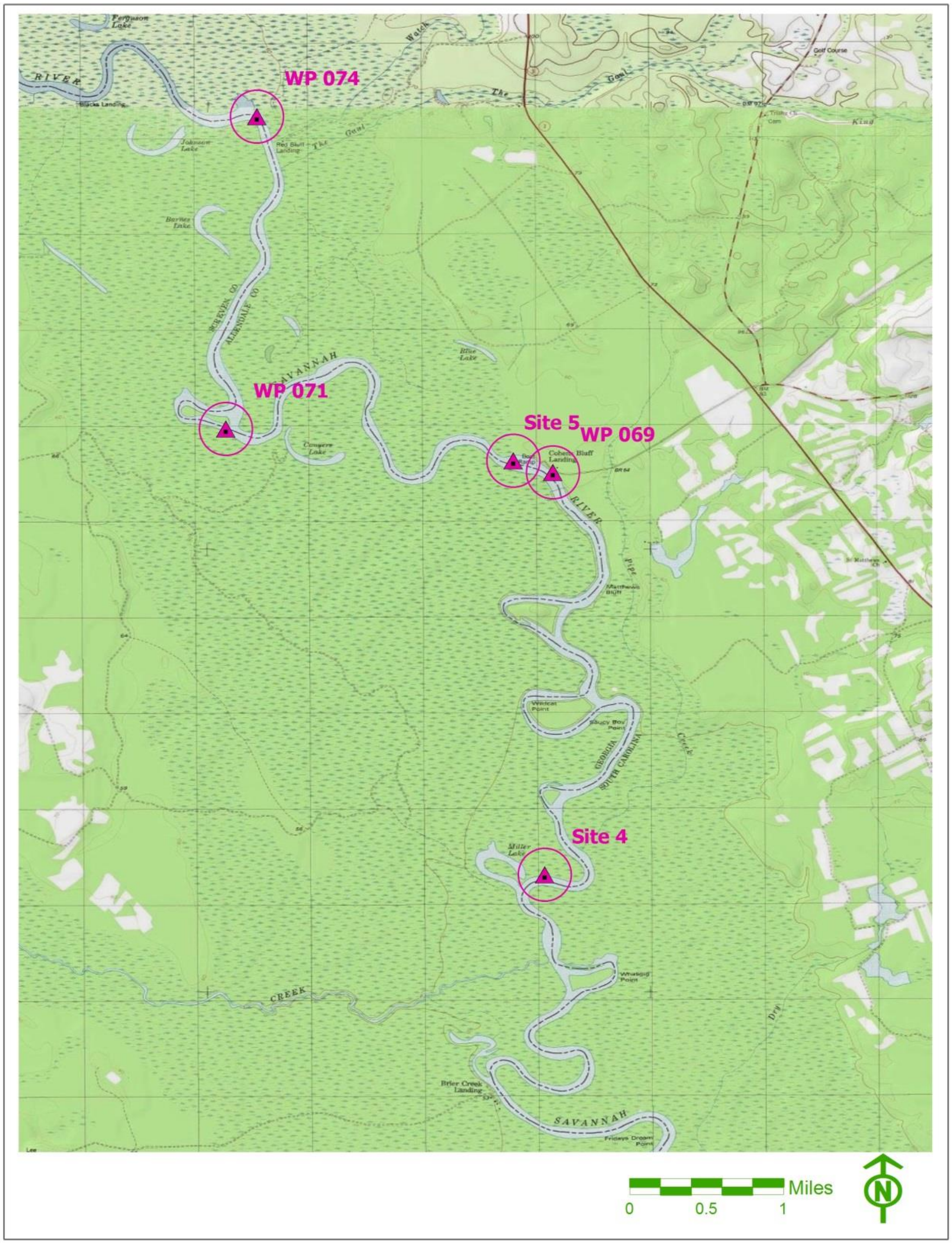


Figure 2. Typical mussel survey locations and collections along Savannah River channel margins.

Figure 3. Map of mussel survey and habitat mapping locations in the upper (A), middle (B), and lower (C) portions of the lower Savannah River.
A)



B)


WP 074
WP 071
Site 5
WP 069
Site 4
SAVANNAH
RIVER
CREEK
Miles
0
0.5
1
N

C)

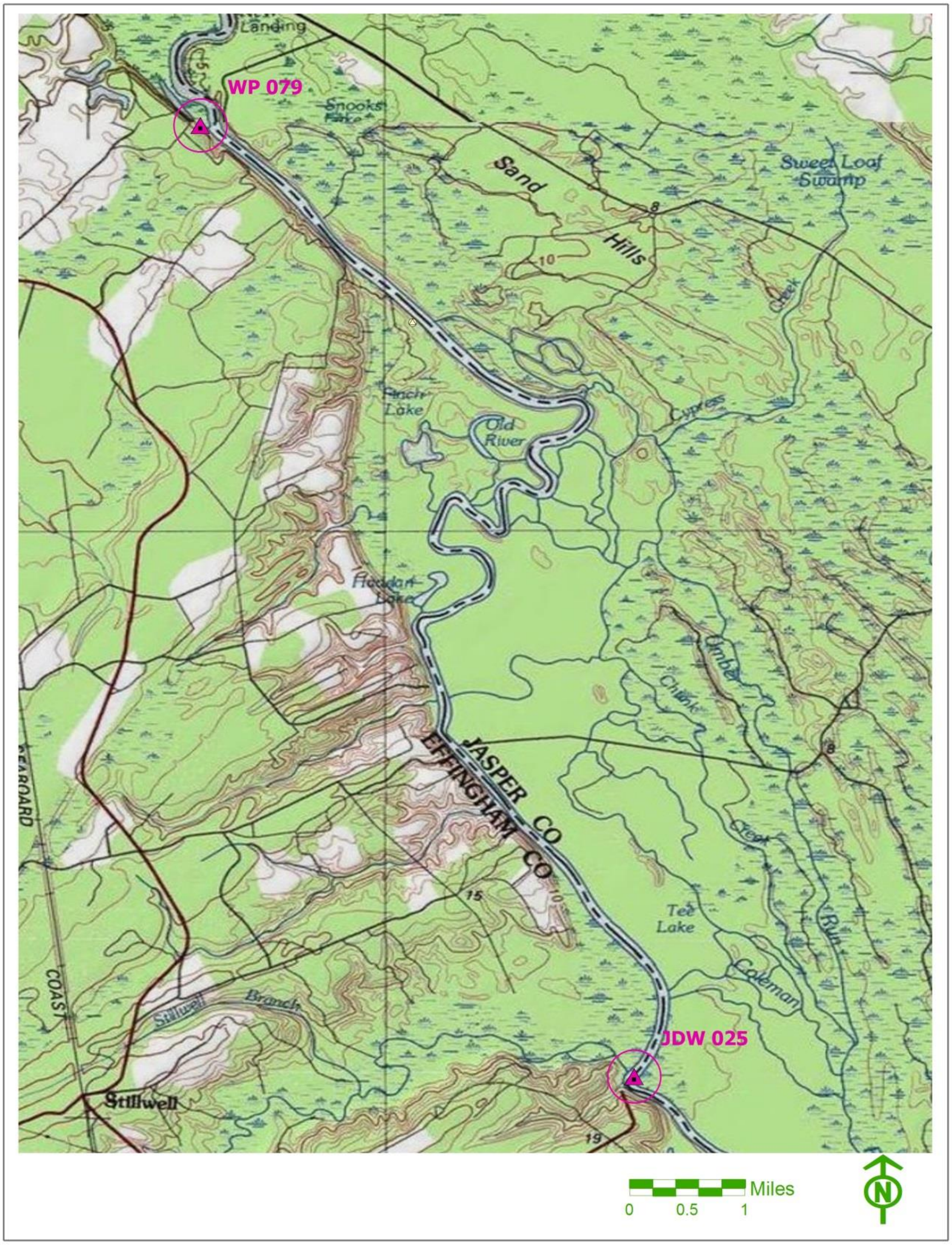
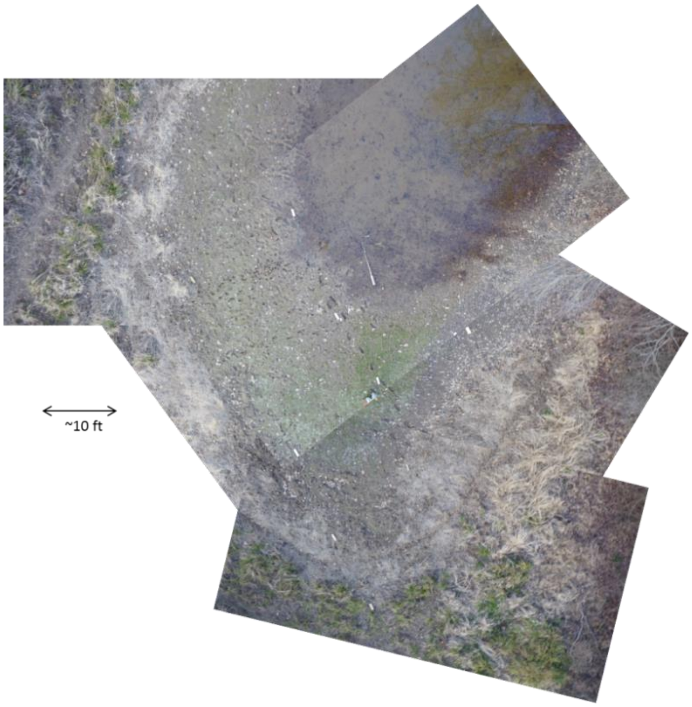

WP 079
Landing
Snooks Lake
Sand Hills
Sweet Loaf Swamp
Finch Lake
Old River
Cypress
Heddan Lake
Umber
Chunk
JASPER CO
EFFINGHAM CO
Creek
Run
Tee Lake
Coleman
Stillwell Branch
Stillwell
COAST
SEABOARD
JDW 025
Miles
0
0.5
1
N

Figure 4. Oxbow H aerial image (A) and polygon (B) of dewatered Savannah lilliput habitat. Oxbow H contains the largest known concentration of Savannah lilliputs in the Savannah River.

A.



B.

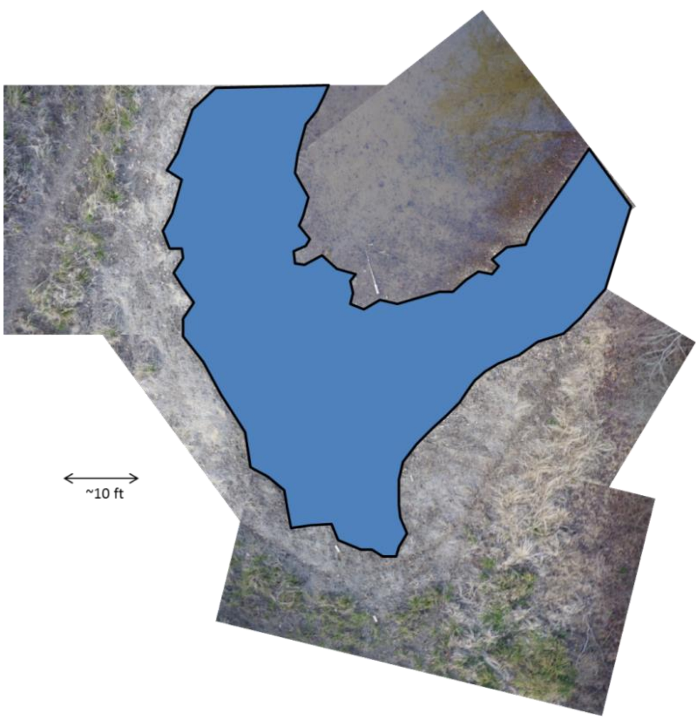
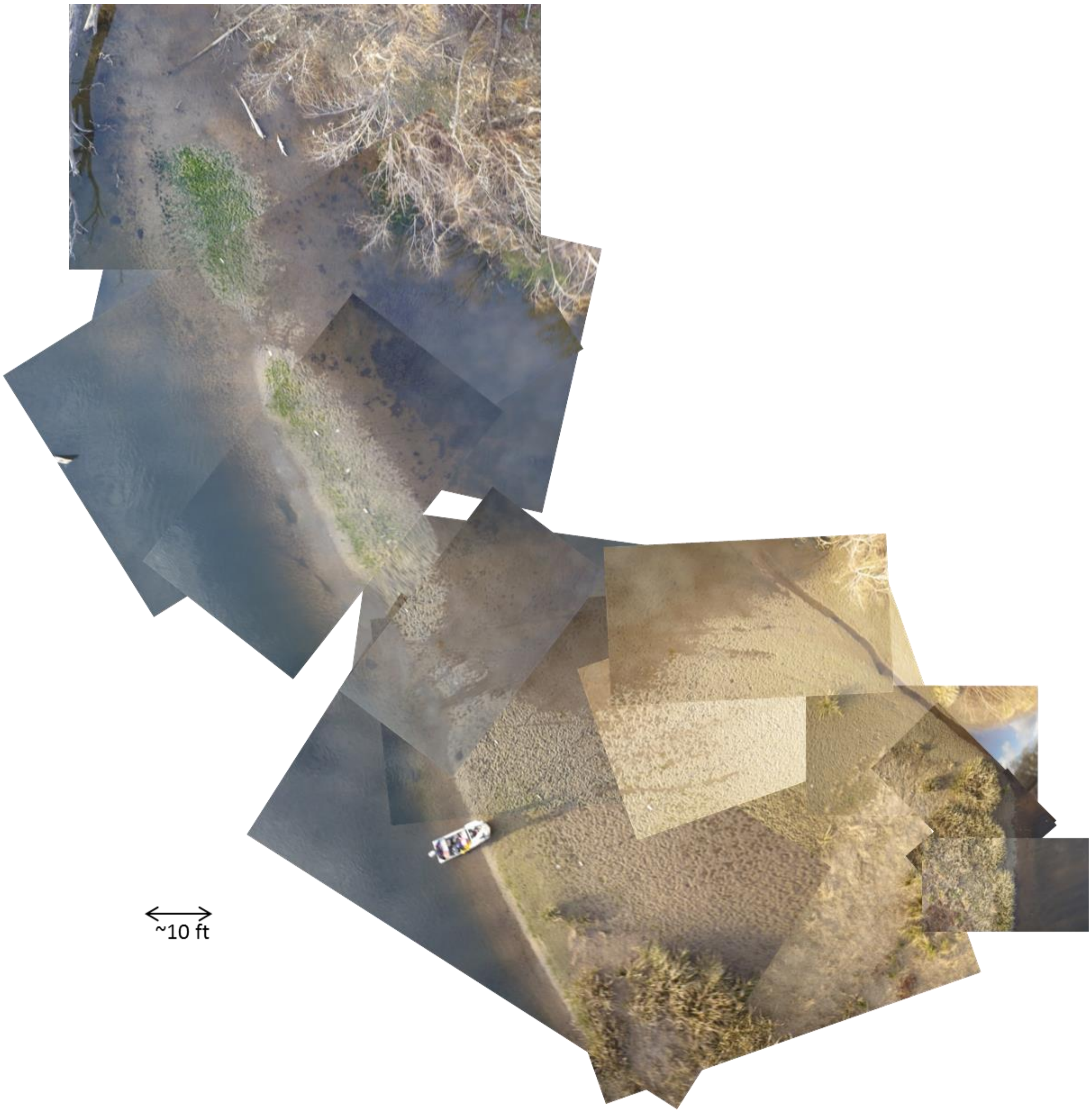


Figure 5. Site BM 098, a partially emersed confluence of a cutoff and the Savannah River at low flow on September 25, 2013. Photographs from top to bottom include a view of the confluence looking upstream, a view from the river into the cutoff, a live Savannah lilliput in one inch of water, mussel trails (top right), and raccoon tracks.

Figure 6. BM098 aerial image (A) and polygon (B) demarcating emersed mussel habitat.
A.



B.

Figure 7. Marl outcrop with Little Hell Landing visible in the background. Photographs (top to bottom) show the microtopographic variation from marl cobbles, and typical examples of a stranded live and recently deceased mussels (*Elliptio* sp.) found in emersed habitat.

Figure 8. Cumulative percent of habitat available as discharge changes for sites that are represented by USGS Burton's Ferry streamflow gage (#02197500).

