Summary Report Supporting the Development of Ecosystem Flow Recommendations for the Savannah River below Thurmond Dam

June 2003

University of Georgia Team:
Judy Meyer, Merryl Alber, Will Duncan, Mary Freeman, Cody Hale, Rhett Jackson, Cecil Jennings, Monica Palta, Elizabeth Richardson, Rebecca Sharitz, Joan Sheldon, and Richard Weyers

EXECUTIVE SUMMARY

This report was prepared to provide background information for participants in a workshop convened to develop science-based flow recommendations for Thurmond Dam that will enhance ecological conditions in ecosystems of the Savannah River below the dam. In the report we explore the extent of hydrologic alteration and the ecosystem flow requirements for the following reaches of the river: Augusta Shoals, Savannah River and floodplain below Augusta, and the estuary. Flow is clearly not the only regulator of ecosystem condition in these reaches; hence we have attempted to put flows into the context of other anthropogenic factors influencing ecosystem condition.

Hydrologic changes: Thurmond Dam was completed in 1954, and its operation has resulted in significant changes in the flow regime: the natural variation in the hydrograph has dampened; low flows have increased; peak flows have decreased; there is less frequent overbank flow and less extensive floodplain inundation. Other geomorphic changes are associated with navigational use of the river: 40 cut-off bends removed approximately 13% of the Lower Savannah River's original 204 mi (330 km). The construction of upstream dams has resulted in an approximate 10% reduction in mean annual flow due to increased evaporation from the reservoirs. The sporadic nature of the pre-dam hydrograph has been replaced by more predictable behavior. Maximum peak flows at Augusta are less than a third of pre-dam flows; these lower flows are less able to move sediment, shape the channel and deliver water to the floodplain. The pre-dam 2-year maximum flow is equal to the post-dam 100 year flow. Mean monthly flows at Augusta have been reduced during the wetter part of the year.

In contrast to the reduction in peak flows, the magnitudes of 7-day low flows have increased. A 7-day low flow condition that would have been expected every 1.5 years before dam construction is now expected only once in 100 years. The date of low flow occurrence became much more variable following dam construction: dates varied 1-2 months around 26 September pre-dam and now vary 4-5 months around that date. According to IHA (Indicators of Hydrologic Alteration) analyses, the median date of minimum flow has shifted about 3 months toward the beginning of the year. Baseflow has been altered only during the three driest months (August – October), when it is higher with less interannual variability than pre-dam. Smaller alterations in flows have been observed further downstream at Clyo because it receives water from an additional 3600 sq. mi. watershed, and the effects of dam operations are therefore dampened. A preliminary analysis of floodplain inundation has shown that post-dam floods have rarely been significant enough to inundate the floodplain, and the percent of floodplain inundated has decreased dramatically.

The Augusta Shoals reach is impacted not only by Thurmond Dam operations but also by the diversion of water at the Augusta Diversion Dam. In this section of the river, extremely low flows are encountered, particularly on weekends when there is no hydropower generation at the dam. Hence the low flow conditions in this section of the river are lower than pre-dam conditions, which is different than the pattern described for Augusta in the previous paragraph. In addition, the diel variation in flow experienced because of hydropeaking results in unpredictable shallow water habitats. At least 77 fish species use the shoal habitat.

Flow requirements of fishes and molluscs: Effects of flow on multiple life stages of representative fish species are presented in detail in the report (Figures 25 – 32). Flow affects foraging, survival, and spawning migrations of adults; egg, larval, and juvenile development, juvenile growth and survival and movement between habitats are also impacted by flow.

Atlantic sturgeon (*Acipenser oxyrhynchus*) are in the river March – October and spawn in spring and fall in strong current over hard substrates. Hence strong flows allowing sturgeon access to suitable conditions in river bends and shoals during spring and fall spawning would be beneficial. After fall and spring spawning periods, maintenance of flows that facilitate downstream larval drift to the juvenile rearing area at the interface of fresh and salt water would also enhance sturgeon populations.

Shortnose sturgeon (*Acipenser brevirostrum*) are found between mile 12.9 - 30.3 (km 20.8 - 48.9) but move downriver to mile 3.4 (km 5.5) in winter and upriver in spring spawning runs, which occur late January - March. Probable spawning sites are channel curves from mile 111 - 118 (km 179 - 190) and mile 170.5 -172.4 (km 275-278), although it is possible that spawning would occur in Augusta Shoals if their passage were not impeded by New Savannah Bluff Lock and Dam and if spring flows above 2600-2700 cfs occurred in the shoals. Availability of cool water refugia may be critical in summer. Juveniles are found near the fresh/salt water interface in salinities ranging from about 0.1 to 5 PSU.

Robust redhorse (*Moxostoma robustum)* likely spawn in shoal habitats and over medium-coarse gravel bed sediments from April through June; flows of 3600 cfs during spawning season in the shoals achieve maximum spawning habitat. The existence of persistent low-velocity habitats is essential to enhance survival of early life history stages, especially during May and June.

Striped bass (*Morone saxatilis*) seek cool water refuges during summer and move upstream to spawn from February through June. Like sturgeon, their passage to Augusta Shoals is impeded by New Savannah Bluff Lock and Dam, so flows allowing movement between estuary and shoals may increase available spawning habitat. Eggs and larvae drift downstream with the current from March to June. Back and Middle rivers of the estuary are nursery areas, and the Front River may be important as well.

American shad (*Alosa sapidissima*) use the river for spawning from January through April. Eggs and larvae drift downstream, and juveniles migrate out of the river in late fall or early winter.

American eel (*Anguilla rostrata*) adults migrate from upstream foraging habitats to the ocean in early spring and elvers migrate into the river in late spring. Flows that allow juvenile eel foraging access to main channel, feeder creek, flooded marsh and floodplain habitats may promote their growth.

The Savannah River system provides habitat for 32 mussel species, most of which are gravid from May to July. Flow requirements are not well known, but some species prefer sand and gravel whereas others prefer mud and silt. Declines in mussel populations may reflect declines in populations of their host fish species, many of which are unknown. Hydropower peaking may reduce juvenile mussel recruitment in the reaches experiencing flow fluctuations.

Floodplain processes: The number of fish species using Savannah River floodplain habitats is estimated at 81-89. Allowing seasonal access to the floodplain would facilitate reproduction for 22-58 species of fishes; 43 taxa have peak larval abundance in spring, 19 in summer, and 2 in winter. Seasonal flooding may also provide forage and refuge habitat for an additional 31 species. Inundation in winter and early spring is the most critical time. Higher low flows may reduce or prevent floodplain drainage, especially in areas affected by dredging and levees. Oxbows are important sites for recreational fishing.

Floods during October through February are important for seed dispersal of floodplain tree species such as bald cypress (*Taxodium distichum*) and water tupelo (*Nyssa aquatica*). In contrast, floods during May - July inhibit seed germination and reduce recruitment of these species. Diameter growth of tupelo is inversely related to mean water levels during the growing season; and cypress growth is greater in shallow vs. deep-water habitats. Studies of size structure of cypress populations in the Savannah River floodplain indicate little recruitment into the population in recent decades. The absence of winter flooding can permit the invasion of flood-intolerant upland species as well as invasive exotics such as Chinese tallow tree (*Sapdium sebiferum*). Bird species such as prothonotary warbler and Mississippi and swallow-tailed kites risk loss of nesting and foraging habitat with decline of bottomland hardwood tree species. Interconnections between upland and floodplain habitats are essential for many reptiles and amphibians.

Estuary: Alterations in river flow can have profound effects on estuarine conditions such as salinity, mixing patterns, transit times, and supply of nutrients. These changing conditions impact estuarine resources. We review several approaches to setting freshwater inflow standards: limiting upstream withdrawal to a certain proportion of river flow; basing inflow standards on requirements of specific resources (e.g indicator species or relating flow to historic catches of fish species); and setting standards such that a certain level of salinity is maintained at a given point in the estuary. Maintaining freshwater marshes with their higher biotic diversity above specified locations in the Savannah River is an approach worthy of careful consideration. This approach would require attention to the changes in salinity distribution within the estuary, in particular the 0.5 PSU high tide surface contour. The location of this contour is affected not only by river flow, but also by the proposed harbor deepening.

To explore the effect of flow alterations on movement of the 0.5 PSU contour, we used the output from different model flow scenarios reported in the Environmental Impact Statement for harbor deepening. One example of the effect of harbor deepening (to 50 feet) on the 0.5 PSU bottom salinity contour is that in the Front River deepening is equivalent to reducing average river flow at Clyo by 4300 cfs; the effect on the surface salinity contour is equivalent to a 2200 cfs reduction in flow. It is unlikely that changes in releases at Thurmond Dam toward pre-impoundment conditions would be great enough to overcome the effects of harbor deepening.

Conceptual models: The final section of the report presents conceptual models of the effects of flow regulation on the three reaches of the river, which are detailed in Figures 34 - 36. Reservoir operations combined with flow diversion lead to lower baseflows, higher daily flow fluctuations, and reduced sediment delivery in the Augusta Shoals reach (Figure 34). These changes impact access to and availability of fish spawning habitat, availability of suitable shallow water rearing habitat for juvenile fishes, conditions suitable for mussel growth and reproduction, and vulnerability of Shoal spider lily to grazers; the result is an altered biotic community. Reservoir operations and past dredging activity have altered the exchanges between the Savannah River and its floodplain (Figure 35). Higher stream banks and lower peak flows have reduced floodplain inundation in some areas and obstructed floodplain drainage in others resulting in reduced spawning and foraging habitat for floodplain fishes and reduced transport of floodplain tree seeds. Higher flows during the growing season and reduced floodplain drainage in some areas have reduced germination and establishment of floodplain trees, which increases the probability of invasion by upland species and flood-intolerant exotics. In the estuary (Figure 36), dam operations combine with harbor deepening to alter salinity distributions and current velocities with resultant impacts on the area of freshwater marsh as well as habitat availability for shortnose sturgeon and striped bass and the production of shrimp and crabs.

Summary Report Supporting the Development of Ecosystem Flow Recommendations for the Savannah River below Thurmond Dam

June 2003

University of Georgia Team:
Judy Meyer, Merryl Alber, Will Duncan, Mary Freeman, Cody Hale, Rhett Jackson, Cecil Jennings, Monica Palta, Elizabeth Richardson, Rebecca Sharitz, Joan Sheldon, and Richard Weyers

Hydrologic alteration from hydropower operation and channel modification has changed the structure and function of floodplain and aquatic ecosystems of the Savannah River. In this report we explore the extent of hydrologic alteration and the ecosystem flow requirements for three reaches of the river below Thurmond Dam: Augusta Shoals, Savannah River and its floodplain below Augusta, and the estuary. This Summary Report was prepared to provide background information for participants in a workshop held on April 1-3, 2003 in Augusta, Georgia. The report was revised in response to reviews from workshop participants. The purpose of the workshop was to develop science-based flow recommendations for Thurmond Dam that will enhance ecological conditions in ecosystems below the dam. A separate report summarizing conclusions reached at the workshop is available at www.rivercenter.uga.edu and is entitled Ecosystem Flow Recommendations for the Savannah River below Thurmond Dam. These reports are products of a collaborative project of The Nature Conservancy, U.S. Army Corps of Engineers, U.S. Fish and Wildlife Service, and the states of Georgia and South Carolina. This report is based on an extensive bibliographic review of priority information resources relevant to the development of ecosystem flow recommendations on the Savannah River (January 2003 report, also available at www.rivercenter.uga.edu).

The Summary Report is divided into five sections (principal authors):

(1) River Hydrologic Regime and Floodplain Inundation Patterns (Hale and Jackson)

(2) Effects of Flow Regime on Riverine and Diadromous Fishes (Duncan and Freeman)

(3) Effects of Altered Flow Regimes on Floodplain Processes (Palta, Richardson, Sharitz)

(4) Effects of Flow Regime on Biological Processes in the Estuary (Sheldon, Alber, Jennings, Weyers)

(5) Conceptual Models of Effects of Flow Regulation on Three Regions of the Lower Savannah River (All)

Figures and Tables are presented in a final section. There are two appendices.

(1) River Hydrologic Regime and Floodplain Inundation Patterns

This section of the report uses existing flow and river morphology data to evaluate how the Savannah River reservoir system and navigational dredging have altered the hydrology and form of the river over the last 50 years. The operation of the dams has significantly changed the natural flow regime in the lower river. The extremes in the natural variation in the hydrograph have been dampened; low flows have increased; peak flows have decreased; and the frequencies of low and peak events have decreased. In general, less frequent overbank flow and less extensive floodplain inundation was observed in the post-dam period. In addition to these hydrologic alterations, the lower Savannah has been directly modified through dredging and channelization to allow barge traffic to reach Augusta. An IHA analysis (Indicators of Hydrologic Alteration, The Nature Conservancy 2001) has been used to compare ecologically relevant components of the flow regime for pre- and post-dam periods of record in the Savannah River. This analysis is consistent with our other findings regarding ecologically significant hydrologic changes in the river.

SITE DESCRIPTION

The Savannah River Basin drains 10,600 square miles (27,575 km^2) and is comprised of portions of North Carolina, South Carolina, and Georgia. The headwaters originate in the Blue Ridge Mountains and flow into the Seneca and Tugaloo Rivers. These rivers join and are then impounded by Hartwell Dam to create Lake Hartwell. The Savannah River begins below this reservoir and flows across the Piedmont where it is dammed two more times. It then crosses the Fall Line at Augusta Shoals and flows through the Coastal Plain before discharging into the Atlantic Ocean at Savannah, GA.

The Lower Savannah River stretches from below Thurmond Dam (just north of Augusta) to the estuary (beginning below Houlihan Bridge on Hwy 17) and collects water from 3,600 square miles (9,365 km^2) below Thurmond Dam. The reach is 181 miles (292 km) in length (USACE, 1992).

There are a number of USGS gages along the Lower Savannah River (Table 1). Our analysis focused on records from USGS gage #02197000, located at river mile 187 (km 302) (Savannah River at Augusta), and #02198500 located at river mile 60 (km 97) (Savannah River near Clyo), because these records begin at least 20 years prior to dam installation. The longer pre-dam record gives us greater confidence in the metrics of hydrologic change generated from these data. Flows at the two gages are highly correlated, but there is about a 9 day lag between flow peaks at Augusta and flow peaks at Clyo. The hydrograph lag between the gages is illustrated in Figure 1 showing an annual hydrograph for both gages. Regressions between the two gage's daily flows were used to determine the most consistent lag-time between the two gages. Figure 2 shows how Augusta and Clyo flows compare using a 9-day lag-time, which gave the strongest correlation between the two gages. Because of the fairly consistent relationship between flows at these two gages, inverse-distance weighted average could be used to estimate flows at river locations between these gages.

MODIFICATIONS

Since the early 1900's, the river has been altered in several ways to meet growing demands of human populations in the basin. Throughout most of the 20th century, the river was channelized and dredged to facilitate navigational needs from Savannah to Augusta. Dredging and channelization have severely modified the Lower Savannah River's original form. The Corps of Engineers commenced dredging operations in the 1950's to maintain a navigation channel nine feet deep and ninety feet wide from river mile 21.3 to 202.2 (km 34.3 to 326). These operations ceased in 1979 due to a lack of demand for barge traffic between Savannah and Augusta (USACE, 1992). The Corps of Engineers has identified forty cut-off bends that were created to shorten and straighten the navigation route (Table 2). The creation of these cuts has removed approximately 13% of the Lower Savannah River's original 204.4 miles (330 km). Reconnecting the cut-off bends to the main channel is a possibility for mitigating problems resulting from their removal. The Corps of Engineers completed partial restoration of bend 3 and the Mill Creek entrance in 2002. They currently hold authorization to restore 11 additional cut-off bends.

Channel configuration has been altered by dredging activity and probably also as a result of dam construction. Upstream reservoirs trap sediment and release "sediment hungry" water that increases downstream channel degradation (Simons 1979). Channels can be deepened and straightened, and the removal of fine sediments can result in armoring of the bed. Aggradation can occur below tributaries carrying a high sediment load because of modifications of the main channel configuration (Maddock 1976). These changes in the channel are likely to have influenced habitat for fishes and invertebrates. Even though channel dredging has been halted, these other impacts of an altered sediment regime are likely to persist.

Dam construction has also altered the river's flow regime, and this is the impact that is most fully explored in this report. Since 1954, three dams have been installed on the Savannah River for the purposes of reducing flood damage, creating recreational opportunities, creating habitat for fish and wildlife, generating hydropower, and supplying water for the public (Augusta, GA, Savannah, GA, and Beaufort and Jasper Counties of SC). Hartwell Dam, which creates Lake Hartwell, is the northernmost dam and was completed in 1963. The next impoundment is Lake Russell, which was filled in 1983 after the completion of the Richard B. Russell Dam. The flows released from these two dams are of little importance to the flow modifications to the Lower Savannah River because of the presence of Clark Hill (Strom Thurmond) Reservoir, which is impounded by Thurmond Dam. The oldest of the three, Thurmond Dam was completed in 1954. It re-regulates the flows released from the upper two dams making their management regimes not directly relevant to flows in the Lower Savannah River. Therefore, in dealing with flow modifications to the Lower Savannah River we will only consider releases from Thurmond Dam. Flow in the Augusta Shoals reach is also reduced by water diversions into the Augusta Canal via the Augusta Diversion Dam. Those hydrologic modifications are addressed in the section dealing specifically with the Augusta Shoals reach (Part 2).

The current Corps release requirements for Thurmond Dam vary depending upon climate conditions and time of year. During times of drought there are three action levels. Level 1 occurs when the pool elevation drops to 325 ft-NGVD and a public notification is made. Level 2 occurs when the pool elevation drops to 322 ft-NGVD and discharge at Thurmond Dam is consequently reduced to 4500 cfs. Level 3 occurs when the pool elevation drops to 316 ft-NGVD and discharge at Thurmond Dam is reduced to

3600 cfs. It is our understanding that the Corps does not allow discharges below these flow rules. During flood conditions there are four control stages. Releases are to be limited so as not to exceed 20,000 cfs at Augusta when at the minimum flood control pool. When the water level is between the minimum flood control pool and 330 ft-NGVD, flow is to be maintained at 20,000 cfs or flow equal to the peak of local flow between Thurmond Dam and Butler Creek, which ever is greater. For pool levels between 330 and 335 ft-NGVD, releases are to be limited so as not to exceed 30,000 cfs. For elevations exceeding 335 ft-NGVD, releases are via the spillway.

This report does not discuss potential impacts of interbasin water transfers on ecosystem conditions in the Savannah River . The extent of this impact will be a function of the amount and timing of water removal from the basin by the states of Georgia and South Carolina. The report and workshop focussed on river flows that are necessary to sustain healthy ecosystems; clearly both dam operations and water withdrawals would need to be incorporated into a management plan to achieve those desired flows.

CHANGES IN FLOW REGIME

Upon completion, Thurmond Dam immediately modified the natural flow regime of the Lower Savannah River in several ways. The hydrograph became very dampened, meaning that the previous variation in flows was reduced. Peak flows, which are essential for floodplain inundation and channel flushing, were reduced significantly. Additionally, low flows increased, reducing the frequency and severity of low flow periods in the river. The dams also caused an approximate 10% reduction in mean annual flow due to increased evaporation (Table 3).

Figures 3 and 4 illustrate the dampening affect the dam has on the annual hydrograph. The difference in the peaks and troughs can be seen to be in excess of 90,000 cfs in the pre-dam hydrograph, while the maximum observed difference in the post-dam hydrograph is approximately 45,000 cfs. The peaks and troughs are not only reduced, but the natural flashiness of the hydrograph has been almost entirely removed. These graphs show that the sporadic nature of the pre-dam hydrograph has been replaced by a much more predictable behavior.

Annual peak flows have been curbed sharply since the installation of Thurmond Dam. Similar to the pre- and post-dam hydrograph, Figure 5 shows a reduction in both peak flows and their variation. The maximum peak flows observed before the dam was installed have been reduced by a factor greater than three. Figure 6 shows the peak flow time series for the adjacent, unregulated Edisto River. The variation in peak flows remains throughout the period of record, indicating that the loss in variation seen in the Savannah River is not a function of climate change. Without significant flood pulses, the river loses its ability to move sediment, flush woody debris, naturally shape its channel, and deliver water to the floodplain.

The flow return period of the Lower Savannah River has been increased as a result of regulation at Thurmond Dam. There are some very large peaks in the pre-dam record that shift the peak flow distribution upward in the pre-dam period regardless of dam operations. In order to isolate the effects of the dam, the USGS generated simulated unregulated peak discharges for the post-dam annual peaks from 1952-85 (USGS 1990). These data allow us to not only compare pre- and post-dam records, but also allow a comparison of peaks that "would be" if the dam were not in place. The simulated unregulated recurrence curve illustrates the fact that until the 10-yr flood event the river would have behaved the same post-dam as it did before. Figure 7 illustrates that the pre-dam 2-year flow and the post-dam simulated unregulated 2-yr flow are approximately equal to the post-dam 100-year flow. Flows that used to occur every other year are now occurring only once in a hundred years. It has been suggested that climate change may be partly responsible for the observed reduction in peak flows in the Savannah. To investigate this, we estimated climate effects by using flow data from nearby unregulated rivers. The peak flow time series and the separated flow recurrence curves for the adjacent Edisto River do not indicate a significant climate effect on flows in the post-dam period (Figure 8).

An analysis of the temporal distribution of peak flows was necessary to determine what effects Thurmond Dam has had on the timing of these events. For peak flows, a histogram was developed to show the frequency with which maximum annual flows occurred in each month (Figure 9). Minor shifts in timing of peak flows have occurred since the installation of the dam. Winter peaks occur a little later, and late summer peaks have nearly disappeared.

The dam has also modified the natural hydrology experienced during drought conditions. Figures 10 and 11 illustrate that the 7-day low flows (derived by Dr. John Dowd's RiverStat software) have increased since dam installation. The annual pre-dam low flow now occurs only once every 5 to 7 years. Even more remarkable is the fact that the current 100-year, 7-day low flow is approximately equal to the pre-dam's 1.5-year low flow. The timing of these low flow events is important to many biological processes. In order to determine whether dam installation caused a shift in the timing of low flows, the average pre-dam day of occurrence was determined for the 7-day low flow. From this, each year's low flow date was plotted as a deviation forward or backward from this mean. The date of low flow occurrence became much more variable following dam construction (Figure 12). Prior to dam construction, date of occurrence of the 7-day low flow varied 1-2 months either earlier or later than the mean date of 26 September. After dam construction, the range extended to 4 – 5 months around that mean date, i.e. 7-day low flows have been observed from May through January.