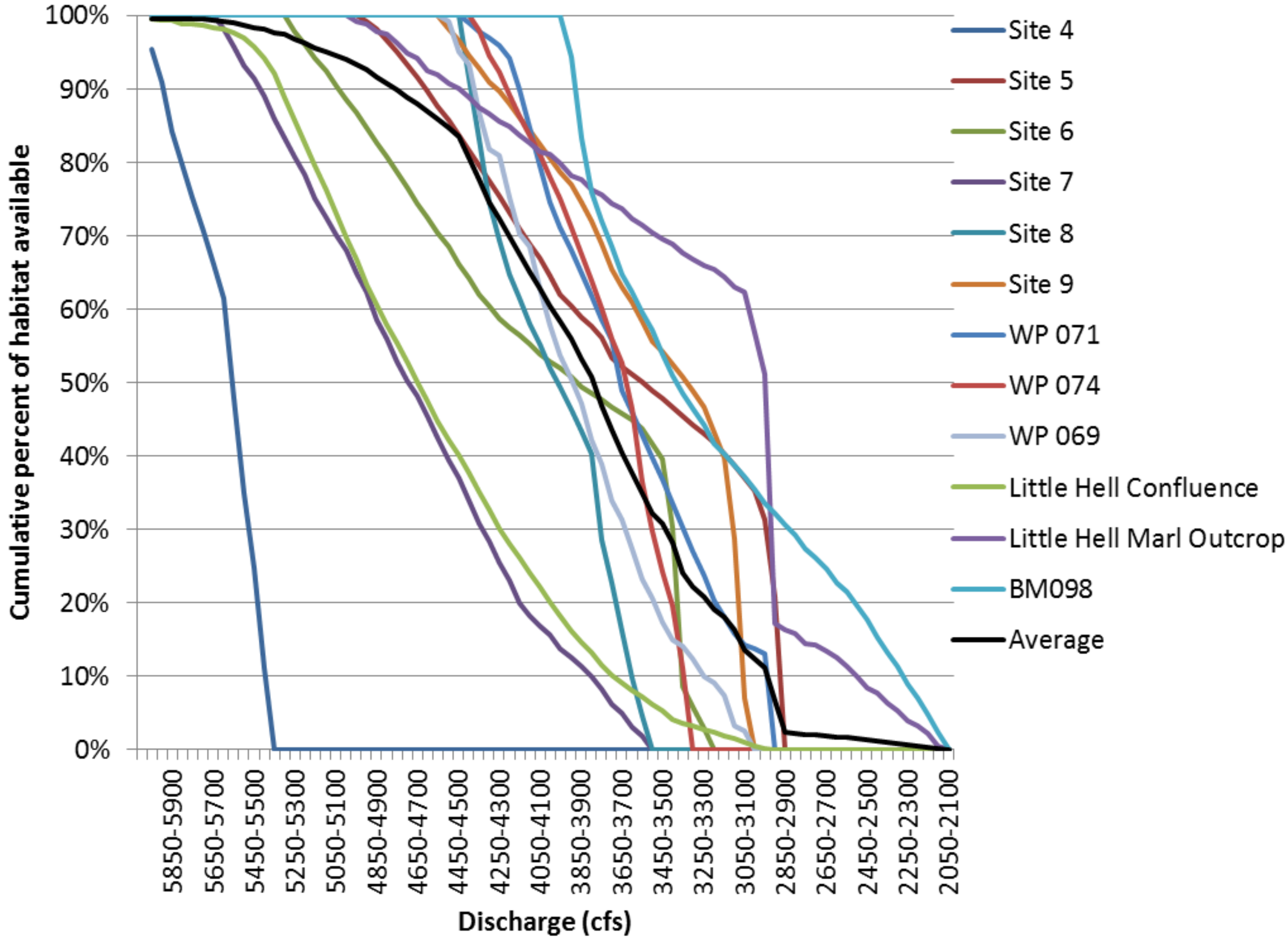


Figure 9. Cumulative percent of habitat available as discharge changes for sites that are represented by USGS Clyo streamflow gage (#02198500).

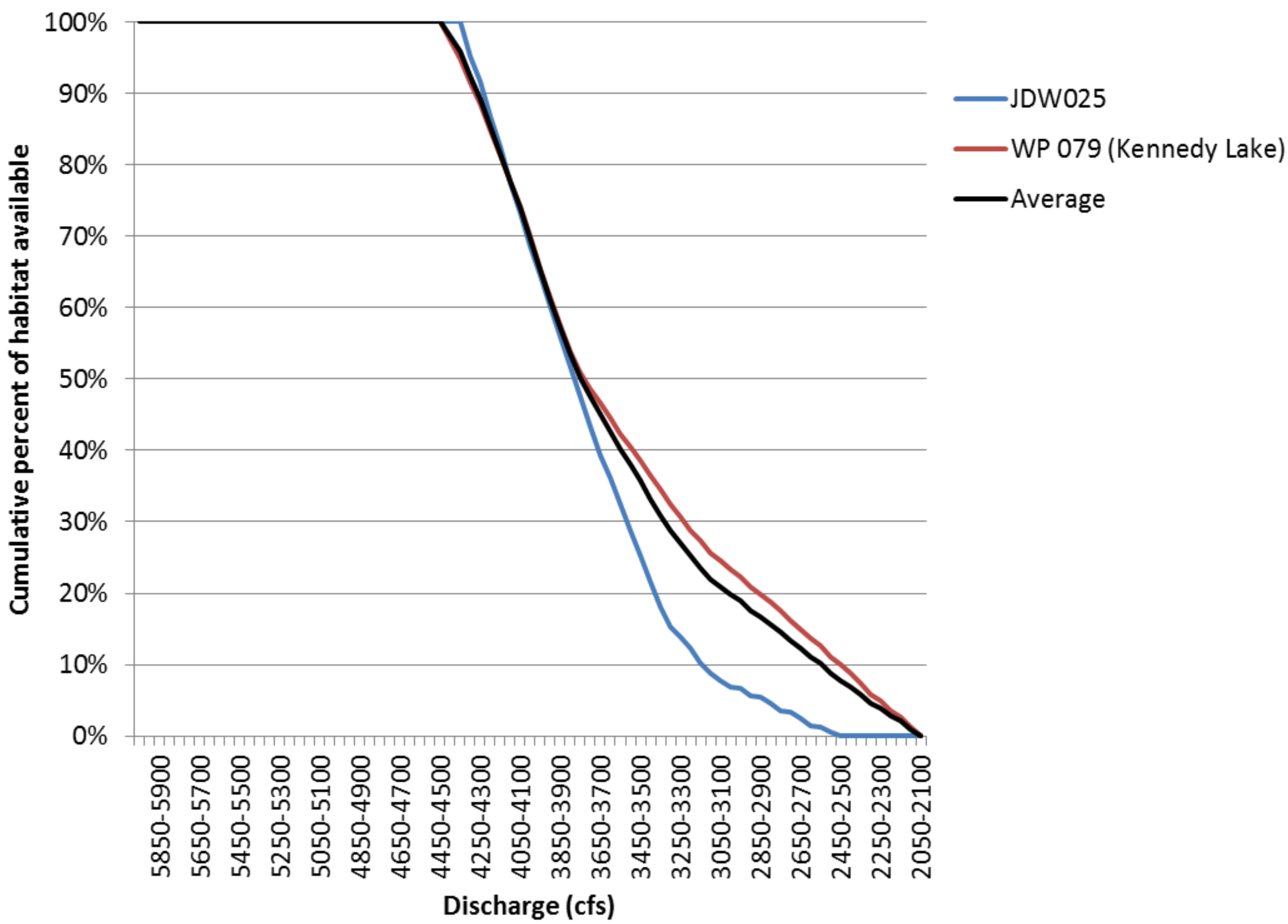


Figure 10. Percent of shallow water mussel habitat available as a function of water volume released from Thurmond Dam. Because basin inflow below Thurmond Dam is variable depending on season and drought conditions, habitat availability based on Thurmond releases may be greater or less than values reported in this graph.

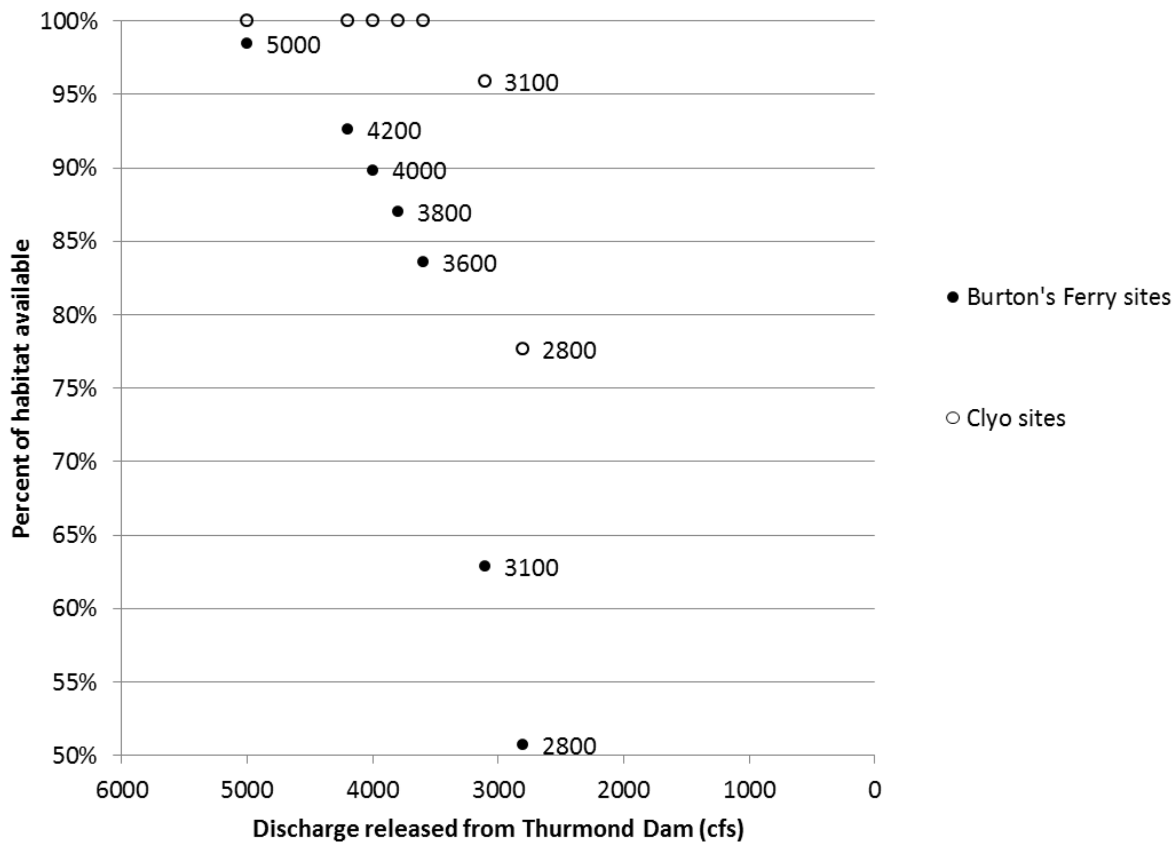


Figure 11. Distances that mussels must move in order to track receding water levels as a function of discharge. Mussels may not need to move in order to remain submerged except at very low discharges (e.g. BM098), whereas mussels must move considerable distances to remain submerged even at moderately low flows (e.g. WP 071 and Site 5).

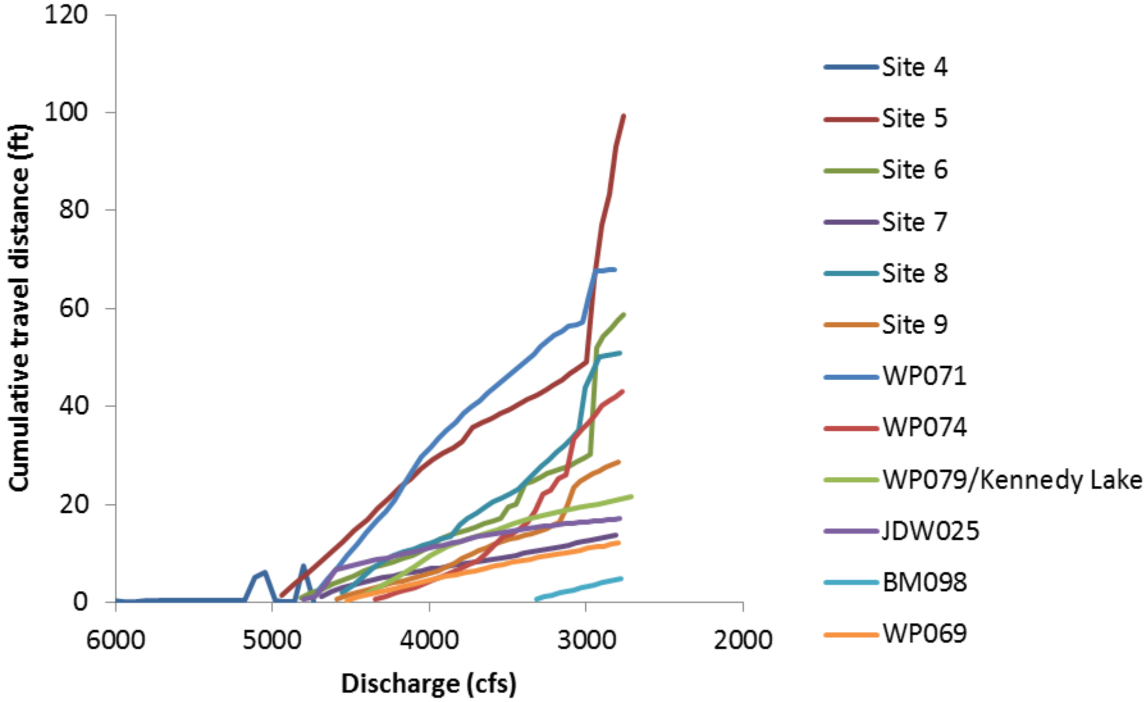


Figure 12. Distances that mussels must travel to remain submerged as a function of average site slope. Distances are based on predicted discharge at nearest USGS gages as Thurmond Dam decreases the volume of water released from 4200 cfs to 3100 cfs. Two sites were eliminated from the analysis because the predicted range of discharges either eliminated (Site 4) or provided (Site BM098) 100% of suitable habitat for the range of discharges considered.

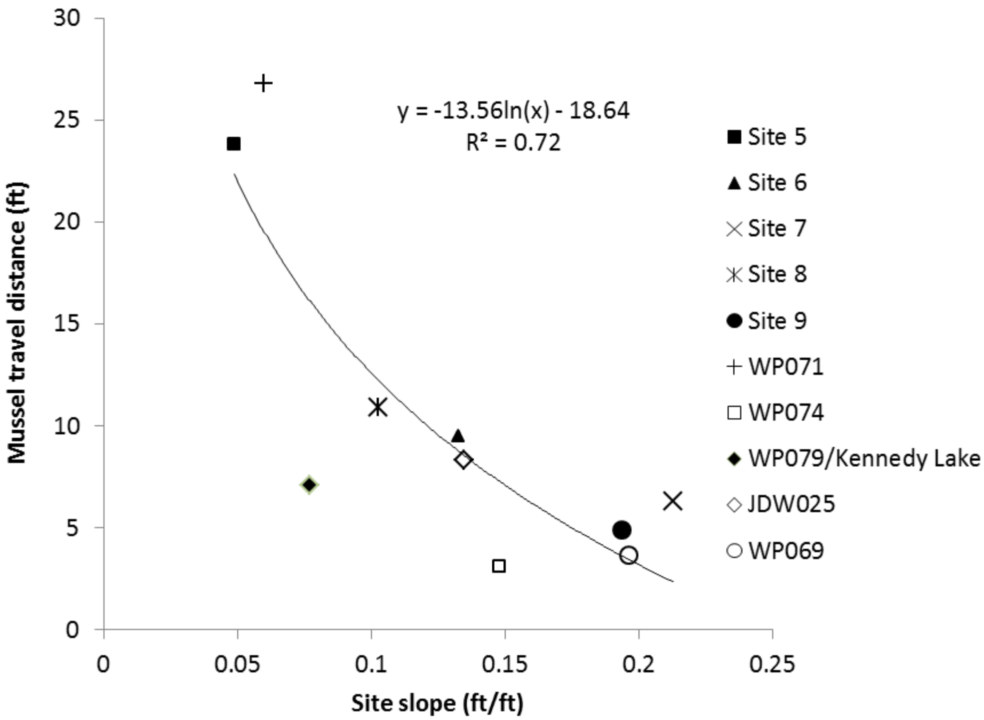


Figure 13. Bathymetry and notable water surface elevations at Oxbow H. The transect represented by the blue line is closest to the Savannah River, and the transect represented by the green line is farthest into the oxbow.

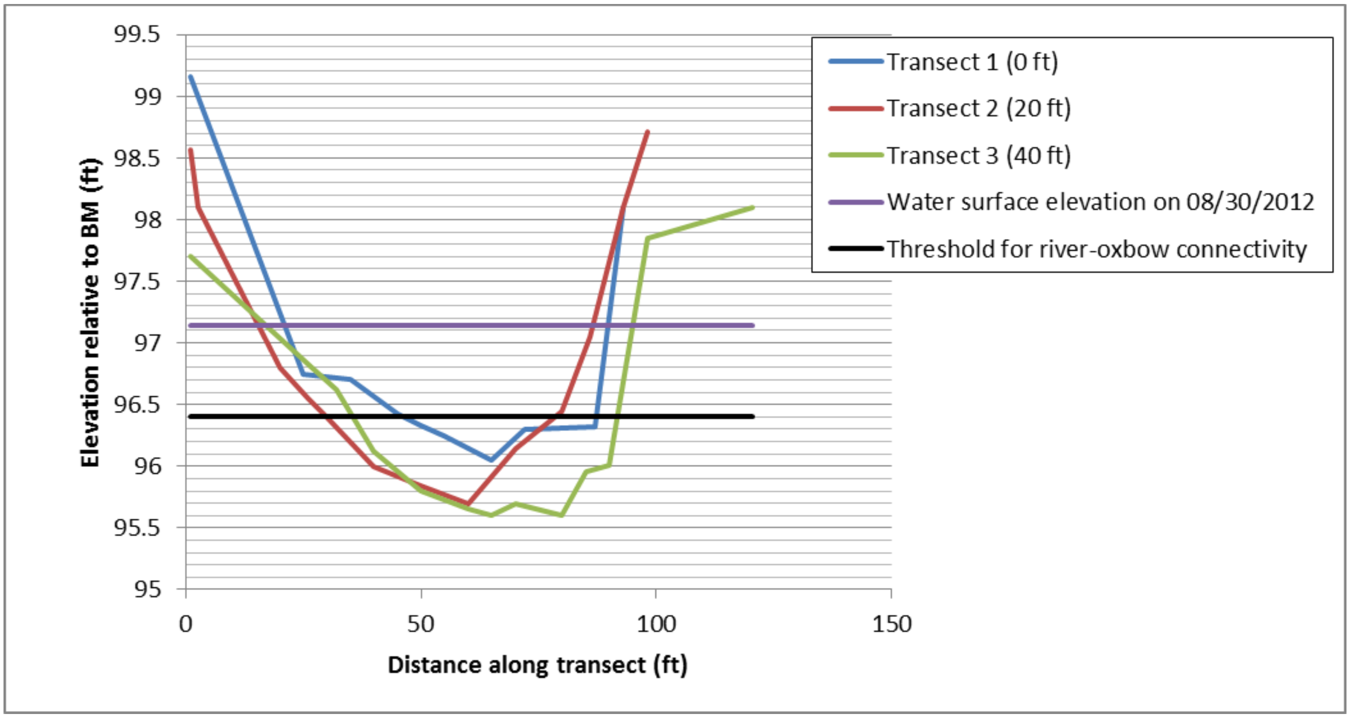


Figure 14. Water surface elevations in Oxbow H and elevations of Savannah lilliputs on August 30, 2012 (red dots) and November 27, 2012 (green triangles).