Mean monthly flows are a useful tool for quantifying how flows have changed over the long term. Mean monthly flows at Augusta have been reduced during the wetter portion of the year since the dam has been installed (Figure 13a). This could be attributed to several factors: change in climate, increased water usage from Clarks Hill Reservoir, the filling of the two upper reservoirs, or evaporation out of the reservoirs. A USGS study adjusted the flood record for the period of regulation to simulate unregulated flow, and concluded that there were 12 large flooding events prior to dam installation that were not present in the post-dam simulation (USGS 1990), suggesting some change in climate conditions. However, the mean monthly flows for the unregulated Oconee River did not decline as severely as those in the Savannah River at Augusta (Figure 14). This suggests that the reduction in mean annual flow is a function of reservoir installation rather than climate. Estimates of evaporative loss for each reservoir (Table 3) indicate about a 10% reduction in mean annual water yield resulting from reservoir construction. Less change in mean monthly flows pre- and post-dam have been observed further downstream at the Clyo gage (Figure 13b). This gage receives water from a large watershed area (~ 3600 square miles) that is unaffected by the dam, so the effects of dam operations are dampened.

A baseflow separation was performed to determine how baseflows have changed since the installation of Thurmond Dam. The average monthly baseflow was determined and then plotted across the period of record. Baseflows responded to the presence of the dam only during the three driest months (August, September and October in Figures 15, 16 and 17). During these months, baseflow is somewhat higher and much more predictable (i.e. less inter-annual variability) than in the earlier part of the record.

IHA RESULTS

The results of the IHA analysis support the preceding information and provide insight into other factors associated with hydrologic alteration. The model has been run on data from USGS gage #02197000 (Savannah River @ Augusta) for two time series comparisons. One output (Run 1) evaluates changes in hydrology based on comparing data from 1884-1953 to data from 1954-2000 (pre- and post-impact, USGS gage #02197000). Another output (Run 2) was made using the same pre-impact data, but using data from 1984-2000 for the post-impact period. The latter interval was chosen because the third dam on the Savannah (Russell) was not in operation until this point. The IHA scorecard first gives a comparison of general hydrologic characteristics followed by an analysis of several different parameter groups. Detailed model outputs are included as Appendix 1.

The general hydrologic output includes a comparison of mean annual flow, flow predictability, and flood-free season. Run 1 indicates that the mean annual flow has decreased approximately 10% during the post-impact period, flow predictability has increased 16% as a function of regulation, and the chance of experiencing a flood-free season has increased by a factor of 2. Run 2 indicates that the mean annual flow has decreased approximately 15% during the post-impact period, flow predictability has increased 11%, and the chance of experiencing a flood-free season has increased by a factor of 9.

Parameter Group # 1 evaluates changes in median monthly flows. The comparison for Run 1 indicates that dry-season flows have increased and wet-season flows have decreased (Appendix 1). The same pattern is observed in Run 2.

Parameter Group #2 determines the change in low and high flows for different time increments. In the first run, the median value for the 1-day, 3-day, and 7-day minimum flow has at least doubled. The 30-day, and 90-day minimum flow has increased by 80 and 40% respectively. Conversely, the median maximum flows for the same categories have all decreased so that 1-, 3-, and 7-day maximum flows are less than half of pre-dam values and the 30- and 90-day maxima are about 3/4 of pre-dam flows (Appendix 1).

Parameter Group #3 defines whether there has been a shift in the median date of occurrence for the annual minimum and maximum flows. Run 1's date of minimum flow shifts 85 days toward the beginning of the year and Run 2's date shifts 99 days in the same direction. The maximum flows for both runs shift only several days later in the year. The degree of interannual variability in these shifts can be seen in Figure 12.

Parameter Group #4 addresses the number of times a low pulse and high pulse threshold has been exceeded. It also addresses the duration of these events. The low pulse threshold was set to 4510 cfs for both runs. Flow for Run 1 dropped below the set threshold a median of 14 times annually before the installation of the dam compared to 0 times since. The median durations are 4.8 and 0 days respectively. Run 2 shows that the flow dropped below the threshold 10 fewer times each year in the post-impact period than in the pre-impact period. The median durations are 4.8 and 1.4 days respectively. There is no significant difference in the count or duration of high pulses (defined as >10,800 cfs) for either run.

Parameter Group #5 analyzes the rise rate, fall rate, and number of reversals. Both runs indicate the pre-impact median rise rate was about three times that of the post-impact rate. The post-impact median fall rate for both runs is approximately half of the pre-impact rate. Run 1 shows the median number of reversals in the hydrograph to have increased by 15 for the post-impact period. Run 2 shows no increase. These analyses are based on mean daily flow data and hence are not sensitive to the diel changes in discharge with hydropower generation experienced immediately below the dam and in the Augusta Shoals reach (see Part 2).

FLOODPLAIN INUNDATION PATTERNS

A floodplain inundation analysis was conducted to help participants in the workshop understand the implications of Thurmond Dam operations on the Lower Savannah River floodplain. An in-depth analysis was beyond the capabilities and budget of this project. In lieu of this, we're providing a rough estimate of floodplain inundation for four sites along the Lower Savannah River. While we feel very confident in all the hydrologic analyses that have been provided up to this point, this inundation analysis is based on several suspect assumptions. This analysis serves as a relative assessment of floodplain inundation trends, and it should not be considered absolutely accurate.

Methods

Four sites along the valley were chosen by team members to represent various ecological considerations. Site 1 is located at River Mile 179.3 (km 289.2), about 8 miles below New Savannah Bluff Lock and Dam. Site 2 is located at River Mile 128.8 (km 207.7), near the confluence of Three Runs Creek. Site 3 is located at River Mile 96 (km 154.8), near the confluence of Brier Creek. Site 4 is located at River Mile 52.6 (km 84.8), about 8 miles below the USGS gage at Clyo (Hwy 119).

Cross-sections were then developed for these sites. USGS topo maps were used in finding elevations and distances for the floodplain. US Army Corps of Engineers Navigation charts were used to obtain in-channel cross-sections. These data were combined and input into HEC-RAS 3.1 to develop a rating curve for each site. Each cross-section was run independently, essentially using Manning's equation. No backwater analysis was conducted. Roughness coefficients were roughly calibrated with previously developed rating curves at three USGS gage sites (Augusta-02197000, Millhaven-02197500, and Clyo-02198500).

A peak flow-time series was synthesized for each site. This was accomplished by inverse-distance weighting USGS peak flow data from gage #02197000 and #02198500 for each site(Savannah River @ Augusta and @ Clyo respectively). A peak flow was determined at each site for every year from 1925-2000.

Using the rating curves and the synthesized peak flow data, stage estimates were predicted for each year's peak flow. These stage estimates allowed us to analyze peak flood stages for our period of record. We also used these stage data in conjunction with the cross-sections developed in the HEC-RAS model to analyze percent cumulative floodplain inundation across the four sites. For each year we measured the total length of floodplain inundated at each site. We then added these figures and divided by the total length of floodplain for the four sites combined. One analysis was performed assuming that water table rise would cause floodplain inundation even if the river did not overtop its levy. A second analysis was run assuming that there was no water table rise, and flooding occurred only when the river overtopped its levy.

Results

We found post-dam floods have rarely been significant enough to inundate the floodplain (Figures 18 through 21). Also, the percent of the floodplain inundated has decreased dramatically since the installation of the dam (Figures 22 and 23). Our calculations are conservative and have most likely under-predicted the frequency and magnitude of flooding events at these sites. However, these figures illustrate the basic trend in flooding events, which is a post-dam reduction in both frequency and magnitude of floodplain inundation.

We have no floodplain inundation records with which to calibrate or verify these model results. It is Rhett Jackson's opinion that these results underestimate inundation for the entire period. The randomly selected cross-sections do not include the low points on the river banks through which floodwaters move onto the floodplain. However, the general trend of less frequent overbank flow and less extensive floodplain inundation is certainly correct.

(2) Effects of Flow Regime on Riverine and Diadromous Fishes

We have divided the river into three major sections (Augusta Shoals, river and floodplain below Augusta, and estuary) because of the habitat complexity and biological significance of each. Maps of each section of the river and floodplain (showing landuse and roads) are included in Appendix 2. This section emphasizes the relationship of flow to fish and mussel life history attributes in the Augusta Shoals area and the river and floodplain below Augusta.

AUGUSTA SHOALS

Shoals typically harbor high species richness of fishes and mussels, owing in part to the complexity of habitats within them. Prior to mainstem impoundment, shoals existed in the Savannah River from the city of Augusta upstream to the mouth of the Tugaloo River, a distance of approximately 110 miles (177 km) (Brown, 1888). The only extant shoal habitat in the Savannah River is a 4.5 mile (7.2 km) reach extending downstream from the Augusta Diversion Dam. Other shoal habitats from river mile 205.3 to 312.2 (km 333.1 to 503.6) are submerged under mainstem impoundments created by five dams.

Flow regime in the Augusta Shoals is largely controlled by flow release from Thurmond Dam, reregulation of flows at Stevens Creek Dam, and the diversion of water into a canal by the Augusta Diversion Dam (ADD). The ADD diverts water into the Augusta Canal at a nearly constant rate that varies around 2400 cfs (based on USGS gauge data from gauges 02196500 and 02196485 from years 1989-1992 and 1997-2001, respectively; ENTRIX, 2002). During the workshop we learned that the amount diverted may be greater than this; however, in the absence of definitive data, we have continued to use a diversion rate of 2400 cfs. Flow into the shoals is the total discharge from Thurmond Dam minus flow diverted into the Augusta Canal (Figures 24, 25). If the diversion rate we used is an underestimate, then the flows shown in those figures are also underestimates.

Low flow conditions in the shoals (measured by USGS gauge 2197000 minus flow diverted into the Canal, Figure 25) are lower compared to conditions prior to mainstem hydropower dam construction (1884-1954 data). Pre-dam low flows in the shoals ranged from 2840 cfs in September to 6410 cfs in April (median of lowest daily flows by month). Following the construction of all major mainstem dams (1984-2001 data) low flows ranged from 1870 to 3431 cfs in October and March, respectively. The shoals are also subject to fluctuations in flow governed largely by the periodicity of upstream hydropower generation. Extremely low flow conditions occur on weekends when power demand and water release from Thurmond Dam are low (ENTRIX, 2002). These low flow conditions that occur on a seasonal and daily basis may harm both anadromous and resident fishes by inhibiting movement and reducing spawning and foraging habitat in the shoals.

Despite the fact that river regulation has negative effects on downstream habitats (Travnicheck et al., 1995 Freeman et al., 2001), a diverse fish fauna is still found in the Savannah River downstream of Thurmond Dam (Tables 4 - 9). However, fish use of the shoals has not been characterized and species richness historically may have been higher than under present conditions. Recent fish collections in the vicinity of Augusta Shoals indicate that the number of fish species that use the shoals may exceed 77 (ENTRIX, 2002; ALDEN, 2002; GDNR, 1998; GPC, 1998; Avondale Mills Inc., 2001).