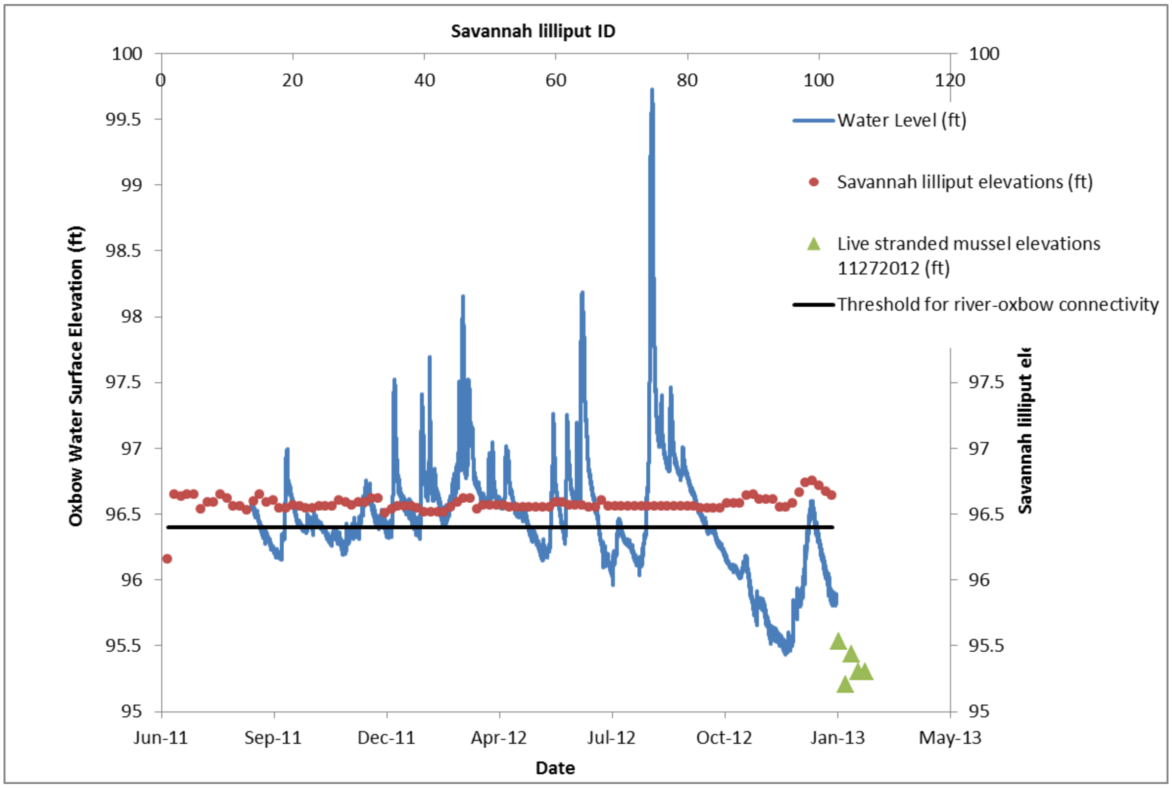


Figure 15. Bathymetry of site BM 098. Lowest elevation measurements were collected in the river and the highest elevations in the cutoff.

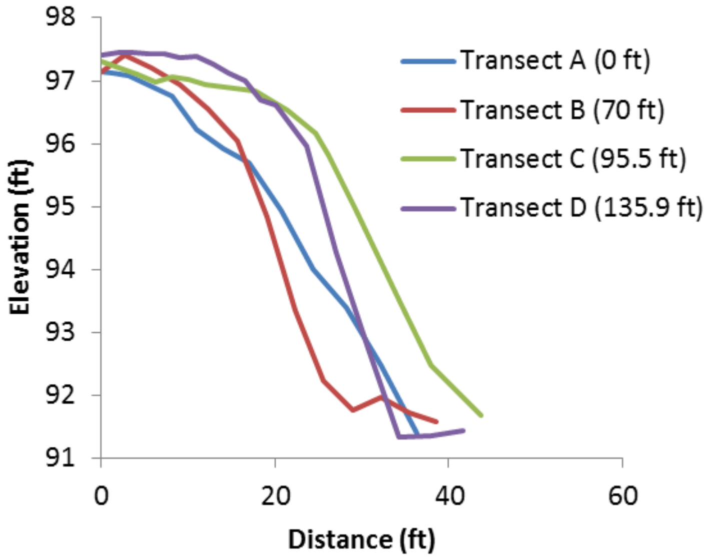


Figure 16. Water surface and mussel elevations on three survey dates at site BM098.

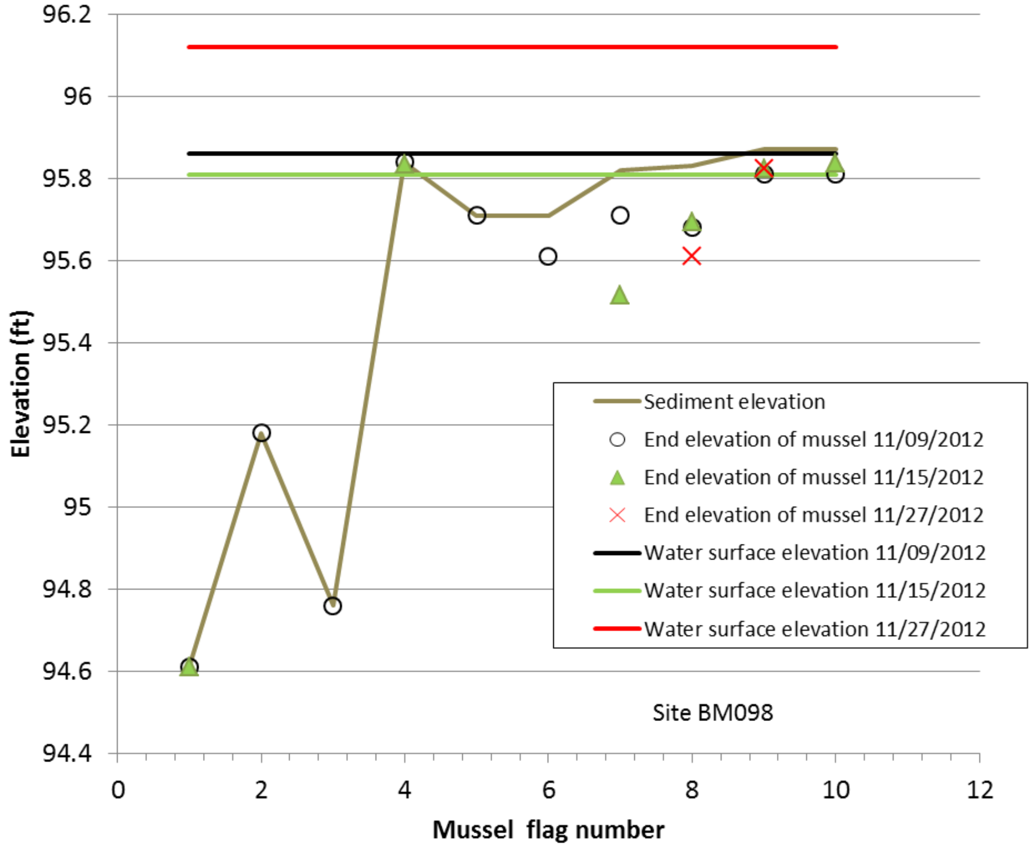


Figure 17. Water surface elevations, mussel elevations, and mussel condition on three survey dates at the marl outcrop near Little Hell Landing.

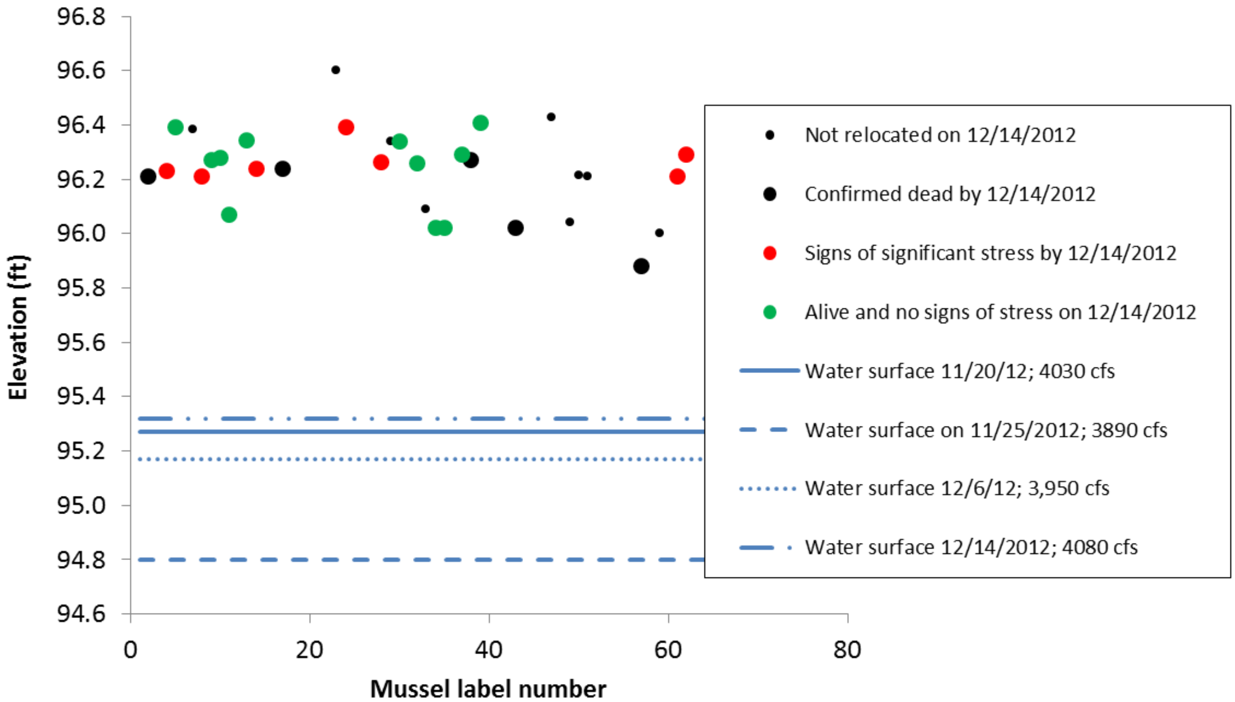
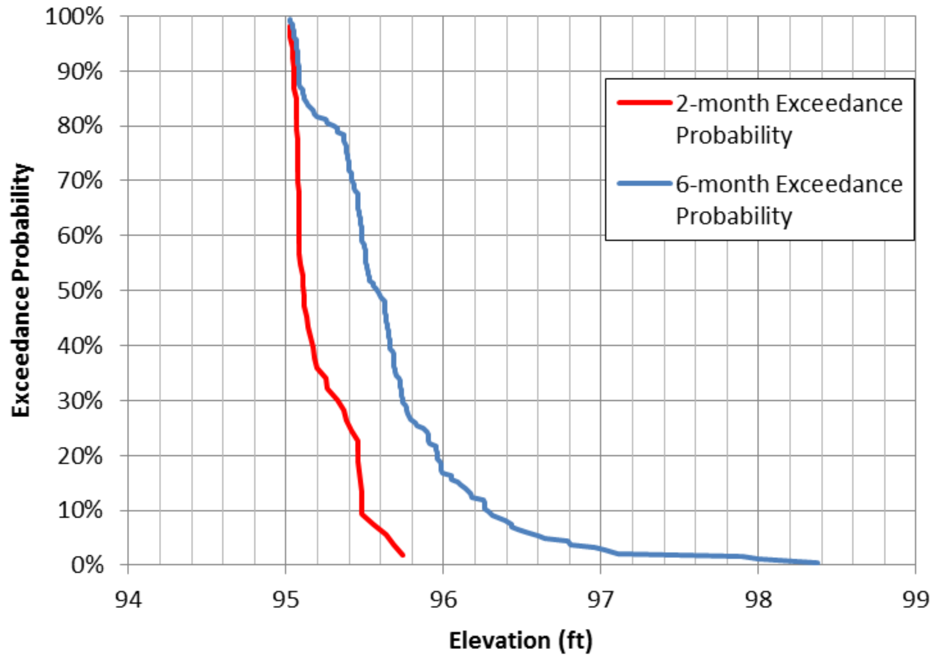


Figure 18. Discharge exceedance probability for the previous two and six months relative to the FWS benchmark at the marl outcrop.



Part IV: Savannah River oxbow and meander cutoff hydrodynamics and water quality responses as a function of river discharge

A report to the
U.S. Army Corps of Engineers
Savannah District

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Executive Summary

Oxbow connectivity has frequently been cited as a management concern for recreational fishing access, game fish production, rare mussel conservation, and wildlife management. Releases from Thurmond Dam have the potential to affect numerous natural oxbows, artificial meander cutoffs, and sloughs for nearly 200 river miles. To our knowledge, very little information has been generated to identify the hydrologic connectivity thresholds between the Savannah River and these habitats. Similarly, no information on recreational fishing access to these habitats exists. With the Corp's support, we developed relationships between river discharge and habitat connectivity, acreage connected to the river, and angler access. At a subset of sites, we evaluated water quality parameters in the mainstem river and artificial cutoffs. We suggest that the results provided in this study can be used to develop performance measures to evaluate and compare flow management alternatives.

Methodology

Mainstem-oxbow connectivity thresholds

To estimate the discharge thresholds at which connectivity to the river mainstem occurs, we selected natural oxbows, meander cutoffs, and sloughs (hereafter termed oxbows) that could be accessed during field surveys associated with other low flow studies dispersed throughout the lower river. Oxbow confluences were identified in ArcGIS and then field surveyed during periods of stable low flows. Because of the geomorphic variation between confluences, multiple techniques were employed to characterize the confluence and identify the incipient point of oxbow flooding. Cross sections were conducted at confluences that were wadable or that would be inundated during wetter low-discharge periods. Cross sections were generally parallel to the mainstem flow direction along the topographic high points that control the flow of water between the oxbow and mainstem. River water surface elevation was also measured. At confluences that were not wadable, water depth was repeatedly measured from the motor boat using either a graduated surveyors rod or depth finder. In such instances, only the depth that would be the incipient point of flooding during extreme low flows was recorded. Because some oxbow inlets and outlets were filled with sediment when the river was straightened, clear field identification of the confluence from the river was difficult. In those circumstances, the floodplain in the vicinity of the confluence was examined to identify the location that would likely serve as the incipient point of oxbow flooding during high flows. The elevation of the river water surface and incipient point of flooding were measured. All elevation measurements were made with a TopCon laser level.

For each location, the stage increase or decrease that would be necessary to reach the incipient point of flooding was calculated. Average daily discharge on the survey date was obtained from the nearest USGS gage: Savannah River at Augusta, Savannah River at Millhaven, and Savannah River near Clyo. The USGS discharge value was then used to calculate stage using the stage discharge relationship developed from the nearest US Fish and Wildlife Service (FWS) monitoring site. The stage increase or decrease required to reach the incipient point of flooding was added to the FWS stage to determine the elevation of the incipient point of flooding, and discharge was calculated using the FWS stage discharge relationship. Oxbow acreage was calculated using NHD+ flowlines and polygons in ArcGIS to determine the relationship between acreage connected to the river and river discharge.

We used USGS discharge data to compare the flows observed during the drought from July 1, 2012 to December 31, 2012 to the minimum flows required for connectivity of each oxbow to the river. We used the relationship between Thurmond Dam outflow and flows observed at USGS streamflow gages (see hydrology chapter) to evaluate the potential effects of drought flow management on oxbow connectivity.