As part of the relicensing of the Augusta Canal Hydropower Projects, the city of Augusta was required to examine potential impacts of the Augusta Diversion Dam on the shoals. The Savannah River Instream Flow (SRIF) study (ENTRIX, 2002) calculated weighted usable area using habitat suitability indices and habitat modeling (Physical Habitat Simulation Model) for selected species and guilds under a range of flows. State and Federal agencies used this model as a basis for developing flow recommendations for each month in the Augusta Shoals. These flow recommendations are not yet available to us. Species examined in the instream flow study were chosen based on federal status, migratory habits, or because they represent a group of organisms that share similar reproductive or habitat traits.

SAVANNAH RIVER AND ITS FLOODPLAIN

In southeastern rivers, the floodplain is considered essential in maintaining the productivity of the system. Floodplains provide important habitat for reproduction, rearing, foraging, and refuge from predators for a wide array of fish species (Junk et al., 1989). The Savannah River floodplain extends from the bottom of the Augusta Shoals to the tidal portion of the river. The degree of inundation, once dependent upon natural peak flows in the winter and spring, is now largely dependent upon discharge out of Thurmond Dam. Peak flows in the Savannah River near Clyo, GA exceeded 100,000 cfs every four years prior to dam construction. Now, flows rarely exceed the maximum generation capacity of 35,000 cfs and only exceed 60,000 cfs every 20 years (Part 1 of this report). Additionally, the main channel of the Savannah River has been extensively altered by dredging. The lower riverbed, reduced peak flows, and altered river discharge have altered the degree and frequency of floodplain inundation (Part 1, this report).

Use of the Savannah River floodplain by fishes has not been extensively characterized. However, static and flowing oxbow, mainstem, and estuary collections were made in the lower Savannah River in the early 1980's (Schmidt and Hornsby, 1985). The survey summarizes the collections of three oxbow rotenone fish collections and 11 electrofishing samples, taken above the freshwater zone of tidal influence or in the transition zone (3 samples; Schmidt and Hornsby, 1985). A comparison of other southeastern oxbow fish collections to collections higher on the floodplain was made to determine if oxbow collections from the Fisheries Survey of the Savannah River (Schmidt and Hornesby, 1985) could be used to represent floodplain fish fauna. The comparison indicated high similarity between the two areas given that 68 of 72 species (94 %) that occurred in oxbows also occurred in seasonal floodplains. A similar percentage of species recorded from floodplain habitats have also been recorded in oxbows. Floodplains usually (i.e. 82 % of samples) had equal or greater abundance compared to the same species in oxbows (Baker et al., 1991). The similarity of species and abundances between oxbows and seasonal floodplain habitats substantiated the characterization of Savannah River floodplain fishes by using oxbow data from the fisheries survey.

In addition to the fisheries survey, several other studies that characterized icthyofaunal use of southeastern floodplains were used to estimate which Savannah River species could use floodplain habitats for rearing or reproduction (Killgore and Baker, 1996; Light, 1995; Baker et al., 1991; Ross and Baker, 1983). However, difficulty in identifying larval fish led most authors to present data on the occurrence of family or genera and only occasionally on species. For example, in a study on Steel Creek (Paller, 1987), a Savannah River floodplain tributary, less than half of the larval taxa were identified to species and no cyprinids were identified below family taxonomic level.

Savannah River oxbows provide habitat for 76 fish species (Schmidt and Hornsby, 1985), most of which are expected to occur on the seasonal floodplain. An additional four species were identified in other studies as either occurring or reproducing on floodplains (Light, 1995; Baker et al., 1991; Ross and Baker, 1983) and an additional nine species belong to families or genera identified on other floodplains (Killgore and Baker, 1996; Paller, 1987; and Baker et al, 1991). Thus, the total number of Savannah River fish species potentially using floodplains ranges from 81-89 (Tables 4-8). Of these, 22 species are known to reproduce on floodplains and another 36 belong to genera from which larvae have been collected from floodplains (Tables 4-7). Most taxa (43) have their peak larva abundance in the spring, with 19 in the summer and 2 in the winter.

In summary, allowing seasonal access to the floodplain would facilitate reproduction or rearing for 22-58 species of Savannah River fishes. Seasonal flooding may also provide forage and refuge habitat for an additional 31 species (Table 8), totaling 83-91% of all fishes that occur below Thurmond Dam.

Timing, duration, and extent of floodplain inundation are closely related to fish reproductive success (Killgore and Baker, 1996; Finger and Stewart, 1987; Turner et al., 1994). Often, rivers have multiple flood pulses that facilitate longer periods of floodplain inundation and access. Cyprinids, centrarchids, percids, and aphedoderids have all been shown to have higher larval abundances in years with two flood pulses and longer periods of inundation rather than one flood pulse and shorter inundation (Killgore and Baker, 1996). Inundation in the winter and early spring favors spring spawners, but may also favor other species by allowing access to nutrient rich areas prior to spawning (Finger and Stewart, 1987). Thus, delayed inundation may reduce available spawning habitat for spring spawners and reduce nutrients available for gamete production for late spring and summer spawners.

As stated earlier, the timing and degree of floodplain inundation is altered from that of conditions prior to river regulation. In addition to lower peak flows, higher low flows in the summer and fall are also characteristic of the Savannah River. Prior to mainstem impoundment, a seven day low flow of 4300 cfs at Clyo occurred nearly every year, whereas now it only occurs every 100 years, never dropping below 3800 cfs (Part 1 of this report). Higher low flows may reduce or prevent floodplain drainage, especially in areas affected by dredging and hydrologic alteration. Such may be the case at the Savannah River Site where dredge spoil prevents wetland drainage (Part 3 of this report). Other areas of the Savannah River may be similarly affected; however, more information regarding spoil placement and inundation-drainage relationships is needed to adequately assess impacts.

In a natural river-floodplain system, seasonal dry periods allow oxygenation of sediment and organic material, which is then processed by aerobic microorganisms. When flooding reoccurs, these nutrients are available to aquatic food webs, thus allowing increased productivity. If the floodplain does not periodically drain, aerobic decomposition is reduced (Junk et al., 1989). Thus, preventing floodplain drainage may substantially reduce floodplain productivity and diversity.

Floodplains may provide aquatic habitats that vary from deep, static sloughs to shallow, flowing streams. Using literature on fish habitat use in southeastern floodplains, it was possible to place most Savannah River fishes into three habitat groups: flowing waters (17 spp.; Tables 4 and 8), lentic waters (17 spp.; Tables 5 and 8), or flowing and lentic waters (37 spp.; Tables 6 and 8). Flowing waters are defined as areas that have moving water, such as flowing oxbows (Schmidt and Hornesby, 1985) or occasions when the channel is high and water is moving in the floodplain (Light, 1996). Lentic waters are defined as areas that have little or no flow such as static oxbows (Schmidt and Hornesby, 1985), isolated ponds, and sloughs (Light et al., 1996). Given that nearly half of these floodplain species are found in both flowing and lentic water, it is not likely that many adult floodplain fishes are restricted to specific habitat types. However, ensuring the availability of these habitats throughout the spawning and rearing seasons may greatly improve floodplain productivity.

The biological significance of the Savannah River floodplain has been clearly established. However, the recreational significance also is substantial. The Fisheries Survey of the Savannah River not only described fish populations in different habitats, it showed that freshwater fishing pressure was much higher than that of the estuary and anglers fished oxbows 2:1 over the mainstem (Schmidt and Hornesby, 1985). These results lend importance to the lower Savannah River as both a significant ecological and recreational resource.

FLOW EFFECTS ON SELECTED FISH SPECIES

A literature search was conducted to identify flow relationships to fish life history aspects that are key to population success of selected fish species. Over 100 freshwater species occur in the lower Savannah River (Schmidt and Hornesby, 1985; Quintrell, 1980; ENTRIX, 2002a; ALDEN, 2002; GDNR, 1998; GPC, 1998; Avondale Mills Inc., 2001). Given the impracticality of identifying flow relationships for each species, species were selected based on the extent of knowledge of flow relationships to elements of that species' life history, federal or state status, and importance to the Savannah River fishery. All selected species have experienced significant abundance declines from pre-impoundment conditions. Diadromous species selected included American shad *Alosa sapidissima*, shortnose sturgeon *Acipenser brevirostrum*, Atlantic sturgeon *A. oxyrinchus*, American eel *Anguilla rostrata*, and striped bass *Morone saxatilis*. Robust redhorse *Moxostoma robustum* were selected because it is imperiled and of particular interest to state and federal regulatory agencies.

Habitat requirements vary between species and life stages (Figure 25).Thus, we examined effects of flow on multiple life stages and activities that are key to individual survival and population success. For adults, flow may affect foraging, survival, and spawning migration and activities. Egg, larva, and juvenile development, juvenile growth and survival, and movement between various habitats are also influenced by flow (Figure 26). If suitable conditions for any one stage are not met, the population will experience poor recruitment and over time, a population decline. So as to not exclude any of these critical stages from consideration, information obtained in the literature search for each species was presented in this framework.

<u>Atlantic Sturgeon *Acipenser oxyrinchus*</u> (Figure 27)

Adult Foraging, Survival, and Gonadal Development

Atlantic sturgeon move out of the river in the late fall from October to November and overwinter in the ocean. They move back into the river in early spring (March) and reside in the river through the summer (Figure 25; Collins, 2000b). The extent to which flows can be managed to maximize summer habitats and facilitate movement between summer and winter grounds may, in part, determine the success of the Savannah River Atlantic sturgeon population.

Spawning Migration and Activity

Historically, Atlantic sturgeon probably ranged throughout the Savannah River, possibly migrating far upstream to reach suitable spawning habitats in both the spring and fall. In neighboring drainages, spring spawning runs take place from mid-February to late March and spawning occurs mid-March to late May (Figure 27; Collins et al., 2000b; Smith and Clugston, 1997). In the fall, spawning probably occurs in September and October, with all adults leaving the river by the end of October.

Atlantic sturgeon are thought to spawn in strong current (Gilbert, 1989) over hard substrates such as rocks, rubble, shale, and sand (Smith and Clugston, 1997; Kynard and Horgan, 2002; Smith, 1985). Although specific spawning sites in the Savannah River have not been identified, affinity for hard substrates and use of shoal habitats in northern rivers (Kynard et al., 2000) indicate that sturgeon may have once used Savannah River shoals for spawning. Presently used spawning localities may be similar to those of the shortnose sturgeon *Acipenser brevirostrum*, which also spawn over hard substrates at river bends (Kynard, 1997). Thus, flows that allow sturgeon access to river bends and shoals during spring and fall spawning should be maintained as well as the strong flows within these areas.

Egg, Larva, and Juvenile Development

Given that Atlantic sturgeon spawn over hard substrates in strong currents (Smith and Clugston, 1997; Kynard and Horgan, 2002), eggs and larva probably require flowing water for proper development. Culture studies indicate that Atlantic sturgeon have a 94-140 hr incubation time that is partly dependant upon temperature (Smith and Clugston, 1997). Thus, spawning habitats probably require stable, high velocity water over a prolonged period. Studies on the closely related Gulf sturgeon *Acipenser oxyrinchus desotoi* indicate high adult tolerance to warm water. However, embryos and larvae exhibit high mortality at temperatures exceeding 25C (Chapman and Carr, 1995). Because water temperature is sometimes related to flow (e.g. hypolimnetic/ coldwater release, ground water mixing), temperature may be a consideration in developing flow recommendations

Laboratory studies of northern U.S. populations indicate that larval sturgeon remain in gravel interstitia until day eight of development, at which time they begin a downstream migration. The duration of downstream migration is dependent upon the distance between the spawning and rearing areas and can range from 6-12 days (Kynard and Horgan, 2002). Flows that facilitate downstream larval drift and access to rearing areas should be maintained during and after the spring and fall spawning periods.

Juvenile Growth and Survival

Estuaries appear to be important nursery habitats for juvenile Atlantic sturgeon in both northern and southern populations (Kynard et al., 2000; Collins et al., 2000a; Smith and Clugston, 1997). Early juveniles tend to remain near the interface between brackish and fresh water near the river mouth for at least a year; older juveniles move extensively both within the river and between rivers (M. Collins, SC DNR, pers. com.). The degree of movement between brackish and fresh water may shift seasonally with river flow, similar to that of the shortnose sturgeon *Acipenser brevirostrum.* Juveniles in the lower Merrimack River occupied a specific habitat type, run with island, used mostly sand substrates but also rock and cobble at mean depths of 7m (Kynard et al., 2000). Atlantic sturgeon may use similar habitats in the Savannah River, in which case habitat availability is influenced by flow.

Shortnose Sturgeon *Acipenser brevirostrum* (Figure 28)

Adult Foraging, Survival, and Gonadal Development

Adult shortnose sturgeon populations in more northern river systems remain in freshwater, but sturgeon in the Savannah River use the freshwater/saltwater boundary throughout the year with the exception of spawning runs. Shortnose sturgeon are found between river mile 12.9 and 30.3 (km 20.8 and 48.9) but frequently use areas around river mile 29.7) (km 47.9) when water temperatures are greater than 22C (Collins, SCDNR). Adults move down river to the estuary in the winter (M. Collins, SC DNR, pers.com). Hall et al (1991) identified three sites between river mile 21.7 and 24.8 (km 35 and 40) where sturgeon resided for over six months during summer and fall. Sites were characterized by depths of 6.1-10.7 m, salinities of 0-6 PSU, coarse sand and small gravel bed sediments with some mud, and a high abundance of the Asiatic clam *Corbicula fluminea*, a probable food source. The extent to which these habitat conditions are maintained depend, in part, on upstream flow regulation.

Sturgeon occupation of deeper waters in the summer may indicate thermal preferences. Movement patterns into various salinity waters in the Ogeechee River System, GA were related to river temperature (Weber et al., 1998). At this time, however, it is uncertain how Savannah River water temperatures compare to pre-regulated conditions, nor is it certain where present coolwater habitat exists. However, if and when this information becomes available, the relationship of adult shortnose sturgeon cool water availability to flow should be examined.

Spawning Migration and Activity

Shortnose sturgeon move upstream during their spawning runs from late January to March (Figure 25; Hall et al., 1991). Adults generally return to the lower river by early May (Hall et al. 1991), although individuals have been known to remain upriver through summer (M.Collins, SC DNR, pers. com.). In the Savannah River, probable spawning sites are sharp channel curves over a mix of rocks, gravel, sand, and logs from river mile 111 to 118 (km 179 to 190) and 170 to 172 (km 275 to 278) (Hall et al., 1991). High velocities (e.g. 82 cm/sec) near the riverbed also characterize spawning habitat of shortnose sturgeon (Kynard, 1997).

Preference for spawning over hard substrate and use of shoal habitats in other populations (Kynard et al., 2000) may suggest that the shoals historically served as spawning grounds for the shortnose sturgeon. However, passage to the shoals is now impeded by the New Savannah Bluff Lock and Dam (pers. comm. P. Brownell). Flows that allow passage into the Augusta Shoals may make more habitat available for spawning, potentially resulting in greater reproductive success of the shortnose sturgeon population.

Sturgeon movement within the shoals was considered during the Augusta Shoals Instream Flow Study (ENTRIX, 2002). Based on the hydraulic analysis and South Carolina criteria for fish passage, flows above 2600-2700 cfs accommodate large fish passage. These results should be considered for spring spawning runs in late January through March (Collins et al., 2000b). Recommended flows for sturgeon spawning in the shoals have not yet been submitted by the National Marine Fisheries Service.

Egg, Larva, and Juvenile Development

Little is known about flow requirements of shortnose sturgeon early life stages. Eggs are adhesive (Dadswell et al., 1984) and probably remain fixed for about five days to hard substrates over which shortnose sturgeon spawn (Kynard, 1997). Larvae are probably benthic and may disperse downstream during the summer but remain upstream of high salinity waters (Hoff et al., 1988; Dadswell et al., 1984). Larval drift to downstream rearing areas is facilitated by flow; drift duration is determined by spawning location and water velocity (Kynard and Horgan, 2002).

Juvenile Growth and Survival

The Savannah River harbor has been extensively altered by dredging. Prior to harbor modification, juvenile shortnose sturgeon released in the Savannah River stayed within 2-5 km (ca. river mile 18.9 or km 30.5) downriver of the saltwater/freshwater interface in the fall and winter (Hall et al., 1991). This area probably served as an important nursery area and foraging ground (Hall et al., 1991; Collins et al., 2002). More recent studies indicate that juveniles no longer occupy this area and are found only between river mile 29.4 (km 47.5) (summer) and 19.3 (km 31.2) (winter; the latter is the confluence of the Front and Middle rivers). Movement in this area is dependent upon seasonal changes in water temperatures. Mean salinities in this area ranged from 5.3 ± 4.3 to 0.1 ± 0.0 PSU and depths from 2.1-13.4 m (Collins et al., 2002). Salinity in this area of the estuary partly depends on river discharge. Flows that allow persistence of suitable shortnose sturgeon habitat conditions, movement between nursery areas, and possibly expansion of suitable habitat during juvenile rearing periods (Part 5 of this report) will likely benefit juvenile growth by allowing access to more foraging and refugia habitat.

Robust Redhorse *Moxostoma robustum* (Figure 29)

Adult Foraging, Survival, and Gonadal Development

Habitat preferences for adult robust redhorse are uncertain, but may be similar to those of other catostomids. Adult *Moxostoma* spp. and *Hypentelium* sp. prefer raceways of 60-149 cm deep and velocities from 30-59 cm/s (Aadland, 1993). It is not known if robust redhorse migrate long-distances to spawning areas. Similarly, it is not known if the proximity of spawning habitat to foraging habitat is related to reproductive success. However, some robust redhorse stocked into the Broad River have migrated downstream and now reside in Clark Hill (Strom Thurmond) Reservoir. This may indicate the use of downriver habitats until spawning season, at which time adults migrate upstream to shoal habitats.

Spawning Migration and Activity

Spawning locations and times for the robust redhorse are not well documented in the Savannah River. Courtship behavior was observed at the end of May which concides with that of spawning robust redhorse in the Oconee River (Freeman and Freeman, 2001). The only other known spawning location is over gravel just below New Savannah

Bluff Lock and Dam. However, GDNR and USFWS collected broodfish in the shoals in May and June (pers. comm. B. Freeman). Thus, robust redhorse probably spawn from April (as in the Oconee River) through June in the Savannah River (Figure 25). Suitable spawning habitat criteria are 0.29-1.1 m depth, 0.26-0.67 m/s water velocity, over medium-coarse gravel (Freeman and Freeman, 2001). Flows that allow access to the shoals or other suitable spawning grounds, as well as the maintenance of suitable spawning conditions, will favor robust redhorse reproduction.

During the robust redhorse spawning season, 3600 cfs achieves 100% possible maximum weighted usable area (PMWUA; i.e. the maximum amount of habitat available; ENTRIX, 2002) in the Augusta Shoals. Flows of 2100-6100 cfs provide at least 80% PMWUA for spawning robust redhorse (Table 10; ENTRIX, 2002).

Egg, Larva, and Juvenile Development

Laboratory experiments of pulsed, high-velocity water effects on larval robust redhorse indicate negative effects on early survival and growth. Pulsed, high-velocity flows impeded larval swim-up ability and gas bladder inflation (Weyers et al., 2003). Delay of this high-energy process has been shown to increase mortality (Bailey and Doroshov, 1995). Additionally, the daily duration of the pulsed flow reduced growth rates. Growth rates and survival were higher in stable, low-velocity conditions (Weyers et al., 2003). Thus, stability of low-velocity habitats during and following larval swim-up is critical for survival and growth of robust redhorse.

Swimming speeds for various size classes of larval robust redhorse were tested in swim chambers. Generally, larval ability to maintain position in the swim chamber decreased with increased water velocity, but increased with increased larva size (Ruetz and Jennings, 2000). Prolonged swimming speeds for larval robust redhorse ranged between 6.9 and 11.7 cm/sec. The persistence and accessibility of these low-velocity habitats is probably critical to the survival of robust redhorse early life stages, especially when swimming speeds are lowest (i.e. May-June; Ruetz and Jennings, 2000).

Juvenile Growth and Survival

Field studies of other catostomids with similar habitat preferences showed similar vulnerability to altered flow regimes. Juvenile northern hog-suckers *Hypentelium nigricans*, white suckers *Catostomus commersoni*, and age- 0 *Moxostoma* spp. show preferences for slow riffles (Aadland, 1993). The Alabama hog-sucker *Hypentelium etowanum* population below Thurlow Dam on the Tallapoosa River, AL responded favorably to a minimum flow release that prevented the periodic loss of flowing microhabitats (Travnicheck et al., 1995). Similarly, young-of-year catastomid abundance was positively correlated with shallow water habitat persistence and negatively correlated with 1-hour maximum flows (Bowen et al. 1998). Habitat persistence for young-of-year catostomids appears critical in the development of early life stages. Although peak flows are partly reregulated (i.e. dampened) by Steven's Creek Dam, flows that ensure shallow-slow habitat stability may improve rearing habitat for young-of-year redhorse.

Striped Bass *Morone saxatilis* (Figure 30)

Adult Foraging, Survival, and Gonadal Development

Adult striped bass use the freshwater portion of the river for a majority of the year. The relationship of flow to foraging habitat is unknown, but flows that allow access to known foraging areas in the estuary and summer cool-water refugia may benefit adult foraging, survival, and gonadal development. Adult striped bass in the Combahee River, SC remained in the tidally influenced lower river from January to early April but moved upstream in late April to late May when water temperatures ranged between 18-26 C (Bjorgo et al., 2000). Movement upstream into cooler water is similar to the movement patterns of other striped bass populations that seek cool springs during warm water periods (Moss, 1982). Flows that allow access to cooler upstream water may benefit adults and adult foraging.

Spawning Migration and Activity

Striped bass are primarily riverine, but spawn in estuarine and riverine habitats (Dudley et al., 1977). Striped bass move upstream and spawn from February to June (Figure 25; Dudley and Black, 1979; Reinert et al., 1996), spawning in a variety of habitats and releasing their eggs into the water column, not requiring a substrate for egg adhesion (Hill et al., 1989). Spawning historically ranged from the estuary to the Augusta Shoals. However, adult striped bass movement is now impeded by the New Savannah Bluff Lock and Dam and consequently they are encountered with much greater frequency below the dam (personal observation, C. Jennings). Flows that allow movement between the estuary and the shoals during upstream and downstream movement (October to November) may increase available spawning habitat.

Currently, the most productive area for striped bass reproduction and rearing is the Savannah River estuary. Because of the habitat dynamics within the estuary, striped bass will be considered separately by the Estuarine Processes group (Parts 4 and 5).