Boat passage thresholds

The discharge required for recreational fishing access into oxbows was calculated in a manner similar to the mainstem-oxbow connectivity threshold. We applied the South Carolina one-way navigation criteria for a minimum of a one foot depth across a 10 foot wide channel (De Kozlowski 1988). In instances where confluence cross section data were available, we graphically displayed the cross section, visually determined the elevation required to meet the one-way passage criteria, and then calculated discharge using the methods described previously. In the absence of cross section data, we added one foot to the incipient point of flooding estimate and assumed that that elevation persisted for a 10 foot distance. Visual inspections of sites without cross sections indicated very low channel slopes, therefore lending support for this assumption. The relationship between oxbow acreage and discharge required for angler access was calculated.

Oxbow water level, temperature, and dissolved oxygen

Oxbow water levels, temperature, and dissolved oxygen were measured at three locations, selected to capture a range of hydrodynamic and water quality responses to river discharge variation. Oxbow H was selected because the elevation of the incipient point of flooding is near the river water surface elevation at low discharge, and therefore had potential to be affected by relatively small changes in outflow from Thurmond Dam. Oxbow H also harbors an unusually high abundance of the regionally rare Savannah lilliput (*Toxolasma pullus*). Oxbow F was selected because the morphology of the confluence facilitates continuous connectivity to the river during the low flows likely to occur during drought. Oxbow F had a diversity of mussels including the Savannah lilliput when sampled previously. For comparison purposes, we also collected the same parameters at Site 8 in the river between Oxbow H and F. HOBO water

Level/temperature loggers (U20-001-01) and HOBO dissolved oxygen loggers (U26-001) recorded measurements at 15 minute intervals. Water level and temperature were measured from August 23, 2011 to January 24, 2013 and dissolved oxygen was measured from November 2, 2012 to January 24, 2013.

Results

River discharge thresholds at which connectivity to the river mainstem occurred were estimated at 3 natural oxbows, 19 meander cutoffs, and 3 sloughs (Table 1). Our study examined connectivity and angler access to 448.9 acres. We estimate that natural oxbows, meander cutoffs, and sloughs in the Savannah River below Thurmond Dam account for 916.9 acres. We acknowledge that there may be additional floodplain lakes and sloughs not accounted for in this total because our focus was on natural oxbows and meander cutoffs in direct vicinity of the river mainstem. Nevertheless, our study accounts for approximately 50% of oxbow, cutoff and slough acreage.

The number of oxbows (Figure 1) and the acreage of oxbows (Figure 2) connected to the river mainstem by either an inlet or an outlet increases nearly linearly until a threshold of 5518 cfs. The threshold is driven by one meander cutoff and two natural oxbows (accounting for 10% of the oxbow acreage in this study), requiring >10,000 cfs to become connected to the river.

The number of oxbows and the acreage of oxbows connected to the river mainstem at both the inlet and outlet increases nearly linearly until a threshold of 12,416 cfs (Figure 3). The threshold is driven by three natural oxbows and two cutoffs (accounting for 19% of the oxbow acreage in this study), requiring >17,000 cfs to become connected.

Four oxbows had potential to become disconnected from the river during drought operations from July 1, 2012 to December 31, 2012 (Table 2). The USGS Millhaven gage was the nearest gage to these oxbows. During this period, outflow from Thurmond Dam ranged between 2943 and 3977 cfs and discharge at Millhaven ranged between 3960 and 4740 cfs. The total acreage of these four oxbows was 66.4 acres, or 14.7% of the total oxbow acreage in this study. During the most extreme drought conditions, 68% of oxbows remain connected to the river.

Five oxbows had potential to become inaccessible to anglers as discharge declines during drought operations (Table 2, Figure 4). These oxbows were dispersed throughout the river and comprised 23.4% of the total oxbow acreage in this study. During the most extreme drought conditions, 32% of the oxbow acreage remains accessible to anglers (Figure 5).

Water level of the connected oxbow (Cutoff 20 Outlet/Oxbow F) was the same as water level measured in the river at Site 8. However, water level in the disconnected oxbow (Oxbow H) fluctuated depending on the hydrodynamics of the river. Oxbow water levels increased when river flows exceeded 4600 cfs (Figure 6). These increases were frequently followed by sharp declines in oxbow water levels, followed by gradual water level recession when river discharge declined below 4600 cfs.

Oxbow water temperature was the strongest predictor of disconnected oxbow dissolved oxygen and accounted for 32% of dissolved oxygen variation (R^2= 0.32, $F_{1,7989}$=3788, p<0.001). Oxbow water surface elevation and ambient air temperature accounted for 74% of water temperature variation (R^2= 0.74, $F_{2,7989}$=4872, p<0.001), with ambient air temperature having the strongest influence (R^2= 0.53). Dissolved oxygen in the disconnected oxbow showed diel variation. Minimum daily dissolved oxygen values were generally lower than in the river and remained below 4 mg/L for prolonged periods (Figure 7), particularly during periods of low oxbow water levels (Figure 8).

Discussion

Thurmond Dam outflow accounts for 60-90% of the baseflow discharge observed at the Millhaven USGS gage during drought, illustrating that Thurmond Dam drought operations have a large potential to affect downstream aquatic resources. As flows increases in the lower river, the number and acreage of oxbows, meander cutoffs, and sloughs connected to the mainstem increases in a nearly linear fashion for a majority of the sites until approximately 5500 cfs at the USGS Millhaven gage. Angler access into these oxbows also increases as discharge increases in a nearly linear fashion until approximately 6550 cfs at the USGS Millhaven gage. However, Thurmond Dam drought flows cited in the Drought Contingency Plan for Savannah River Basin projects range between 4200 and 3100 cfs. At the lowest drought flow observed, 68% of the oxbow acreage remains connected to the mainstem, illustrating that a large proportion of the oxbows have surface water connectivity to the river during drought. However, angler access is limited to 32% of the oxbow acreage. These results illustrate that the effects of drought flow management on oxbow connectivity may be less severe than previously hypothesized, but that effects on angler access into oxbows is substantial.

We characterized water level dynamics, temperature, and dissolved oxygen at a subset of cutoff and mainstem sites. Our data show that for Oxbow H, a periodically disconnect oxbow that harbors an abundance of regionally rare mussels, approximately 4600 cfs is required to connect the oxbow to the river. Our estimates of hydrologic connectivity using the methodology described previously indicate that 4781 cfs corresponds to the incipient point of Oxbow H flooding. The higher value may be a reflection of variation in the stage discharge relationship between Site 8 (the nearest FWS water level monitoring site) or error in estimates. Nevertheless, the 181 cfs difference corresponds to a 0.2 foot difference in stage at Site 8, suggesting that our methodology is reasonably accurate for low flows.

However, hydrologic connectivity predictions that report discharge values lower than those observed during the study should be viewed as rough estimates only. Similarly, high flow values (above baseflow) have a stronger potential to be less accurate for reasons described in the hydrology chapter. We therefore recommend that incipient point of flooding estimates at high flows be cautiously applied and interpreted.

Dissolved oxygen and water temperature can have a strong influence on biota and ecology. We expected that the influx of water above the incipient point of flooding in the disconnected oxbow (4600 cfs) would facilitate the mixing of oxygenated river water with potentially deoxygenated oxbow water. However, continuous dissolved oxygen data was collected for a relatively short duration, conducted in the winter when dissolved oxygen levels were presumably higher, and included only one flow above 4600 cfs, the threshold for connecting the oxbow. Thus, conclusions regarding the relationship between river discharge and periodically connected oxbow dissolved oxygen cannot be made without additional data collection. However, we established that dissolved oxygen dynamics in this oxbow are similar to other waterbodies. Water temperature is a strong predictor of dissolved oxygen, and air temperature and water level are predictors of water temperature. These relationships highlight the potential for river water to affect both the temperature and dissolved oxygen of oxbow habitats. This is especially important given the low dissolved oxygen levels observed in the disconnected oxbow during this study.

The variation in the connectivity thresholds and hydrologic dynamics among oxbows, cutoffs, and sloughs illustrates that substantial hydrological variation exists across sites. This means that habitat conditions may vary substantially between natural oxbows, meander cutoffs, and sloughs, and that treatment of these waters for habitat management purposes may warrant further classification and characterization of habitat types.

In summary, the results from this study address a research need identified during multiple interagency meetings. These data have been developed in a manner that should allow the Service and the Corps to quantitatively evaluate flow management effects on oxbows and recreational fishing opportunities.

Areas for improvement

1) Inclusion of the remaining oxbows, meander cutoffs, and sloughs would make the analysis more comprehensive.
2) Hourly stage fluctuations at oxbows immediately below New Savannah Bluff Lock and Dam and in tidally influenced oxbows made estimation of incipient point of flooding estimates rough approximations. Additional analyses would be necessary to fine tune the estimates.
3) Characterization of habitat and a classification of oxbows, meander cutoffs, and sloughs would be beneficial in order to better differentiate potential effects on these aquatic habitats.

4) Monitor dissolved oxygen in disconnected oxbows for longer periods of time in order to evaluate potential effects of river flows on oxbow water quality.

Citations

de Kozlowski, Steven J. 1988. Instream Flow Study-Phase II; Determination of minimum flow standards to protect instream uses in priority stream segments. South Carolina Water Resources Commission Report Number 163.

Table 1. Natural oxbows, meander cutoffs, and sloughs included in the USFWS oxbow-river connectivity study. Details on the nearest water level monitoring location can be found in the hydrology chapter of this report.

Location	Outlet River Mile	Inlet River Mile	Acreage	Nearest water level monitoring location	Average discharge at nearest USGS gage on survey date	Nearest USGS gage
NaturalOxbow1Outlet	140	141.65	18.180	Site 9	4646	Burton's Ferry
Cutoff20Inlet	137.27	137.42	8.631	Site 8	4451	Burton's Ferry
Cutoff20Outlet/ Oxbow F	137.27	137.42	8.631	Site 8	4437	Burton's Ferry
CutoffRM136.8Inlet	136.35	136.63	6.105	Site 8	4451	Burton's Ferry
CutoffRM136.8Outlet/ Oxbow H	136.35	136.63	6.105	Site 8	4860	Burton's Ferry
Cutoff19Inlet	135.2	135.34	21.519	Site 7	4646	Burton's Ferry
Cutoff19Outlet	135.2	135.34	21.519	Site 7	4646	Burton's Ferry
Devil's elbow inlet	135.518	135.65	21.519	Site 7	4451	Burton's Ferry
Devil's elbow outlet	135.518	135.65	21.519	Site 7	4646	Burton's Ferry
Cutoff18Inlet	135.19	135.34	11.680	Site 6	4646	Burton's Ferry
Cutoff18Outlet	135.19	135.34	11.680	Site 6	4646	Burton's Ferry
Cutoff 14 Inlet	99.38	99.545	13.131	Site 4	4862	Burton's Ferry
Cutoff 14 Outlet	99.38	99.545	13.131	Site 4	4862	Burton's Ferry
NaturalOxbow7Outlet	100.18	100.21	24.240	Site 4	4862	Burton's Ferry
NaturalOxbow7Inlet	100.18	100.21	24.240	Site 4	4862	Burton's Ferry
Cutoff101.3Outlet	101.05	101.22	7.441	Site 4	4862	Burton's Ferry
Cutoff101.3Inlet	101.05	101.22	7.441	Site 4	4862	Burton's Ferry
Alligator lagoon	101.95	101.95	1.120	Site 4	4862	Burton's Ferry
Cutoff 15A Inlet	102.06	102.19	29.962	Site 4	4320	Burton's Ferry
Cutoff15AOutlet	101	101.2	29.962	Site 4	4862	Burton's Ferry
Bailey's Cut Inlet (WP 088)	181.9	181.78	36.997	USGS SR at Augusta	4030	Savannah River at Augusta
Bailey's Cut Outlet	181.9	181.78	36.997	USGS SR at Augusta	4030	Savannah River at
Beckum's Cut Inlet	181.17	181.33	21.451	USGS SR at Augusta	4030	Savannah River at
Beckum's Cut Outlet	181.17	181.33	21.451	USGS SR at Augusta	4030	Savannah River at
Fritz Cut Outlet	183	183.19	43.262	USGS SR at Augusta	4030	Savannah River at
Fritz Cut Inlet	183	183.19	43.262	USGS SR at Augusta	4030	Savannah River at
102.8 Outlet	102.6	102.89	22.003	Site 5	4320	Burton's Ferry
102.8 Inlet	102.6	102.89	22.003	Site 5	4320	Burton's Ferry
Oxbow inlet 4 at JDW 029	41.17	41.35	32.491	JDW029	4360	Clyo
Oxbow 4 outlet	41.17	41.35	32.491	JDW029	4360	Clyo
Cutoff 6 Inlet Big Kiffer Point	43.172	43.42	23.408	JDW025	4360	Clyo
Cutoff 6 Outlet	43.172	43.42	23.408	JDW025	4360	Clyo
Cutoff 5 Inlet	41.79	41.64	12.018	JDW029	4360	Clyo
Cutoff 5 Outlet	41.79	41.64	12.018	JDW029	4360	Clyo
Cutoff 3 Inlet	40.95	40.8	8.540	JDW029	4360	Clyo
Cutoff 3 Outlet	40.95	40.8	8.540	JDW029	4360	Clyo
Cutoff 2 Inlet	37.17	37.41	20.519	JDW029	4360	Clyo
Cutoff 2 Outlet	37.17	37.41	20.519	JDW029	4360	Clyo
Unnamed slough	38	38.42	4.854	JDW029	4360	Clyo
Fox lake	39.1		11.770	JDW029	4360	Clyo
NatOx6Out	109.64	109.82	12.847	LL074	4320	Burton's Ferry
Cutoff17Inlet	107.28	106.9	18.473	LL071	4320	Burton's Ferry
Cutoff112.6OUtlet	112.4	112.65	16.753	LL074	4320	Burton's Ferry
Cutoff112.6Inlet	112.4	112.65	16.753	LL074	4320	Burton's Ferry

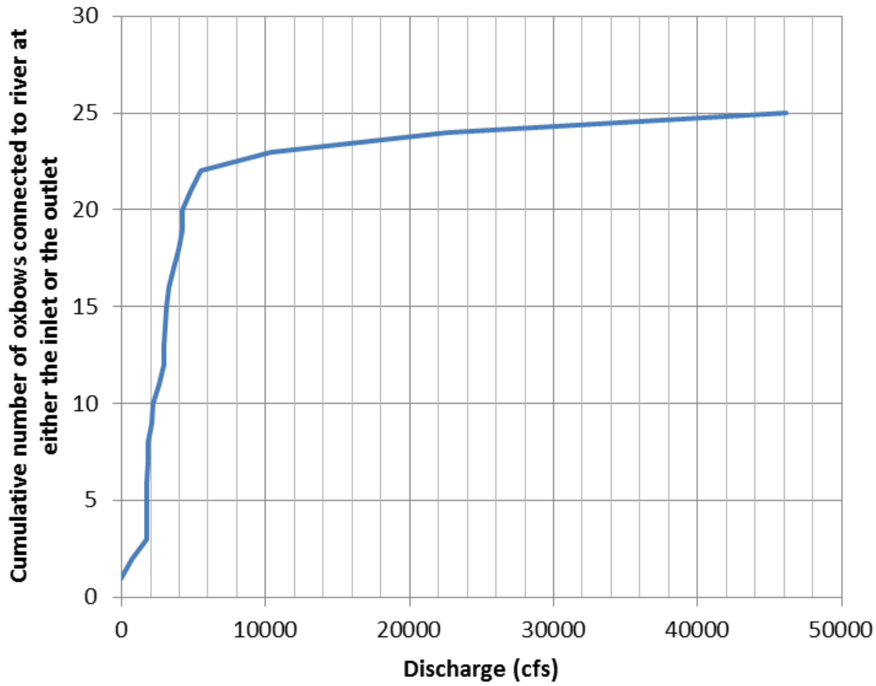
Table 2. Locations that are the most likely to be hydrologically affected by changes to the drought plan.

Oxbow name	Connectivity threshold (cfs)	River mile	Acreage
Cutoff 112.6 Outlet	3953.6	112.4	16.8
Cutoff 19 Outlet	4197.8	135.2	21.5
102.8 Outlet	4212.0	102.6	22.0
Cutoff RM136.8 Outlet	4781.9	136.35	6.1

Table 3. Locations where angler access is most likely to be affected by changes to the drought plan.

Oxbow name	Angler access threshold (cfs)	River mile	Acreage
Fritz Cut Outlet	4002.9	183	43.3
Cutoff 3 Inlet	4045.4	41.0	8.5
Cutoff 20 Outlet/Oxbow F	4053.1	137.3	8.6
Bailey's Cut Inlet (WP 088)	4067.7	181.9	37.0
Cutoff 101.3 Outlet	4721.6	101.1	7.4

Figure 1. Cumulative number of oxbows connected to the river at either the oxbow inlet or outlet as a function of river discharge. Note that discharge values reported are for the USGS or FWS monitoring location nearest to the site. Thus, the graph is a display of estimated discharges required for hydrologic connectivity over a broad geographic area.



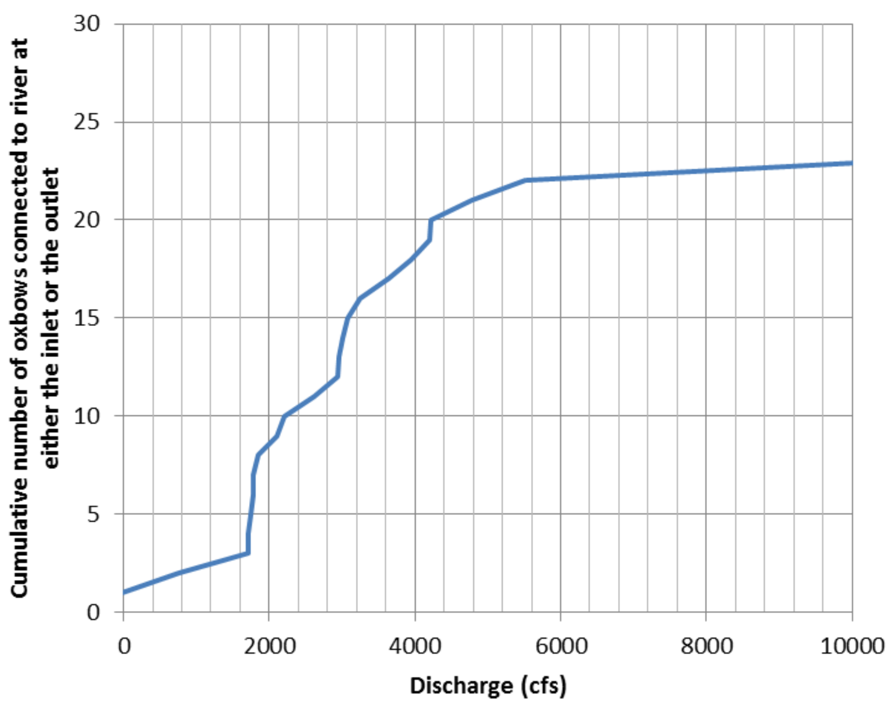


Figure 2. Cumulative oxbow acreage (2A and 2B) and percent of surveyed oxbow acreage (2C and 2D) connected to the river as a function of discharge. Note that discharge values reported are for the USGS or FWS monitoring location nearest to the site. Thus, the graph is a display of estimated discharges required for hydrologic connectivity over a broad geographic area.

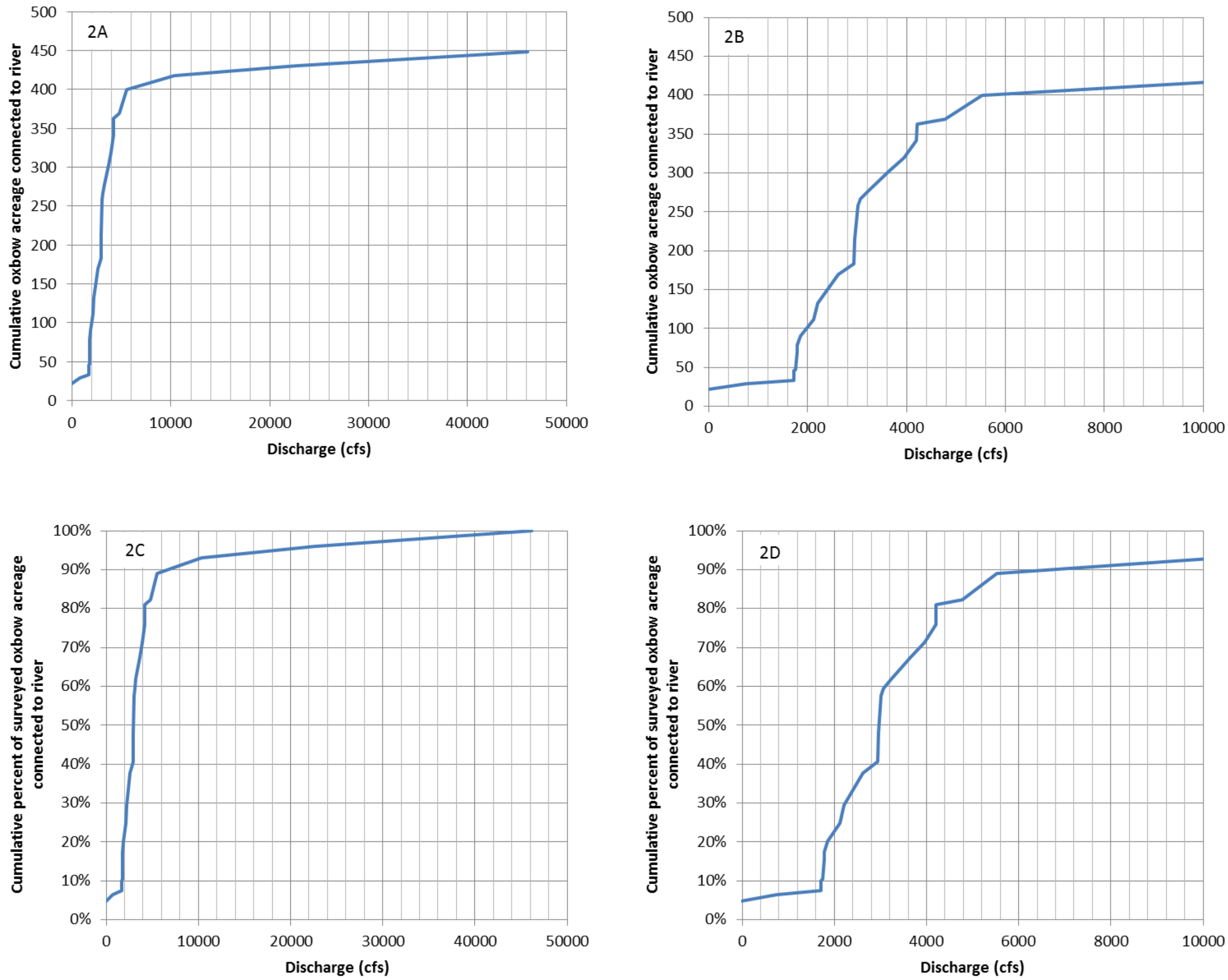


Figure 3. Cumulative number of oxbows (3A and 3B) and cumulative percent of surveyed oxbow acreage (3C) connected to the river at the oxbow inlet and outlet as a function of river discharge. Note that discharge values reported are for the USGS or FWS monitoring location nearest to the site. Thus, the graph is a display of estimated discharges required for hydrologic connectivity over a broad geographic area.

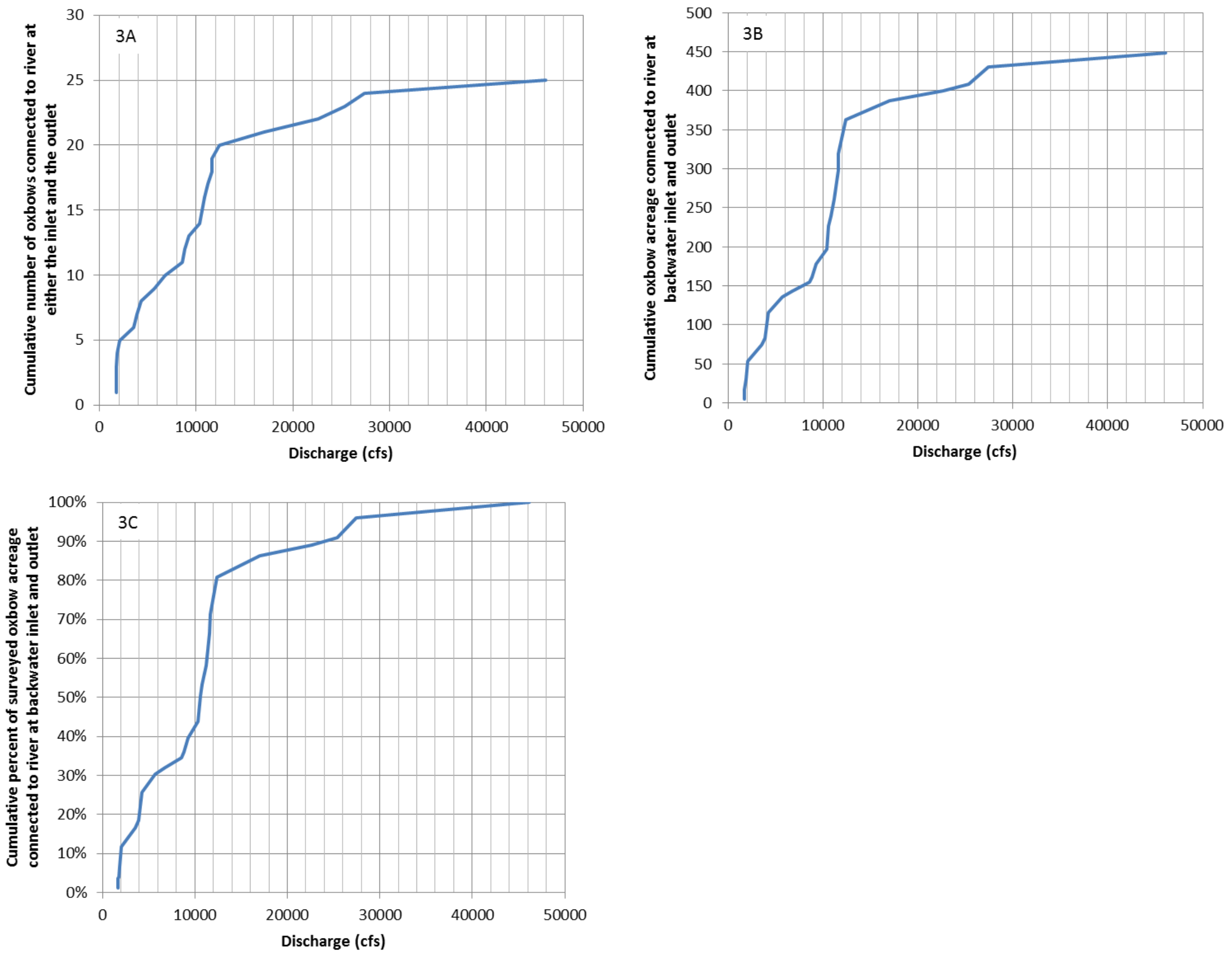


Figure 4. Cumulative number of oxbows passable by boat using the South Carolina 1-way criteria. Note that discharge values reported are for the USGS or FWS monitoring location nearest to the site. Thus, the graph is a display of estimated discharges required for hydrologic connectivity over a broad geographic area.

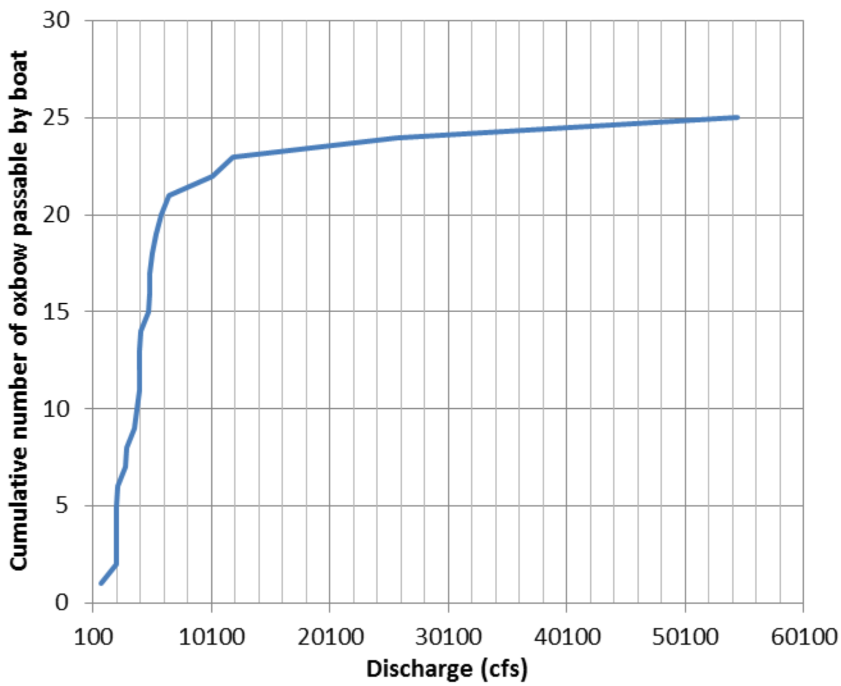


Figure 5. Cumulative oxbow acreage (5A and 5B) and cumulative percent of surveyed oxbow acreage (5C and 5D) accessible by boat. Note that discharge values reported are for the USGS or FWS monitoring location nearest to the site. Thus, the graph is a display of estimated discharges required for hydrologic connectivity over a broad geographic area.

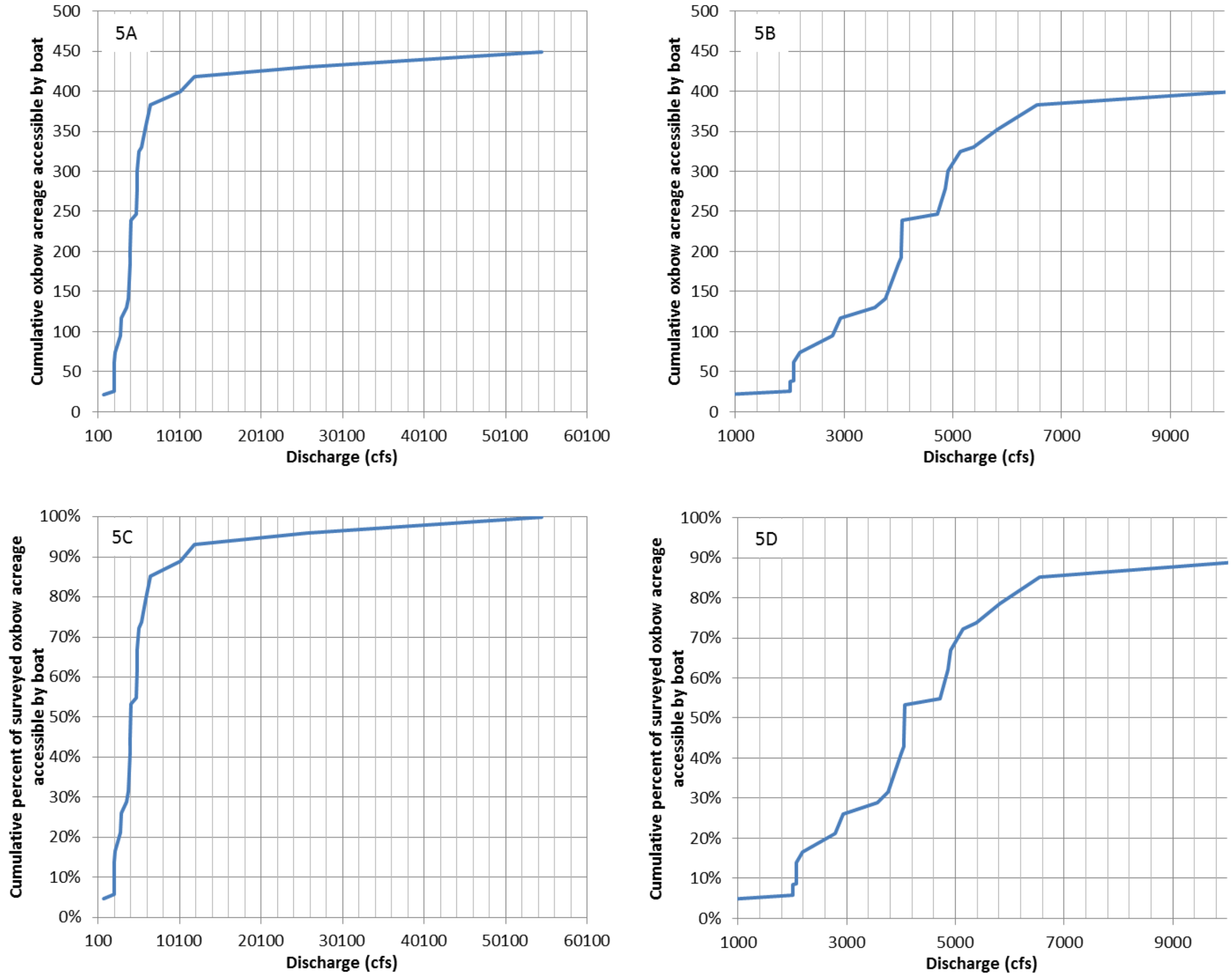


Figure 6 Oxbow H water surface elevation and mainstem river discharge (USGS Burton's Ferry gage) for a subset of the monitored period. The discharge threshold at which surface water connectivity occurs is indicated for some occasions. The USGS gage data has been shifted to accurately account for the 8.5 hours water travel time from the site to the gage.