Egg, Larva, and Juvenile Development

Egg viability and juvenile abundance indices were developed and related to river discharge from long-term striped bass studies in the lower Roanoke River, North Carolina (Rulifson and Manooch, 1990). Reservoir discharge in the lower river influences spawning activity by controlling river flow and water temperatures (Rulifson and Manooch, 1990 and sources therein). Recruitment was best when flows were low to moderate and poor when flows were very low or high during the spawning season. Additionally, juvenile abundance indices (JAI) and egg viability indices were highest when flows were within the 25^{th} to 75^{th} percentile range during spawning season, with the exception that JAIs were low when early April flows were low. Flow patterns for good recruitment years closely resembled that of pre-impoundment conditions (Rulifson and Manooch, 1990). In the Savannah River, similar flow patterns may be essential for good striped bass recruitment.

Striped bass release eggs into the water column and eggs drift downstream with the current from March to June (Van Den Avyle and Maynard, 1994). Velocities that maintain egg buoyancy and facilitate downstream transport of eggs and larvae influence recruitment success (Bain and Bain, 1982; Crance, 1984; Rulifson et al., 1988). Striped bass were considered in the SRIF study on the Augusta Shoals.

Conditions for striped bass egg and larval drift increase with discharge to the highest flow simulated (8000 cfs); a flow of about 6100 cfs achieves 80% PMWUA (Table 10). These findings do not necessarily apply to the river reach below the Augusta Shoals, however. Water velocity throughout the river varies with the geomorphological features. Thus, velocity that is required to suspend and transport eggs in the shoal water column may or may not be adequate in other river sections.

Juvenile Growth and Survival

Little is known about the habitat and flow requirements for juvenile striped bass in the shoals or floodplain. In the Roanoke River, however, recruitment success was related to river flow during the spawning season (Rulifson and Manooch, 1990), as discussed in the previous section.

The Back and Middle rivers of the estuary are known nursery areas. The relationship of flow to habitat and juvenile striped bass development in the estuary will be discussed by the Estuarine Processes group (Part 4 of this report).

American Shad *Alosa sapidissima* (Figure 31)

Adult Foraging, Survival, and Gonadal Development

Adult American shad forage mostly offshore but are dependant upon riverine habits for spawning (Facey and van den Avyle, 1986).

Spawning Migration and Activity

The American shad once made spawning runs from the Savannah River mouth to the Falls of Tallulah, the headwaters of the Savannah River (McDonald, 1884). Although American shad movement is now restricted by mainstem dams, the shad population continues to persist in the lower Savannah River.

American shad spawn from January through April in Georgia (Probst, 1988; Figure 25). Spawning normally occurs in water velocities ranging from 30-90 cm/sec, probably in a range of habitats since shad eggs are released into the water column and do not adhere to substrates (Facey and Van Den Avyle, 1986). However, McDonald (1884) noted that "favorite spawning grounds" are on the sandy flats that border streams and sandbars. In the shoals, the SRIF study shows that habitat for spawning and egg incubation increases with flow, achieving 80% PMWUA at about 4900 cfs (Table 10; ENTRIX, 2002).

Egg and Larva Development* and *Juvenile Growth

American shad eggs sink and are gradually carried downstream and larvae are carried passively downstream to the estuary (Stier and Crance, 1985) probably from February to June. Stier and Crance (1985) noted that spawning velocities are probably adequate to facilitate egg drift. Flow recommendations should ensure that dissolved oxygen levels remain above 5.0 mg/L for egg viability (Facey and van den Avyle, 1986). Juvenile American shad use rivers, estuaries, oxbows, and tidally influenced freshwater (Facey and van den Avyle, 1986). Juvenile shad are found in Savannah River oxbows as early as September (Schmidt and Hornesby, 1985). Juveniles migrate out of the river in late summer in the Ogeechee River (Probst, 1988) and migrate out of the river by January in the Altamaha River (Goodwin and Adams, 1969). Flows that allow juveniles to move between these areas may facilitate juvenile growth.

Downstream migration of juvenile American shad and blueback herring also was studied in the Connecticut River. Migration peaked during the new moon phase in October and diel patterns showed a peak in the late afternoon to evening of both years (O'Leary, 1984). Moon phase should be considered along with flows that facilitate juvenile migration.

American eel *Anguilla rostrata* (Figure 32)

Adult Foraging, Survival, and Gonadal Development

Pre-migratory adult eels range throughout large rivers, with higher densities near the coast and a higher proportion of females upstream (Krueger and Oliveira, 1999). Although the mechanism of sex determination is uncertain, it may be density dependent. Allowing access to upstream foraging habitats may be essential in producing large numbers of females (Krueger and Oliveira, 1999). Additionally, available habitat for American eel migration was once over 34,000 km in the Savannah and Ogeechee river systems, but is now restricted to 4508 km. Both large- and small-scale impoundments impede eel movement into upstream habitats, probably contributing to the decline of this species (AEPDT, 2000). Flows that facilitate movement around instream structures may increase foraging habitat, female production, and consequently, population success.

Spawning Migration and Activity

The American eel is a catadromous species and thus, riverine spawning requirements are not applicable. However, flows that ensure movement between upstream foraging habitats and the ocean in early spring should be considered.

Egg, Larva, and Juvenile Development

American eel spawning and early development occur in the Sargasso Sea (McCleave et al., 1987). River flows during early development are not applicable.

Juvenile Growth and Survival

American eel elvers emigrate from the same source, the Sargasso Sea, and do not differentiate between rivers (Avise et al., 1986). Elver migration into the Annaquatucket River, RI in late March is related to increased river temperatures and a decreased flow (Martin, 1995). Flows peak in the Savannah River from February to April, and assuming that the onset of river immigration occurs near the same time, the cues for river immigration may be different. In mid-May to mid-June, however, migration in the Annaquatucket River was more closely related to tide stage (Martin, 1995).

Yellow eels move between mainchannel habitats, feeder creek mouths, flooded marshes and floodplains to forage (Facey and Van den Avyle, 1987; Schmidt and Hornesby, 1985). Flows that allow access to all of these habitats may promote juvenile growth.

Mussels

Adult and juvenile foraging and survival

Foraging by freshwater mussels is strongly influenced by water velocity and temperature. At higher velocities and temperatures, algal uptake increases significantly for the eastern elliptio *Elliptio complanata* (Stuart et al., 1999). Extremely high temperatures (i.e. above 25C) increases mortality of juvenile mussels (Eric Krueger, pers. com.). Low water temperatures associated with hypolimnetic release result in slow mussel growth and inhibited reproduction (Heinricher and Layzer, 1999). Thus, ensuring flowing water and a natural temperature regime will likely benefit foraging for these species.

Of the 32 mussel species that occur in the Savannah River system, six show preferences for strong or swift current. Although some of these are found in a variety of substrates, all show preferences for sand and gravel. Additionally, gravid individuals are mostly found in the summer months from May to July, the exceptions being the Appalachian elktoe *Alasmidonta raveneliana,* which has been found gravid in October through January and in May, and the Roanoke slabshell *Elliptio roanokensis*, in which gravid individuals were found as early as March. Many mussels that are dependent on host fish for glochidia release and transport are also dependent upon flowing water for suspension of the superconglutenent. Thus, ensuring flowing water in sand and gravel areas, especially during the summer months (May through August), may facilitate reproduction of these species.

Although flow preferences are known for only a handful of mussels, substrate preferences are better documented. A mix of sand and gravel, cobble, and bedrock is preferred by nine species and mud and silt are preferred by seven. Because mussels are relatively sedentary, ensuring that these habitats remain inundated during daily low flows (ie. non- power generation periods) may benefit these species. The remaining 16 species either have no flow or substrate preferences or the preferences are not known (Table 11).

Old river bends, which are now cut off my main-channel straightening, probably once harbored a diversity of mussels. Alderman (1992) found reproducing populations of Savannah lilliput (*Toxolasma pullus*) in these cutoff bends, but found few other species.

Alderman speculated that sediment accumulation in these cutoffs will result in the extirpation of these species. A flow regime that maintains remaining habitats may facilitate the persistence of these populations.

Reproduction

River regulation and altered water quality affects freshwater mussels by altering or eliminating host fish movement and population dynamics (Watters, 1999). Management decisions that are intended to benefit fish may also facilitate the reproductive processes of mussels. Many mussels require a host fish for their parasitic glochidial stage of development. Although host fish have been identified for some mussels, many more mussels have yet to be linked with a host fish. The yellow lampmussel *Lampsilis cariosa*, for example, was one of the most abundant mussel species near the Savannah River Site in the 1950's and 1960's and is now one of the least abundant species (Thomas et al., 2001). The host fish of the yellow lampmussel is unknown, but based on its distribution, it is suspected to have an anadromous host (ncwildlife.org; Table 12). Management decisions that benefit anadromous fish movement and population growth may also improve the yellow lampmussel population.

Another species that should receive special attention in the Savannah River is the Atlantic pigtoe *Fusconaia masoni*. The Atlantic pigtoe is globally ranked G2, or very rare. Few host fish for this species have been identified, and the only one known to occur in the Savannah River drainage is the bluegill *Lepomis macrochirus* (ncwildlife.org; Table 12). It is likely that the Atlantic pigtoe has other host fish, but because they are unknown, it is appropriate to consider flow relationships to its preferred habitat type, swift flowing waters in a substrate of stable gravel or a sand and gravel mix. Maximizing available habitat for this species as well as allowing fish access to these areas will likely benefit the Atlantic pigtoe population.

As previously mentioned, cold tailwater temperatures that result from hypolimnetic discharge result in reduced growth (Heinricher and Layzer, 1999). Non-reproducing mussels that have been transplanted from a cold tailwater to warmer water subsequently reproduced, demonstrating the importance of warmer temperatures for growth and reproduction (Heinricher and Layzer, 1999). Although it is uncertain how the temperature regime in the Savannah River differs from pre-regulated conditions, this should be considered in developing flow recommendations for Thurmond Dam.

Juvenile Growth and Survival

Hydropower peaking, the fast increase and decrease in river discharge that results from hydropower generation, may prevent the settlement of juvenile mussels (Layzer, 1996). Although hydropower peaking immediately below Thurmond Dam is evident, effects are moderated by flow reregulation at Stevens Creek Dam. Flow fluctuations still occur below Stevens Creek Dam, and the effects of these fluctuations on juvenile settlement are uncertain. Potential effects of peaking should be considered in developing flow recommendations.

(3) Effects of Altered Flow Regimes on Floodplain Processes

The link between fluvial geomorphic disturbances and dynamics within riparian vegetation and animal populations in the Southern United States has been well documented. Because of the close connection between the hydrologic regime of a river and organisms living in its floodplain, alterations in river hydrology can greatly affect processes within riparian ecosystems. The pulsing of the river discharge is the major force controlling the biota in river floodplains, lateral exchange between the floodplain and the river channel, and nutrient cycling within the floodplain (Junk et al. 1989). The construction of dams and reservoirs has had tremendous impacts on important ecological processes within rivers and associated wetlands, altering the flow of water, sediment, nutrients, energy, and biota within these systems. A number of impoundments in the Savannah River basin constructed in the mid-1900's have altered the hydrology, geomorphology, and sediment composition of the floodplain system (USACE 1992). These alterations have potentially had multiple impacts on the productivity, recruitment, and species composition of floodplain trees in the basin. The status and flow-related life history characteristics of dominant floodplain tree species on the Savannah River floodplain are detailed in Tables 13 – 15; Table 16 details information on threatened and endangered floodplain plant species. Details of relevant life history characteristics of selected bird species from the Savannah River floodplain can be found in Tables 17 – 19. The following sections discuss key floodplain processes influenced by flow regime.