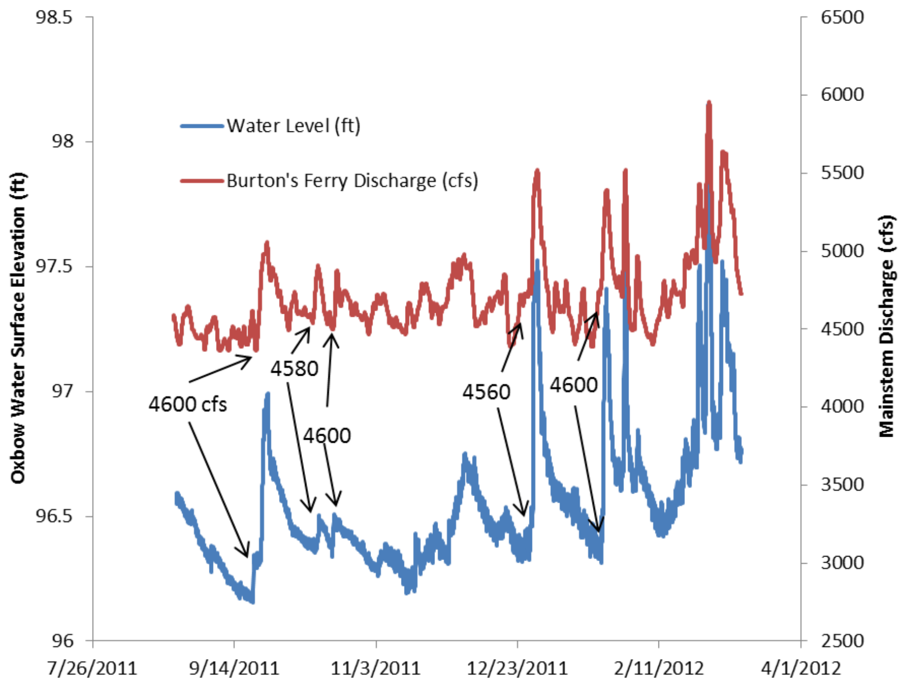


Figure 7. Comparison of minimum daily dissolved oxygen levels in the Savannah River at Site 8 and an adjacent periodically disconnected meander cutoff (Oxbow H).

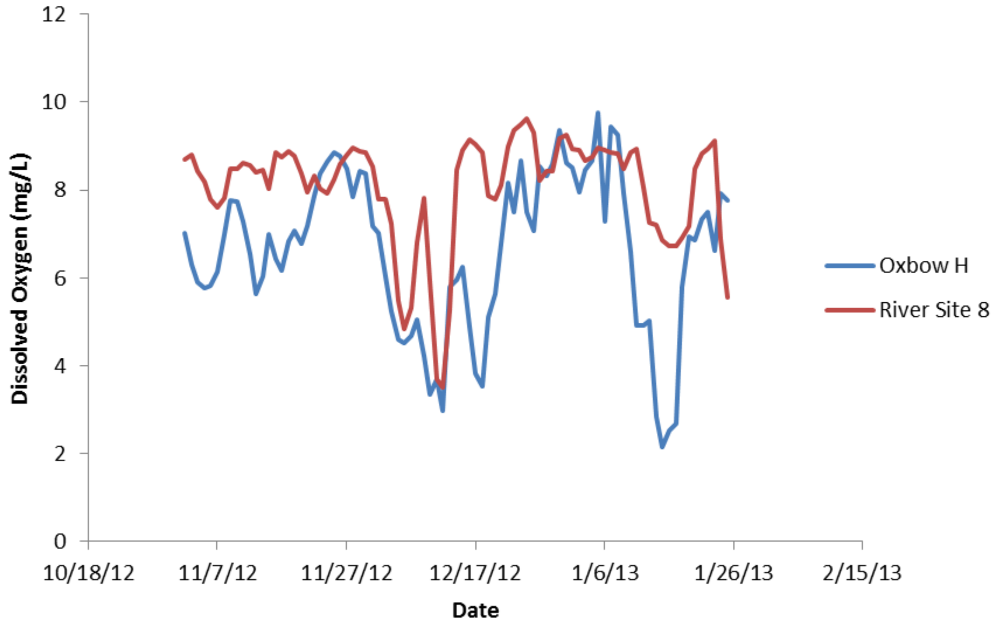
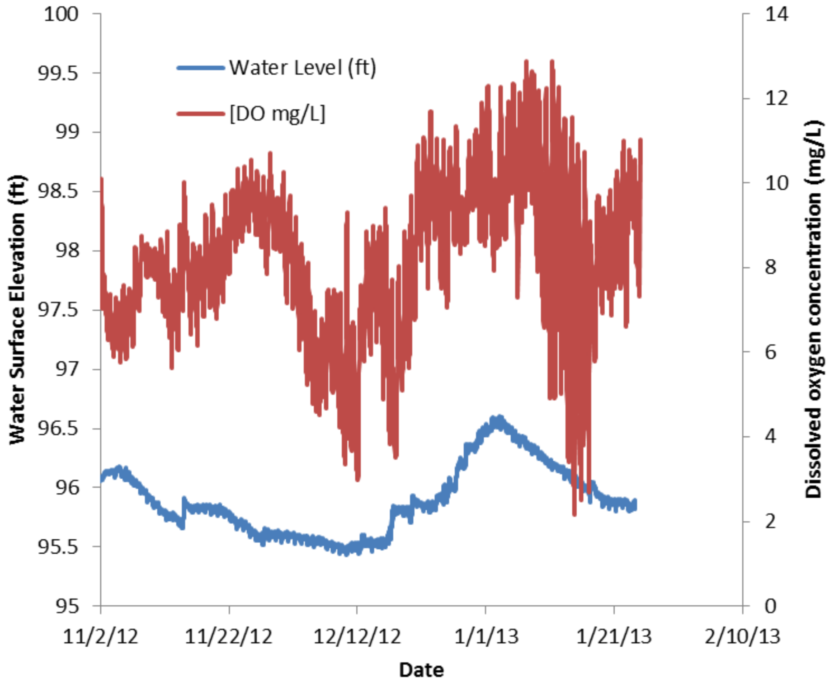


Figure 8. Water level (blue line) and dissolved oxygen (red line) in Oxbow H, a periodically disconnect oxbow.



Part V: Effects of flow reductions from J. Strom Thurmond Dam on Interstitial Marsh Salinities at the Savannah National Wildlife Refuge

A report to the
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Savannah District

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Effects of flow reductions from J. Strom Thurmond Dam
on Interstitial Marsh Salinities at the Savannah National Wildlife Refuge

Introduction

Since 1986, the Savannah River basin experienced a series of droughts. The drought of record from 1986 – 1989 compelled the Army Corps of Engineers (Corps) to re-evaluate traditional management of its upstream reservoirs; Hartwell, Russell, and Thurmond, which led to the development of the Savannah River Basin Drought Contingency Plan (SRBDCP) in March 1989 (U.S. Army Corps of Engineers 1989). However, extreme droughts occurred between 1998 and 2002. New droughts of record prompted the Corps to update the SRBDCP through the Savannah River Basin Comprehensive Study authorized under the Water Resources Development Act of 1996. An Environmental Assessment and Finding of No Significant Impact (EA/FONSI) was developed in 2006 that addressed potential environmental impacts to resources within the Savannah River Basin from the proposed modifications to the 1989 SRBDCP. Since the EA/FONSI of 2006, a new drought of record from 2007-2009 was documented prompting the Corps to deviate once again from current plans. The Corps requested deviations to the SRBDCP on nine separate occasions to reduce flows through the J. Strom Thurmond dam since the EA/FONSI of 2006. The most current request is to reduce flows from Thurmond Dam to 3,100 cubic feet per second (cfs) from November 1 – January 31 in Drought Level 3 or 4 or to the end of February with approval from the National Marine Fisheries Service (U.S. Army Corps of Engineers 2012a). The reduction in flows during the November – December timeframe presumably would reduce the impacts on water quality, supply, and habitat. The SRBDCP will be updated beginning in 2013; therefore; better quantitative information is necessary to model the effects of flow management alternatives with specific regards to drought.

Tidal freshwater wetlands are unique ecosystems defined by freshwater communities of plants and animals subject to daily tidal action. These ecosystems are found where large river systems flow into the ocean with tidal amplitudes greater than 1.6 ft. and where the geomorphology constricts and amplifies the tidal wave in the upper reaches of the estuary (Odum et al. 1984). A high diversity of plants and animals characterize tidal freshwater wetlands as well as high primary productivity. Freshwater inflow from the river into the estuary greatly affects the quality and quantity of tidal freshwater marsh, a habitat type that is regionally becoming scarce. A resource management challenge in the lower Savannah River estuary and the Savannah National Wildlife Refuge (NWR) is monitoring, assessing, and managing the effects of changes in discharges from Thurmond Dam. Early studies on the Savannah River estuary focused on the effects of the tide gate and its removal on the tidal freshwater marsh. More recent studies examined effects of drought and developed models to predict community shifts with changes in salinity related to recent droughts of record. Additionally, two Marsh Succession Models were produced to predict the potential shift in community types within the estuary as a result of mitigation actions associated with the Savannah Harbor Expansion Project. These models produced unreliable results that stem from predictions of marsh salinities from the adjacent river where mitigation actions significantly altered flows (U.S. Army Corps of Engineers 2012b). Thus, critical research needs include quantification of interstitial salinities as a function of freshwater inflow and adjacent river salinity. It is important to quantify the potential effects of reduced discharges resulting from management of the reservoirs, particularly Thurmond Dam, on the tidal freshwater marsh within the lower Savannah River estuary and specifically within the Savannah NWR where the majority of the remaining tidal freshwater wetlands remain.

The drought in 2011 and 2012 and concurrent reductions in outflow from Thurmond Dam afforded us the opportunity to 1) collect marsh salinity data at a range of marsh inflows that were not measured during previous marsh studies, 2) collect information that could be used to evaluate the accuracy of the Marsh Succession Models, and 3) accumulate information that can be used to quantitatively inform proposed water management changes during updates to the SRBDCP. Thus, the objective of this study focuses on quantifying the effects of declining freshwater inflows on pore-water or interstitial salinity in the tidal freshwater marsh of the Savannah NWR and the potential changes in marsh vegetation composition using a combination of empirically derived data from this study and results from previous studies.

Study Area

The Savannah NWR was established in 1927 as a migratory bird refuge with emphasis on providing migration and wintering habitat for waterfowl and other wetland-dependent birds. The refuge consists of approximately 29,175 acres located in the lower Savannah River estuary in Chatham and Effingham Counties, Georgia and Jasper County, South Carolina between river miles 18-41 (Fig. 1 inset). It is one of the largest federally protected tracts of land on the Georgia and South Carolina coasts. The habitats that make up the refuge are diverse and include mature bottomland hardwoods, hardwood hammocks, emergent and forested tidal freshwater wetlands, freshwater impoundments, brackish marsh, and mixed pine/hardwood upland forests (U.S. Fish and Wildlife Service 2011).

The freshwater impoundments are the most important managed habitat on the refuge and the principle means of meeting the refuge's primary objective of providing migration and wintering habitat for waterfowl. Of the 6,000 acres of impounded wetlands, 3,000 are actively managed through a variety of techniques including seasonal disking and burning. The most critical and effective means of management is through water level control, which requires managing a complex system of water control structures and a consistent and ample supply of freshwater. The plant communities within the impoundments are highly diverse and provide habitat for up to 23% of South Carolina's wintering waterfowl as well as other high priority, wetland-dependent birds such as purple gallinules, swallow-tailed kites, and the threatened wood stork. The remaining 3,000 acres of impounded, non-tidal wetlands lie within the semi-managed East Marsh unit. The vegetative diversity of East Marsh is equal to that of the managed impoundments, but East Marsh is more structurally diverse providing large areas of forested wetlands interspersed with emergent and scrub-shrub types. In addition to the managed impoundments, the most important non-managed habitat is made up of tidal freshwater forested and emergent wetlands.

The City of Savannah lies immediately downstream of the refuge with the Port of Savannah adjacent to the western boundary. Growth of the City of Savannah and a series of harbor expansions to accommodate larger ships has drastically altered the ecology of the Savannah River estuary. Prior to 1875, the controlling depth of the estuary was approximately 12'-15' and the saltwater/freshwater interface extended seven miles upstream (U.S. Fish and Wildlife Service 2008). Since the establishment of the refuge in 1927, the Savannah Harbor navigation channel has been deepened during four major projects in 1937, 1958, 1975, and 1994 with the current channel depth at 42' and the saltwater/freshwater interface extending beyond river mile 21. The Sediment Control and Works project was completed in 1977 and included installation of the tide gate.

In addition to the alterations of the estuary from repeated harbor deepening, the estuary also is greatly influenced by freshwater flow from upstream, which is largely regulated by controlled releases through Thurmond Dam as well as freshwater input below the dam. The combination of regulated and reduced freshwater flows and upstream intrusion of saltwater significantly reduced the amount of tidal freshwater marsh in the estuary. Approximately 8,000 acres of the estimated 12,000 acres of freshwater tidal marsh were lost with the majority of the remaining marsh on the Savannah NWR. The proposed deepening of the harbor to 47' will result in the loss of an additional 223 acres based on model predictions (U.S. Army Corps of Engineers 2012b). Additionally, the increase in salinity at the intake of Lucknow Canal is cause of great concern to the Savannah NWR because of its implications for management and long-term function of the freshwater impoundment system.

Methods

The methods used in this study to measure interstitial salinity on the Savannah NWR replicate those of Dusek and Kitchens (2003) and others. Four sampling sites were identified with three sites corresponding to previous sites used by Dusek and Kitchens (2003) (Fig. 1). A new site, SAV2, was established close to the entrance to Lucknow Canal between SAV1 and SAV3 to evaluate the potential intermediate effects on interstitial salinity between Rifle Cut and SAV1, the most upstream site. Rifle Cut is small cut connecting Middle River with Back River but can transport large volumes of saline water into Back River (U.S. Army Corps of Engineers 2012b, S. Davie, TetraTech, personal communication.). These sites encompass a range of marsh types and the portion of the marsh with the highest vegetation diversity. The USGS gaging station located at the FWS dock on Savannah NWR (USGS gage 021989791) is located 1.1 river miles from the entrance to Rifle Cut. Salinity at the FWS dock is consistently two to three times greater than the Lucknow gaging station, 1.9 river miles upstream from the gage on the FWS dock (C. Hayes, U.S. Fish and Wildlife Service, personal observation).

Dataloggers (HOBO U24-002 Conductivity Loggers) were placed in the marsh sites on October 24, 2012 prior to the ACOE reducing Thurmond Dam outflows to 3,100 cfs (as measured at the dam) in November 2012. Data were collected until February 9, 2013 to include a range of flows. Interstitial salinity was measured every 15 minutes in double-nested PVC wells installed at each sampling point (Dusek and Kitchens 2003). The sensor on each datalogger was placed approximately 6” below the surface of the emergent marsh in the root zone. To calibrate the dataloggers, an initial measurement was taken within a known conductivity solution (10,000µS/cm @ 25ºC) in conjunction with a YSI meter. Final measurements also were taken within the known solution prior to download. Data were downloaded in the field via a waterproof shuttle. Specific conductance was converted to salinity in parts per thousand (ppt) using the Conductivity Assistant in the HOBO software. We analyzed our salinity data with the intent of building relationships between salinity and average daily discharge at the USGS Clyo gage (USGS gage 02198500), the nearest non-tidal Savannah River discharge gage located at river mile 61.4. Discharge data collected during our study also were compared to data collected by Welch and Kitchens (2006). Welch and Kitchens (2006) indicated that the average growing season (March – October) salinity for the previous year had the strongest influence on marsh community type. Thus, to place our results in the context of prior studies, we compared discharges that occurred during our study to the discharges encountered during the years prior (2001 and 2004) to vegetation sampling (2002 and 2005) in the estuary.

To correctly relate interstitial salinities to discharge data, it was necessary to calculate the water travel time, or lag time, from the Clyo discharge gage to the salinity monitoring stations. This was accomplished by repeatedly correlating time series average daily discharge data with average daily salinity data from SAV2 and SAV3, the two sites with the most salinity variation. Salinity data were repeatedly offset from the discharge data, and correlations were repeated to identify the largest correlation coefficients. Once large correlation coefficients were identified, the number of time steps between the discharge data and the offset salinity data were used to identify the lag time. Time lags were calculated for minimum, maximum, and mean salinities. Time lags and associated correlation coefficients were also calculated for both 20 and 30 day periods.

Because the intent of the study is to examine potential effects of reduced freshwater inflow (a potential drought-related dam management option) on interstitial salinities in the estuary, we focused our analysis on low flows. Visual inspection of Clyo hydrographs during the 2001 and 2012 droughts indicated that flows remained less than 6,000 cfs. Therefore, we focused our analysis on flows less than 6,000 cfs. Multiple regression analysis was used to assess the influence of precipitation (measured at the Clyo gage) and discharge on average daily salinity. Microsoft Excel was used to derive best fit lines between predictor variables and salinity for each site. Best fit lines were then used to predict marsh types for the range of flows likely to be encountered during droughts and future analyses of drought management alternatives. Although best fit lines can be used in a predictive manner, they have the potential to over or under predict substantial portions of the data depending on the data distribution. Hence, we also used local regression curves (LOESS curves with alpha = 0.33) to visually depict relationships between discharge and salinity.

Results

Average daily flows at Clyo varied from 3,920 cfs to 14,600 cfs, and most discharge measurements ranged between 4,200 and 4,800 cfs (Fig. 2). Discharge was generally lower and less variable than discharge measured in the growing seasons of 2001 and 2004 (Fig. 3). Correlations between Clyo discharge and salinity at SAV2 and SAV3 were highest at five daily time steps, indicating that approximately 120 hours is required for water to travel from Clyo gage to the study sites (Fig. 4).

Discharge predicted salinity best at SAV2 and SAV3 (R^2=0.54 and 0.45, respectively). However, at the lowest discharges, salinity is underestimated by the best-fit lines. Salinity increases more per unit discharge decrease when flows are < 4,500 cfs at both sites (Fig. 5). Local estimation functions (i.e. the LOESS curve) provided better visual depictions of the relationship between discharge and salinity at a large range of discharges compared to power functions.

Interstitial salinity was lowest in all wells during higher freshwater flows with salinity increasing as river flows decreased and in the downriver sites. The distinction between estuarine and palustrine emergent wetlands is 0.5 ppt (Cowardin et al. 1979). Salinity exceeded 0.5 ppt in the most upriver sites (SAV1 and SAV2) during the lowest flows below 4,400 cfs and 4,390 cfs, respectively (Table 1). SAV1, the most upstream site, occasionally had higher salinities (0.38-0.59) than SAV2 (0.15-0.85), especially during the higher flows observed and modeled from best-fit lines (Table 1, Fig. 6). Interstitial salinity in SAV3, closest to Rifle Cut, exhibited the greatest range (0.43-1.64) and was twice to three times the values of SAV1 and SAV2 at the lowest flows. Only at flows >5,700 cfs did interstitial salinity retreat to freshwater levels at SAV3. At flows of 6,000 cfs and below, the most downriver site, SAV4, remained in an oligohaline condition ranging from 1.4-1.6 ppt (Table 1, Fig. 7). Flows of >10,000 cfs are required to reduce salinity at SAV4 to freshwater levels. The relationship between time-lagged discharge and salinity is statistically significant at all sites except for SAV4 (Table 2). Inclusion of precipitation amount in multiple regression models was not a significant predictor of interstitial salinity at any site.

Discussion

Salinity is a driving force in the composition and structure of marsh communities in tidal wetlands (Odum et al. 1984, Pearlstine et al. 1990, Bossart 2002 and others). Tidal freshwater wetlands have high primary productivity, high diversity, and are sensitive to changes in salinity, which affects species composition and structure (Odum 1984, Pearlstine et al. 1990, Dusek and Kitchens 2003). The lower Savannah River estuary experienced dramatic changes over the past

100+ years with the loss of approximately 66% of an estimated 12,000 acres of tidal freshwater wetlands (Army Corps of Engineers 2012b). The loss of these freshwater wetlands has been associated with repeated deepening of the shipping channel for the Savannah Harbor to allow larger ships upstream, which also allows intrusion of saltwater farther upstream. Also affecting the upstream movement of the freshwater/saltwater interface is the amount of freshwater flow moving downstream. The Corps regulates flow in the Savannah River through management of three large dams; Hartwell, Russell, and Thurmond. Approximately 58% of the Savannah River watershed is regulated through Thurmond Dam (Wrona et al. 2007). Management of flows through the dams to support multiple purposes altered the timing and magnitude of hydrologic events downstream. This resulted in negative impacts to the resources throughout the Savannah River corridor below Thurmond Dam including reduced freshwater input into the Savannah estuary (Wrona et al. 2007).

Our results are consistent with those of previous studies both before and after the tide gate but with less magnitude of change in response to low flow alone. In addition to the repeated expansion of the harbor and restricted freshwater flow, installation of the tide gate in 1977 and subsequent removal in 1991, has had the most influence in changing salinities and community composition within the estuary (Wetzel and Kitchens 2007). Interstitial salinities varied considerably from the operation of the tide gate ranging from 0.7 ppt in upstream sites to 10.5 ppt downstream with the operation of the tide gate but decreased with the removal of the tide gate to 0.0 ppt to 2.2 ppt (Latham and Kitchens 1996).

Since the removal of the tide gate, research shifted focus to the effects of low flows and management of discharge from Thurmond Dam during drought conditions. Droughts affect interstitial salinity by reducing freshwater flow downstream, thereby facilitating the upstream movement of the saltwater/freshwater interface. This effect has been especially pronounced with two new droughts of record since removal of the tide gate. Dusek and Kitchens (2003) reported changes in interstitial salinities in the Savannah estuary in response to the drought of record from 1998 – 2002 with salinities increasing during the drought as a result of lower flows. Conrads et al. (2006) used M2M applications to simulate interstitial salinity changes in response to water level and salinity variation in the riverine system surrounding the Savannah NWR. Additionally, earlier modeling of interstitial salinity with various flow regimes used average river or channel water salinity extrapolated across the marsh (J. Bossart, Environmental Consulting and Design, personal communication). These simulations tended to over-predict interstitial salinity.

In addition to documenting changes in interstitial salinities, multiple studies documented shifts in marsh communities along the salinity gradient within the Savannah estuary (Pearlstine et al. 1990, Dusek and Kitchens 2003, Latham and Kitchens 1996, Welch and Kitchens 2006, Wetzel and Kitchens 2007). Overall, as salinity increases, diversity decreases. Vegetative community shifts were more pronounced and, in one site, permanent with the operation of the tide gate (Pearlstine et al. 1990, Dusek and Kitchens 2003, Latham and Kitchens 1996, Wetzel and Kitchens 2007). The effects of drought on vegetation communities were less pronounced and tended to be ephemeral (Welch and Kitchens 2006, Wetzel and Kitchens 2007). Welch and Kitchens (2006) observed slight changes in dominant species during drought (2002) and non-drought conditions (2005) with lower diversity during drought and associated higher saline conditions. The structure and composition of the freshwater vegetative communities did change, however, with the loss of subdominants during drought. When flows returned to non-drought conditions the loss of native sub-dominants was replaced by an exotic invasive species, *Murdania kesiak*. Generally, the thresholds of interstitial salinity for community shifts were similar between drought and non-drought conditions.

The vegetative composition as well as soil characteristics surrounding the current sites was not sampled; thus, potential community responses were inferred from past studies. In their development of models predicting vegetation communities in the Savannah estuary during drought and non-drought conditions, Welch and Kitchens (2006) assumed "interstitial salinity was a more direct stressor than river water salinity" and that salinity levels in the prior growing season had the most influence on marsh community type. Additionally, soils and vegetative components were used to classify the distribution of marsh community types. Based on Welch and Kitchens (2006) and using interstitial salinity alone, freshwater marsh community types occur at salinities <1.0 ppt. during the growing season. The duration (four months) and season (fall/winter) of this study probably would not have resulted in detection of changes in the community even if vegetative and soil components were sampled. The flows experienced during this study were exceptionally low and the most upstream site, SAV1, experienced elevations in interstitial salinity similar to those during tide gate operations (Table 1). However, even at the lowest flows during this study, the site only slightly exceeded the defined upper salinity threshold (Cowardin et al. 1979) of a freshwater marsh (0.5 ppt) and remained below freshwater communities defined by Welch and Kitchens (2006) of 1.0 ppt. Both Conrads et al. (2006) and Bossart (2002) showed modeled salinities higher than actual measurements approaching or exceeding 1.0 ppt at SAV1 at flows approximating 4,000 cfs. The site, SAV2, although not a sample point in previous studies, also experienced an increase in interstitial salinity as flow decreased. This site experienced a large range in salinity and a more dramatic salinity increase as flows were reduced. Additional sampling of soils and vegetation is needed as well as a characterization of the topography to help explain this variation. Relying on interstitial salinity alone, it appears the potential vegetative composition for these two freshwater sites would remain relatively fresh with greater diversity especially given that the recent low flows occurred during the non-growing season (Fig. 7, Table 1).

The site, SAV3, showed the most variability in salinities in response to flows and has the potential to change to a more intermediate, transitional site dominated by *Scheonoplectus tabernaemontani* (syn. *Scirpus validus*, ITIS 2013) at flows less than 4,500 cfs based on Welch and Kitchens (2006) modeled communities (Table 1). Modeling efforts by Conrads et al. (2006) showed that this site had the greatest percent change (approximately 300 percent) in response to a 25 percent simulated increase in freshwater inflow. The large change and variability is probably a result of its location near Rifle Cut and a breach in the canal berm that allows channel water direct access to the site. Modeling in relation to the Savannah Harbor Expansion Project showed Rifle Cut to have the single greatest influence on salinity intrusion into Back River (S. Davie, TetraTech, personal communication). Nevertheless, salinities measured during this study are well below those needed to transition SAV3 from a freshwater to a brackish community dominated by *Spartina* or *Bulboschoenus robustus* (syn. *Scirpus robustus*, ITIS 2013) (Fig. 7, Table 1). Additionally, the dominant community type is determined more by interstitial salinities from the previous growing season (Welch and Kitchens 2006). Average monthly growing season flows less than 4,500 cfs have occurred three times since 2000, so it is unlikely that community types will change. The most downstream site, SAV4, remained in an oligohaline condition for all flows below 6,000 cfs and should be dominated by *S. tabernaemontani* at virtually all flows. Similar to SAV3, this site should not move into the more brackish community type dominated by *Spartina* or *B. robustus*.

Summary

This study provides valuable information regarding flow thresholds at Clyo and effects on the timing and magnitude of interstitial salinity changes within the marsh. Based on previous research, the two most upstream sites will remain dominated by freshwater communities with average daily flows as low as 3,900 cfs. However, flows below 4,500 cfs at Clyo will begin to move the two downstream freshwater marsh sites to transitional, oligohaline marsh types. Although the changes from freshwater to an oligohaline community type would most likely be ephemeral, the potential replacement of some freshwater species by exotic, invasive species could result in long-term loss of diversity. Exotic invasive species colonization has the potential to be affected by drought discharge management decisions and should be considered in future drought related assessments and management plans.

This study documents the extremely low flows the Lower Savannah estuary can experience as a result of drought and the management of Thurmond Dam within the framework of the SRBDCP and associated deviations. Although the flow and interstitial salinity was measured during the non-growing season, extrapolation of the potential effects to the marsh during the growing season is important to inform future revisions and updates to the SRBDCP and other plans such as the Savannah River Basin Comprehensive Study. Thus, the results found within this report can be used to quantitatively evaluate and compare flow management alternatives and their relative effects on freshwater sites in the Savannah River estuary.

Two new droughts of record occurred and several severe droughts significantly reduced estuary freshwater inflow for extended periods over the past 25 years. The Savannah Harbor Expansion Project will deepen 35 miles of the existing shipping channel an additional five feet allowing the saltwater/freshwater interface to move farther upstream. Although some mitigation measures associated with SHEP are designed to increase the amount of freshwater into Back River adjacent to the Savannah NWR, the harbor expansion is projected to result in a direct loss of 223 acres of tidal freshwater marsh. The potential scenario of more severe droughts with increasing frequency and the uncertainty associated with the mitigation of SHEP forebodes more severe and long-term stress on an already degraded tidal freshwater system. Intensive monitoring efforts will begin in the near future documenting changes in the estuary with emphasis on the tidal freshwater wetlands during pre-construction, construction, and post-construction phases of SHEP. Interstitial salinity should continue to be monitored with inclusion of our sampling sites and expanded to include edaphic and vegetative characteristics for a more comprehensive understanding of the effects of flow management.

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Figure 1. Location of Savannah National Wildlife Refuge and sampling area within the tidal freshwater wetlands.

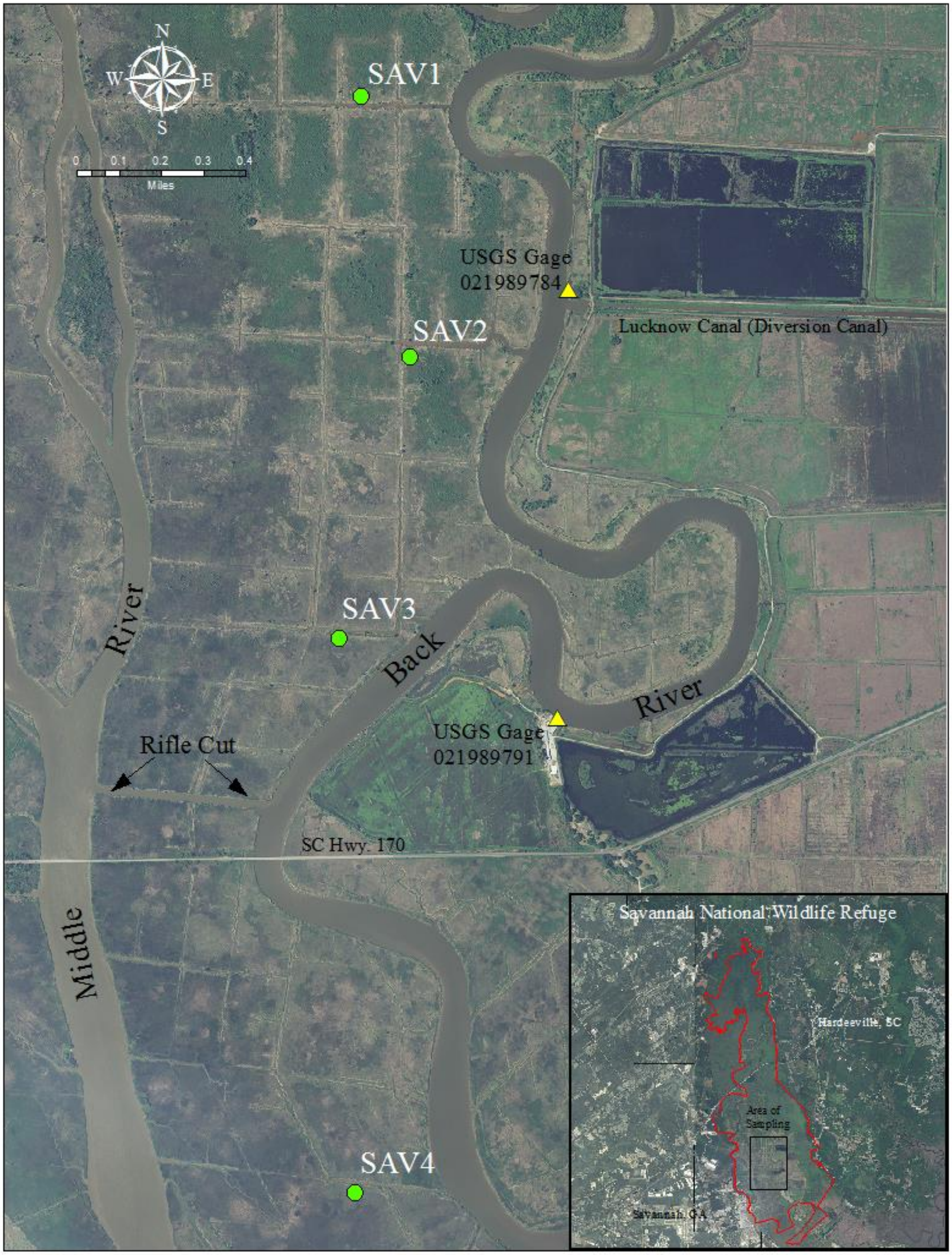


Figure 2. Frequency of discharge (cfs) measured at the Clyo Gaging Station from October 24, 2012 through February 9, 2013.

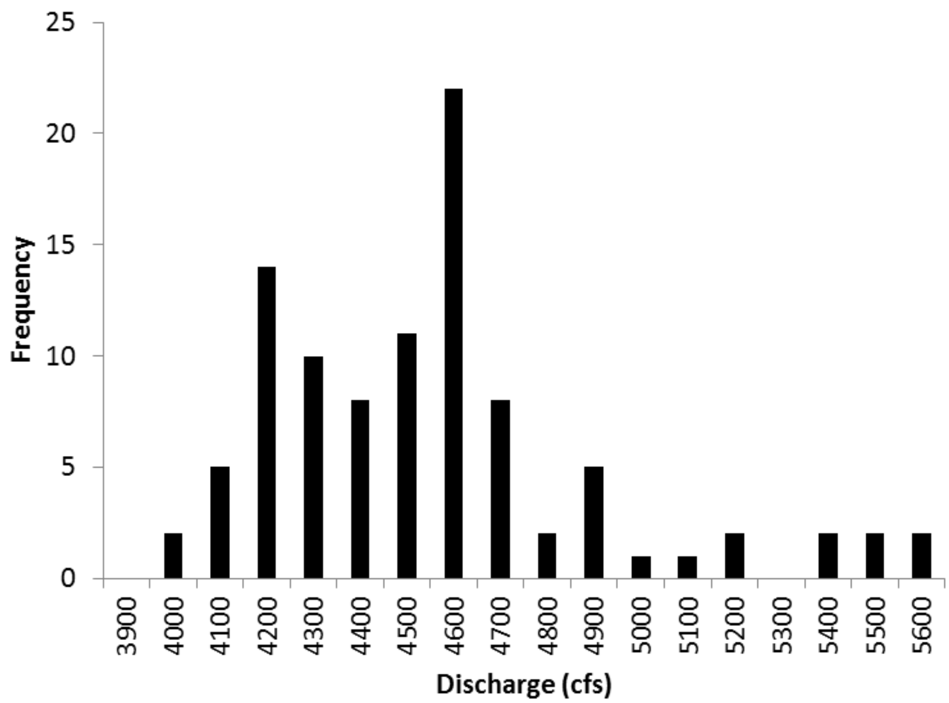


Figure 3. Comparison of growing season freshwater inflows during Welch and Kitchens' study and inflows during FWS salinity study.