SOUTHEASTERN FLOODPLAIN FORESTS

The floodplain forests of southeastern rivers are dominated by a diverse assemblage of tree communities; the species composition of these communities reflects the flood regimes characterizing the particular sites at which they occur. For the purposes of this report, the forests on the Savannah River floodplain are divided into three categories: bottomland swamp forests, which are flooded throughout most or all of the growing season and are dominated by highly flood-tolerant tree species; wet bottomland hardwood forests, which flood every 1-2 years for varying duration during the growing season and are dominated by both highly and moderately flood tolerant tree species; mesic bottomland hardwood forests, which flood more infrequently, and for a shorter portion of the growing season, and are dominated by less flood tolerant tree species (see Table 13). In order to more closely examine the potential effects of alterations in flood regime to the Savannah River, we selected nine tree species that are canopy dominants in the three different forests community types on the Savannah River floodplain and an exotic invasive tree species that may become a threat to these floodplain forests (Table 13).

SEEDLING RECRUITMENT AND SURVIVAL

The timing, duration, and magnitude of floods play an integral role in the establishment and survival of tree seedlings. A number of studies have demonstrated the importance of floods during the winter months (October through February) for seed dispersal in both bottomland swamp and bottomland hardwood forests (Liu et al. 1990, Schneider & Sharitz 1988). For many species, seeds are released beginning in September or October, and continue to fall until as late as March (Table 14). During this period, short-term, high discharge floods transport seeds among bottomland hardwood communities that are spatially separated or differ in species composition, increasing diversity of the seed banks in these sites (Schneider & Sharitz 1988). These floods also increase the chances of seeds finding appropriate sites for germination and establishment on the floodplain (Huenneke & Sharitz 1990). Ideal germination sites are often found some distance away from the parent plant, as some floodplain tree species show conspecific allelopathy and/or low tolerance to shading (E. Krueger, *personal communication*; see also Table 14). Among the species considered in this report, those utilizing hydrochory as a primary mode of dispersal in bottomland swamp forests are bald cypress (*Taxodium distichum*), swamp tupelo (*Nyssa sylvatica* var. *biflora*), and water tupelo (*Nyssa aquatica*); those species utilizing hydrochory in bottomland hardwood forests are water hickory (*Carya aquatica*), green ash (*Fraxinus pennsylvanica*), laurel oak (*Quercus laurifolia*), and swamp chestnut oak (*Quercus michauxii*). The invasive exotic Chinese tallow (*Sapium sebiferum*) also disperses via hydrochory (Table 14). Comparisons of mean monthly flows in the Savannah River prior to and following construction of the Thurmond Dam show a sharp post-dam decrease in discharge during the months December – May, and a similar decrease in or absence of overbank flooding (Hale & Jackson 2003, Part 1). These hydrologic changes suggest an overall decrease in seed transport, especially in bottomland hardwood forests higher up on the floodplain.

In contrast, floods occurring during the growing season limit seedling survival during early phases of recruitment, and summer floods of more than a few days are likely to cause mortality of newly germinated seeds (Sharitz & Lee 1985). Mean monthly flows in the Savannah River have been slightly higher in the months May – July following dam construction, and 7-day low flows are significantly higher (Hale & Jackson 2003, see Part 1). Artificially elevated water levels during typically low flow periods in late spring and early summer may reduce seed trapping and incorporation into the floodplain substrate, as well as inhibit seed germination and reduce annual recruitment of common floodplain tree species (Schneider et al. 1989, see also Tables 14-15). Reduction in seedling germination and survival due to elevated water levels may particularly be of concern in the lower-lying bottomland swamp forests on the Savannah River floodplain. Canopy dominants bald cypress (*Taxodium distichum*) and water tupelo (*Nyssa aquatica*), though highly flood tolerant, do not germinate while submerged, and cannot survive prolonged inundation of their foliage (Table 14). Newly-germinated bald cypress seedlings (under 2 weeks of age) subjected in one study to complete submergence began to show clear signs of stress after approximately one month and substantial mortality following 45 days of submergence (Souther & Shaffer 2000). Two-month-old water tupelo seedlings have been shown to lose all of their leaves after four weeks of flooding (Hochman 1999). A study by Schneider & Sharitz (1986) observed that the "chronically flooded" conditions in a bottomland swamp forest site on the Savannah resulted in an unexpectedly large pool of nonviable cypress and tupelo seeds; these flooded conditions were believed to be influenced by dam operations upstream (Schneider & Sharitz 1986). Some studies on the Savannah have indicated that floods of even shorter durations can have an adverse effect on seedlings if they are large enough to overtop seedling foliage. A number of high magnitude, short duration floods resulting from releases from upstream reservoirs have been documented during the growing season on the Savannah River. These floods have resulted in high seedling mortality of a number of floodplain species (Table 15). Two observed floods lasting around 2 weeks during the growing season of 1984 on the Savannah River floodplain resulted in 22% survival and 5% survival, respectively, in a study population of bald cypress and water tupelo seedlings (Sharitz et al. 1990). Floods observed during the growing season of 1994 on the Savannah River floodplain were deep enough to overtop a study population of water tupelo seedlings, with a subsequent 19% reduction in their survival (McLeod et al. 2000). These 1994 floods also had an effect on some bottomland hardwood species, resulting in 100% mortality of laurel oak (*Quercus laurifolia*) seedlings (McLeod et al. 2001). Water hickory (*Carya aquatica*) and bald cypress seedlings, however, suffered little mortality (< 10%) (McLeod et al. 2001).

MATURE TREE PRODUCTIVITY AND SURVIVAL

Hydrologic regime affects the growth and survival of mature floodplain trees in bottomland forests on the Savannah River floodplain (Keeland et al. 1997, Jones et al. 1994). During the growing season, dominant species in different areas of the floodplain demonstrate different levels of tolerance to flooding, ranging from very tolerant species, which tend to dominate bottomland swamp areas (eg. bald cypress, water tupelo) to weakly tolerant species, which tend to dominate mesic bottomland hardwood forests (eg. swamp chestnut oak) (Tables 13-14). Significant negative relationships between weekly changes in water level and diameter growth of tupelo trees have been found on Savannah River plots with periodic shallow flooding; cypress demonstrates both positive short-term and negative long-term relationships between diameter growth and weekly changes in water level (Keeland & Sharitz 1995, Keeland & Sharitz 1997). Most tree stems in the cypress-tupelo forests of the Savannah River floodplain begin to grow in late spring; the growing season ends in late summer. Diameter growth of cypress and tupelo in the Savannah River floodplain is inversely related to mean water levels during the growing season (Keeland et al. 1997). Megonigal et al. (1997) found aboveground net primary production (NPP) of bottomland forests on the Savannah River floodplain to be significantly lower on wet (mean growing season flooding depth > 0 cm) plots than on intermediate (groundwater table depth = 0 to –60 cm) and dry (groundwater table depth < -60 cm) plots. For similar tree species on bottomland forest sites in Louisiana, the slope of the mean water depth-NPP relationship was more negative in areas showing evidence of severe hydrologic alteration (i.e. elevated growing season water levels due to a nearby impoundment) (Megonigal et al. 1997). Following dam construction on the Savannah River, the channel has experienced higher mean monthly flows in the months May – July and higher 7-day low flows (Hale & Jackson 2003). This alteration in hydrology may inhibit growth of mature trees in some areas of the floodplain. Indeed, some observational evidence suggests that water hickory (*Carya aquatica*) may be experiencing a decline in sites that have been experiencing growing season flooding in recent years (Table 15).

Conversely, floods occurring in winter, before the growing season begins, may improve soil water availability during the growing season in floodplain forests (Megonigal et al. 1997, McLeod et al. 2000). These floods may also be important in supplying nutrients to areas of the floodplain forest. Several studies of cypress swamps (Mitsch et al. 1979, Brown 1981) report positive correlations between sediment-associated nutrient inputs from floods and aboveground NPP of cypress trees. A reduction in maximum monthly discharge during winter months could lead to nutrient depletion or desiccation of soils in areas of the Savannah River floodplain. Soil water and nutrient deficits potentially reduce height and diameter growth of woody plants, as well as inhibit all stages of reproductive growth (Brown 1981, Kozlowski 2002).

COMMUNITY STRUCTURE AND SUCCESSION PATTERNS

Hydrology is a major factor determining forest structure (Conner et al. 2002). Significant changes in the magnitude and duration of flooding on a given site may elicit shifts in stand composition (King 1995, Townsend 2001). Changes in forest community structure and successional processes in areas of the Savannah River floodplain may be related to changes in hydrology following dam construction. One study on the Savannah River floodplain found less than 16% of 474 bald cypress trees, a canopy dominant in bottomland swamp areas, are smaller than 10 cm in diameter at breast height at sites on the Savannah; additional analysis at one site revealed individuals in this < 10 cm size class to be as old as 10 years (Sharitz et al. 1990). A study by Jones et al. (1994) found decreases in small stem density and increases in large stem density over a ten-year period in forest plots on the Savannah River floodplain (Jones et al. 1994). These studies imply that very few individuals have been recruited into the population in recent decades. Decreased regeneration of bald cypress and water tupelo is attributed to their exacting requirements for germination and early seedling growth (Sharitz et al. 1990), namely their inability to germinate and/or establish in permanently flooded conditions (Table 14).

Decreases in discharge of peak annual flows in the Savannah River, as well as reductions in flood recurrence and flood duration, may have an impact on community structure of infrequently flooded bottomland hardwood forests at higher elevations. Wet years effectively eliminate from a location those species that cannot physically tolerate longer than average flood regimes for that site. Periodic perturbations to the average disturbance regime (such as unusually high flows) are therefore critical to maintaining community composition and species diversity on the floodplain (Townsend 2001). With a reduction in the periodic perturbation of high discharge floods, flood-intolerant upland species have an opportunity to invade bottomland hardwood forests (Brown 1981, Schneider et al. 1989). Similarly, reductions in inter-annual variability can adversely affect the diversity of tree assemblages on the floodplain (Deiller et al. 2001). Since construction of Thurmond Dam, fluctuations in the hydrograph between years have been highly reduced (Hale & Jackson 2003, Part 1). These reductions may be causing a more homogeneous composition of tree species.

Changes in hydrologic regime may also lead to greater susceptibility of the floodplain ecosystem to exotic invasive species. The Chinese tallow tree (*Sapium sebiferum* (L.) Roxb.) is an invasive species on the Savannah River floodplain. Recruitment and growth of this highly shade and flood tolerant species may be accelerated by changes in floodplain hydrology which adversely affect native species (Jones & Sharitz 1990, Conner et al. 2001, Conner et al. 2002).