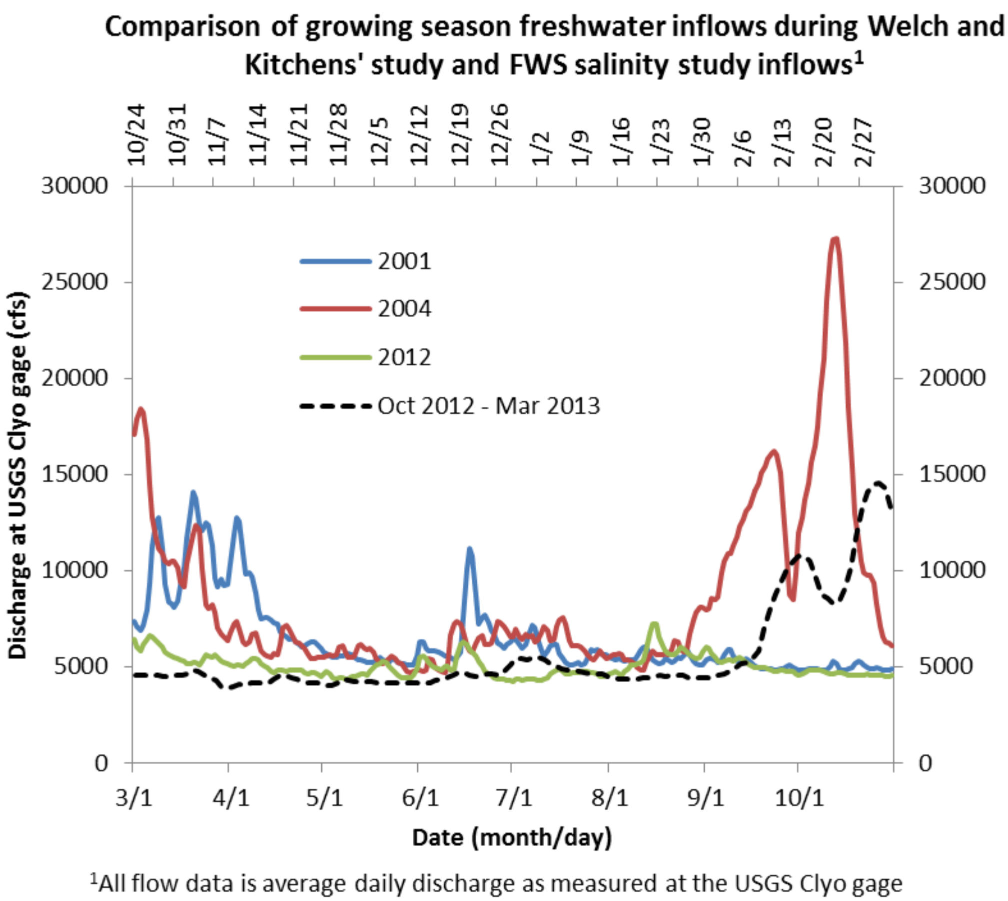


Figure 4. Correlation between Clyo discharge and interstitial salinity at SAV2 and SAV3 indicating a lag time of 120 hrs (5 days) for water to travel from the Clyo gage to the study site.

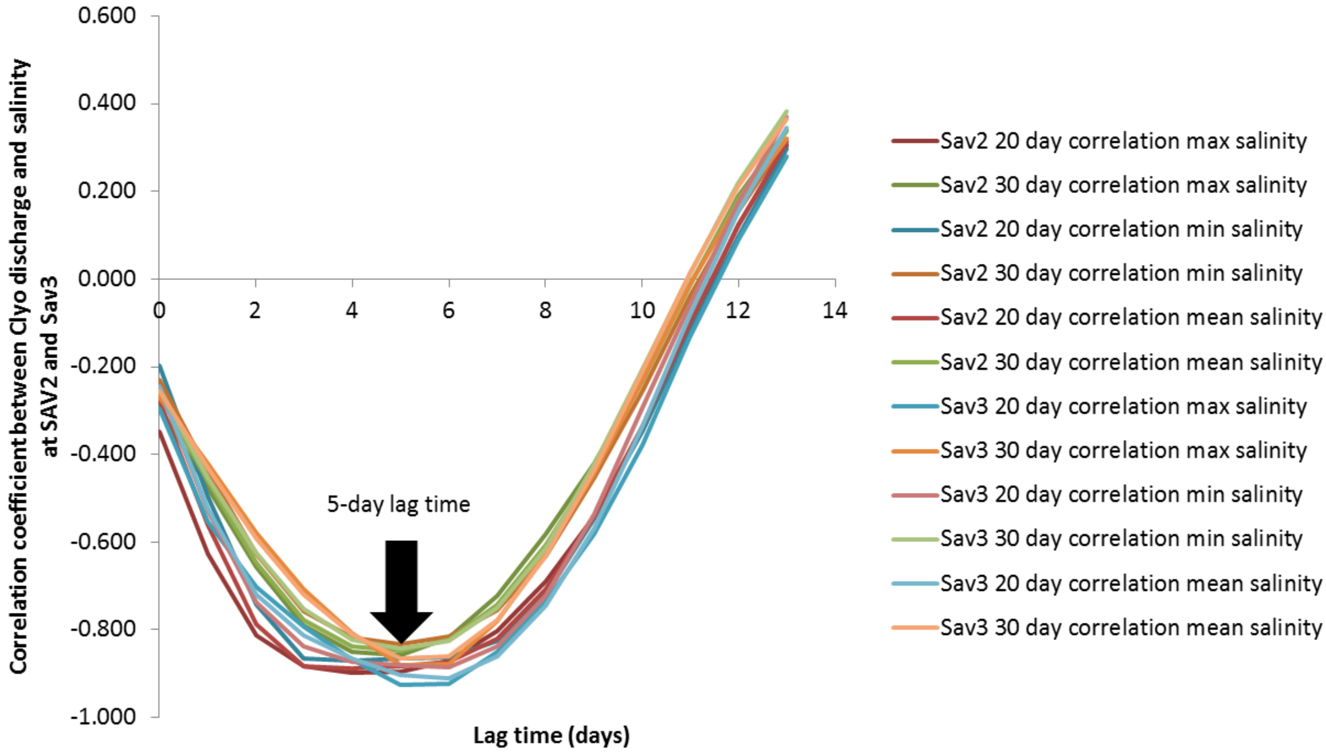
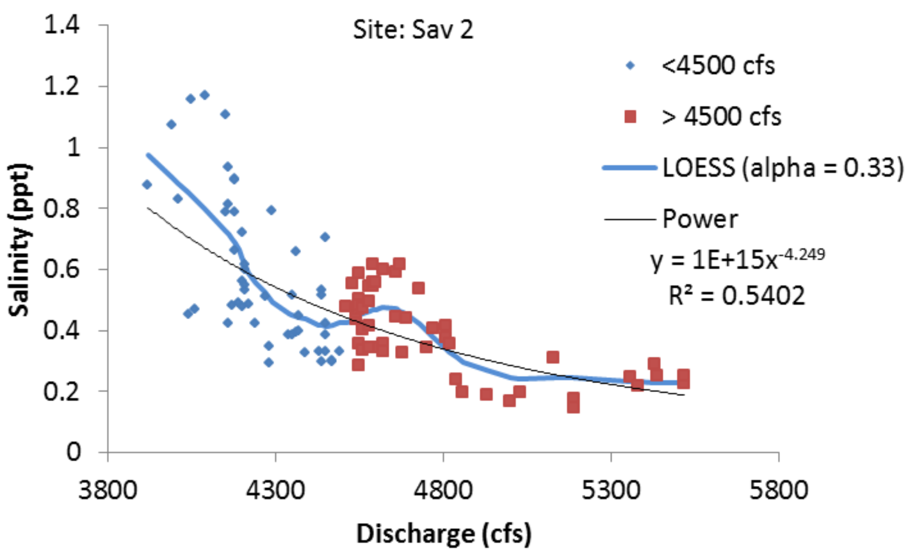


Figure 5. Relationship between average daily discharge at Clyo and salinity at SAV 2 and SAV 3. Best-fit lines (power relationships) are shown, although salinities are generally underestimated at discharges less than 4,500 cfs (blue dots). The local regression (LOESS curve) which provides a better fit is also depicted.



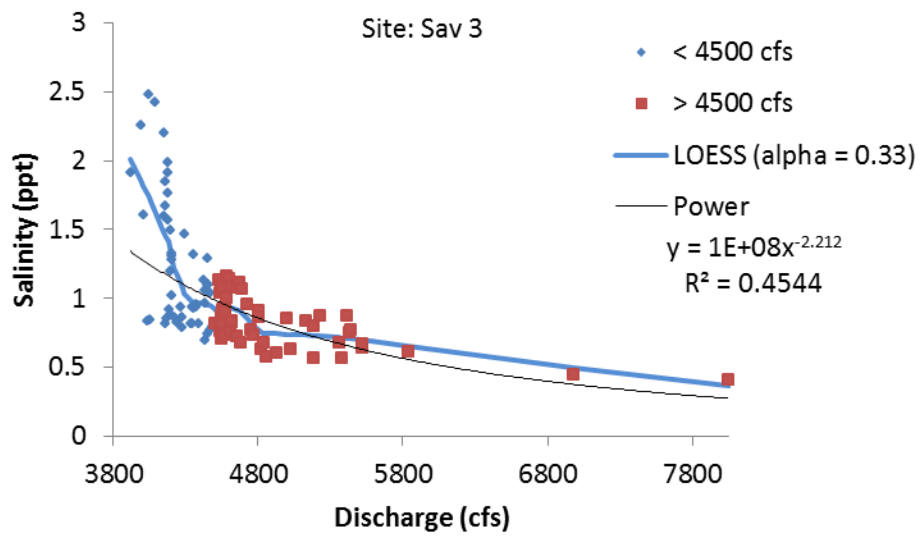


Figure 6. Predicted interstitial salinity of each study site based on discharge as measured from the Clyo gaging station. Relationships were developed from best fit lines, although the local regression curves (LOESS curves) show underprediction of salinity for the lowest discharges at SAV2 and SAV3.

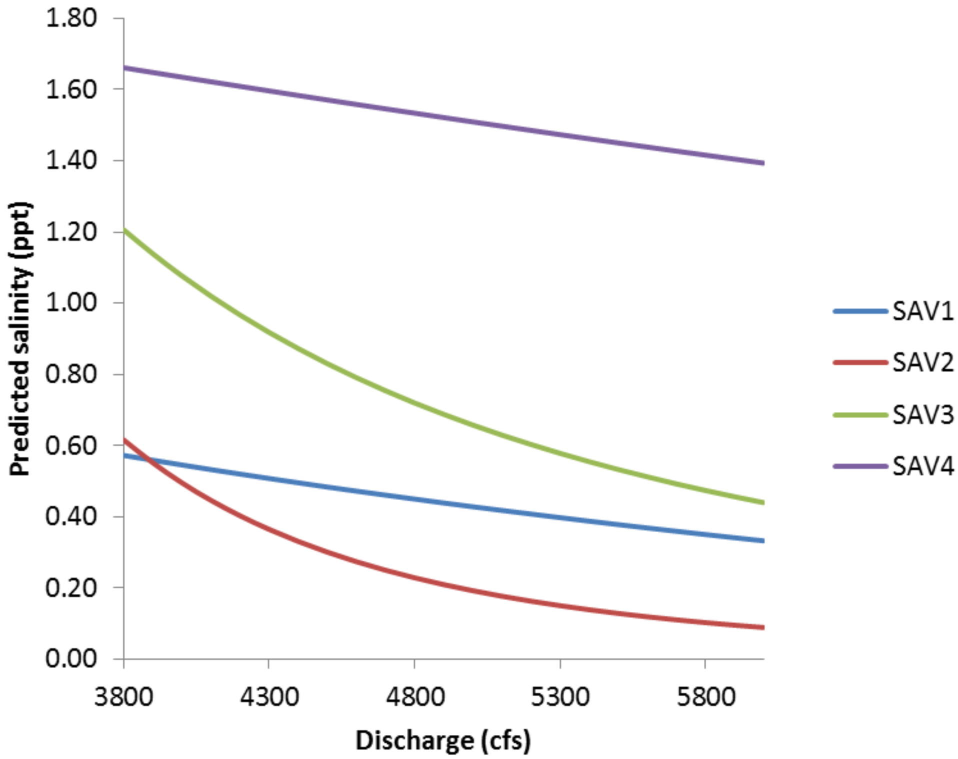


Figure 7. CART model from Welch and Kitchens (2006) showing the distribution of marsh community types identified by a Cluster and Indicator Species analyses for the 2002 (drought). Reprinted with permission.

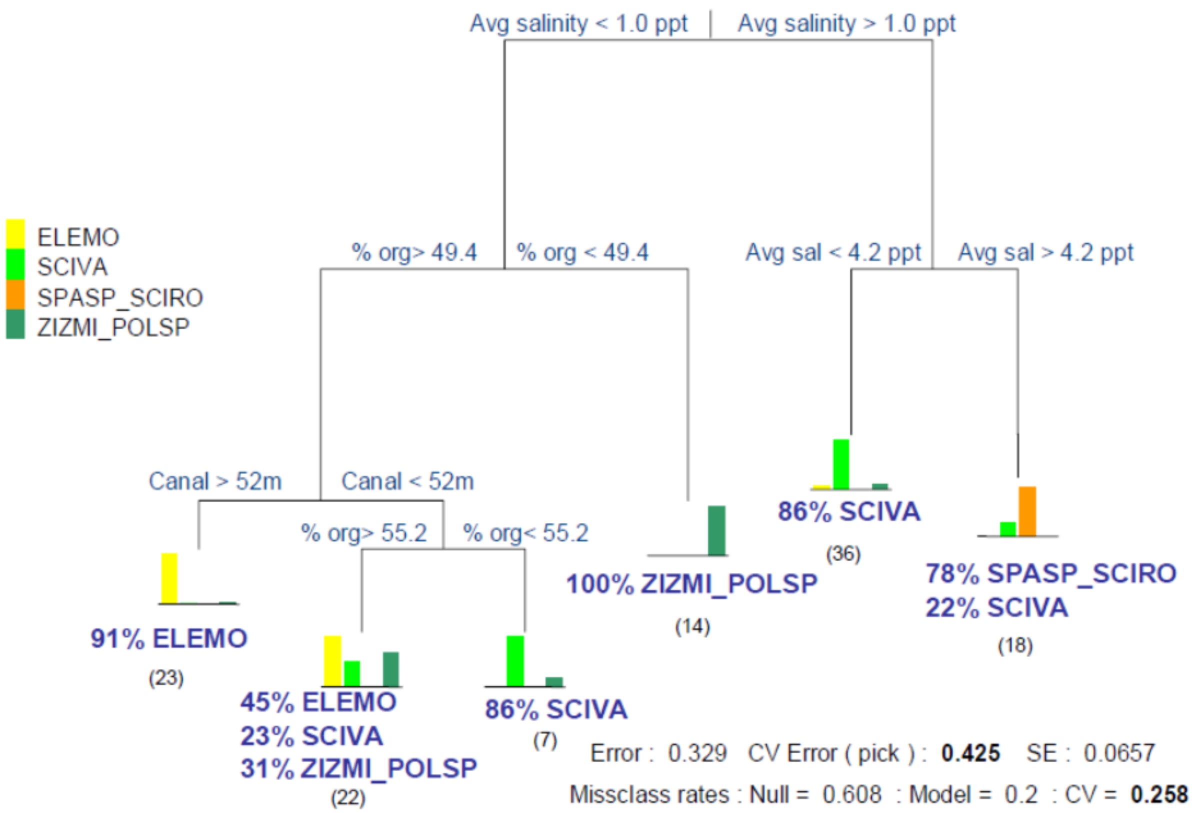


Table 1. Interstitial salinity for the Savannah NWR for the four marsh monitoring sites. Data are predictions from the best-fit lines, although the local regression curves (LOESS curves) show underprediction of salinity for the lowest discharges at SAV2 and SAV3.

	Site			
	Upriver ←		→	Downriver
Clyo Discharge	SAV1	SAV2	SAV3	SAV4
3800	0.57	0.62	1.21	1.66
3900	0.56	0.55	1.14	1.65
4000	0.55	0.50	1.08	1.64
4100	0.53	0.45	1.02	1.62
4200	0.52	0.40	0.97	1.61
4300	0.51	0.36	0.92	1.60
4400	0.50	0.33	0.87	1.58
4500	0.48	0.30	0.83	1.57
4600	0.47	0.27	0.79	1.56
4700	0.46	0.25	0.75	1.55
4800	0.45	0.23	0.72	1.53
4900	0.44	0.21	0.69	1.52
5000	0.43	0.19	0.66	1.51
5100	0.42	0.18	0.63	1.50
5200	0.41	0.16	0.60	1.49
5300	0.40	0.15	0.58	1.47
5400	0.39	0.14	0.55	1.46
5500	0.38	0.13	0.53	1.45
5600	0.37	0.12	0.51	1.44
5700	0.36	0.11	0.49	1.43
5800	0.35	0.10	0.47	1.42
5900	0.34	0.09	0.46	1.40
6000	0.33	0.09	0.44	1.39

Table 2. Relationship between time-lagged discharge and salinity on the four sampling sites in the estuary.

	Does 5-day time lag improve regression results?	Is Clyo discharge statistically significant?	Is precipitation statistically significant?	Best-fit relationship between discharge (x) and salinity (y)[1]	R-squared[1]
SAV1	Yes (~6% of variance)	Yes	No	$y = -0.526\ln(x) + 4.9079$	$R^2 = 0.18$
SAV2	Yes (~15% of variance)	Yes	No	$y = 1E+15x^{-4.249}$	$R^2 = 0.54$
SAV3	Yes (~18% of variance)	Yes	No	$y = 1E+08x^{-2.212}$	$R^2 = 0.45$
SAV4	No	No	No	$y = 2.2519e^{-8E-05x}$	$R^2 = 0.01$

[1]Formula and R-squared value is reported with a 5-day lag time for all sites.