IMPACTS ON BIRD AND OTHER ANIMAL COMMUNITIES OF THE FLOODPLAIN

The persistence of a number of bird species inhabiting the Savannah River floodplain during the breeding season (roughly March – October) depends on the presence of bottomland hardwood and swamp forest tree species. Alterations in river flow can cause the death of native trees, which creates canopy gaps and increases groundcover. Non-aquatic birds show a direct response to changes in these structural elements of the environment (Straney 1974). With a decline in species such as bald cypress, bird species such as the prothonotary warbler (*Protonotaria citrea*) and the Mississippi (*Ictinia mississippiensis*) and swallow-tailed (*Elanoides forficatus*) kite risk loss of nesting and foraging habitat (Meyer 1995, Parker 1999, Petit 1999). The timing of floods can have a direct impact on a number of bird species during the nesting season. Prothonotary warblers can be subject to increased nest predation from snakes if water levels are not sufficiently high in early spring (R. Cooper, *personal communication*). Birds building nests on the ground of the Savannah River floodplain, such as the belted kingfisher (*Ceryle alcyon*), may exhibit increased nest abandonment due to flooding, if mean monthly flows are higher following nest-building in April (Hamas 1994). A prolonged hydroperiod during the breeding season (February-June) may, however, be beneficial for some aquatic birds such as the wood duck (Kennamer 2001), since greater inundation means increased foraging and nesting habitat. Details of relevant life history characteristics of selected bird species from the Savannah River floodplain can be found in Tables 17 – 19.

Floodplains support a unique and highly productive assemblage of invertebrates, and the dynamics of this assemblage are shaped by specific patterns of inundation on the floodplain (Batzer & Wissinger 1996, Benke 2001). A specific flood regime can often be linked to particular assemblages of invertebrates. A study by Wiggins et al. (1980), for example, found that permanently flooded conditions during the winter in a woodland pond habitat tended to support those invertebrate species without drought-resistant stages, while a more seasonal flooding pattern supported invertebrate assemblages demonstrating drought-resistance (Wiggins et al. 1980). High levels of inter-annual variability in extent and depth of floodplain inundation are therefore essential to maintaining an assemblage of invertebrates utilizing a diverse array of life history strategies. Similarly, maintaining the connection between the river channel and floodplain is vital for diverse and productive invertebrate assemblages and the higher trophic levels that depend on them (Benke 2001). The high biomass and production of insects inhabiting snags on the floodplain is made possible by an abundant supply of microbially enriched amorphous detritus that primarily originates from the floodplain forest (Benke 2001). During high flow periods, the floodplain becomes an important part of the aquatic system food web as fishes migrate into snag habitats and use the vast invertebrate food resource (Junk et al. 1989). Alterations in the magnitude and duration of flooding during typically high flow periods and reductions in inter-annual variations in flooding on the Savannah could result in lowered productivity or diversity of the floodplain invertebrate assemblages. These alterations could in turn adversely affect the foraging success of waterfowl and fishes that depend on insect and insect larva as a primary food source (Kingsford 1999, Batzer & Wissinger 1996).

The Savannah River floodplain supports diverse assemblages of reptiles and amphibians. Modifications to both the physical and hydrologic characteristics of the Savannah River may, however, be having an impact on these organisms. The brown water snake, for example, exhibits a preference for perches along the steep-banked outer bends of the river (Mills 1995). This habitat is eliminated by channelization, a practice used extensively on the Savannah River (Hale & Jackson 2003, Part 1). Development along the river and lowering of peak flows may disconnect portions of the floodplain or narrow the riparian zone, reducing the abundance of amphibians and reptiles (Bowers 2000).

CONCLUSIONS

Undisturbed riparian ecosystems normally provide abundant food, cover, and water for wildlife, and often contain some special ecological features or combination of features that are not found in upland areas. In hydrologically altered systems, processes inherent to the survival and growth of unique floodplain species are also altered. Restoration of the tree species native to a floodplain ecosystem requires examination of the specific flow requirements necessary for recruitment, growth, and survival. In the Savannah River basin, timing, magnitude, and duration of flood inundation must be carefully considered in efforts to revitalize key processes within its floodplain ecosystem. Increased peak flows during the winter months are necessary to ensure seed dispersal and to supply nutrients and water to floodplain soils. Periods of lower flows are needed during late spring and summer to reduce seedling mortality and enhance mature tree growth. Inter-annual variability must be reestablished to ensure a diverse assemblage of species on the floodplain.

(4) Effects of Flow Regime on Biological Processes in the Estuary

An additional consideration for the management of freshwater flow in reaches of the Savannah River below Thurmond Dam is the eventual effect that different river flow regimes could have on the estuarine ecosystem. Although a specific study has not been conducted on the Savannah River estuary, the effect of changing freshwater inflow to estuaries is an area that is now receiving increased attention [see Montagna et al. (2002) and also, generally, Estuaries Vol. 25:6B]. Below we review some of the general consequences of changing freshwater inflow to estuaries as well as the types of management approaches that have been used in other places. We then present a preliminary analysis of the effects of changing inflow to the Savannah River estuary.

EFFECTS OF FLOW ALTERATION

The quantity, quality, and timing of freshwater input are characteristics that define an estuary. The effects of changes in inflow to estuaries are reviewed in Alber (2002) and Sklar and Browder (1998). These papers describe how changing freshwater inflow can have a profound effect on estuarine conditions: salinity, mixing patterns, transit times, the size and shape of the estuary, and the distribution of dissolved and particulate material all may be altered. Inflow-related changes in estuarine conditions will in turn affect estuarine resources. Many estuarine resources are directly linked to salinity: the distribution of plants, benthic organisms, and nekton can shift in response to changes in salinity (Drinkwater and Frank 1994; Ardisson and Bourget 1997). Potential effects of freshwater regulation and diversion on the adult and larval stages of fish and invertebrates include effects on migration patterns, spawning habitat, species diversity, water quality and distribution and production of lower trophic levels (Drinkwater and Frank 1994). Changes in inflow will also affect the delivery of nutrients, organic matter, and sediment, which can in turn affect estuarine productivity rates and trophic structure. Changing the timing of freshwater inflow can also alter estuarine conditions, and will have varying effects depending on the life histories of estuarine organisms.

There are numerous papers that detail the effects of changing flow to specific estuaries. Halim (1991) and Aleem (1972) both provide information on the dramatic effects of inflow reduction to the Nile due to the Aswan Dam. Copeland (1966) describes the effects of a drought on Texas estuaries and documents the changes in invertebrate populations; Flint (1985) looks at longer-term variability in benthic invertebrates in Texas in response to changes in inflow. Drinkwater and Frank (1994) discuss in detail the marine response to specific river regulation projects on the Nile, Indus, and rivers flowing into the Black Sea, San Francisco Bay, and James Bay in Canada.

Livingston et al. (1997) looked at propagation of changes in inflow through an ecosystem in the Appalachicola River estuary, Florida, where a two-year drought led to an approximately 50% reduction in river flow. This resulted in an initial increase in primary production (due to reduced turbidity), followed by a long-term decrease in production, which may have been due to decreased delivery of nutrients to the estuary. There were also dramatic effects on trophic structure: overall trophic diversity decreased and there were increases in some groups (herbivores, detritivorous omnivores, primary and secondary carnivores) and decreases in others (tertiary predators were virtually absent). The effects of the drought took several years to make their way through the food web of the estuary.

FRESHWATER INFLOW REQUIREMENTS

There are a number of approaches for setting freshwater inflow requirements to an estuary. Alber (2002) classifies these as inflow-, condition-, and resource-based approaches. An inflow-based approach is one in which withdrawal is kept within some prescribed bounds under the assumption that taking too much water away is bad for estuarine resources. A condition-based approach is one in which inflow standards are set in order to maintain a specified condition (e.g. salinity) at a given point in the estuary. In a resource-based approach, inflow standards are set based on the requirements of specific resources. Below we briefly review some examples where estuarine freshwater inflow requirements have been established.

Florida law requires that the Water Management Districts establish “minimum flows and levels for surface waters and aquifers within their jurisdiction” (section 373.042(1), F.S.) The minimum flow is defined as “the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area." Steps in the development of minimum flows and levels (MFLs) include identifying water resource functions, defining significant harm, and providing standards to protect these functions against significant harm. Water resource functions protected under Chapter 373 are broad, and include flood control, water quality protection, water supply and storage, fish and wildlife protection, navigation, and recreation.

The Southwest Florida Water Management District (SWFWMD) sets upstream withdrawal limits as a proportion of river flow. This is an interesting approach in that it links withdrawal to daily flow, thereby preserving natural streamflow variations. This type of inflow-based policy is very much in keeping with the approach that is often advocated for river management, where flow is considered a master variable because it is correlated with many other factors in the ecosystem (Poff et al. 1997; Richter et al. 1997). In this case, the emphasis is on maintaining the natural flow regime with the premise that maintaining inflow will also maintain complex estuarine interactions regardless of whether scientists understand them.

The SWFWMD approach, along with some of the underlying biological studies that support the percent-of-flow approach, is detailed in Flannery et al. (2002). Since the responses of key estuarine characteristics (e.g. isohaline locations, residence times) are frequently non-linear, regulations are designed to prevent impacts to estuarine resources during sensitive low-inflow periods and to allow water supplies to become gradually more available as inflow increases. A high sensitivity to variation at low flow extends to many zooplankton and fish that move upstream and downstream in synchrony with inflow. Total numbers of estuarine and estuarine-dependent organisms have been found to decrease during low inflow periods, including mysids, grass shrimp, and juveniles of the bay anchovy and sand sea trout. The interaction of freshwater inflow with seasonal processes, such as phytoplankton production and the recruitment of fishes to the tidal river nursery, indicates that withdrawal percentages during the springtime should be most restrictive. Ongoing efforts are oriented toward refining percentage withdrawal limits among seasons and flow ranges to account for shifts in the responsiveness of estuarine processes to reductions in freshwater inflow.

The South Florida Water Management District (SFWMD) uses a resource-based approach. The proposed inflow to the Caloosahatchee Estuary was based on the distribution of indicator species. In this case, three species of seagrass (*Vallisneria americana*, *Halodule wrightii*, and *Thalassia testudinum*) were identified as key species that provide important benthic habitat for juvenile estuarine and marine species. These seagrasses are sensitive to changes in salinity, and maintaining their distribution patterns along the longitudinal axis of the estuary was proposed as an overall indicator of estuarine health. The SFWMD did a combination of field and laboratory research to determine the salinity sensitivity of the various seagrasses, and their results were then combined with modeling and hydrologic studies to determine the flow rates needed to maintain target salinities within the estuary (Doering et al. 2002). Chamberlain and Doering (1998) describe how the optimal flows determined for the seagrasses will also be beneficial for fish, shellfish, and other resources.

The proposed inflow to the Loxahatchee River and Estuary, which is also in the SFWMD, was initially based on maintaining the distribution of bald cypress, *Taxodium distichum*. In proposing a minimum flow for this system, the assumption was made that maintaining suitable environmental conditions for cypress would also be important for other desirable species (South Florida Water Management District (SFWMD) 2001). However, cypress are long-lived and slow-growing, so it may be many years before they would show a change in response to a change in inflow. This proposal has been revised and is now focused on sensitive plants in the floodplain-cypress community.

The approach taken by the Suwannee River Water Management District (SRWMD) for setting inflow for the Suwannee River estuary is summarized in Mattson (2002). The District's approach involves maintaining a natural inflow regime (in terms of magnitude, frequency, duration and timing of freshwater flows) and identifying important habitat targets to be protected. The District uses salinity ranges, limits of distribution of communities or habitats, and other characteristics to define the appropriate salinity and corresponding flow ranges needed to protect and maintain the resource targets. Habitats (and factors considered in setting salinity criteria) include tidal freshwater swamp (downstream limit of treeline; salinity tolerances of dominant species), low salinity submerged aquatic vegetation (SAV) beds (downstream limit of SAV beds; salinity tolerances of dominant taxa), brackish tidal marshes (ratio of *Cladium* to *Juncus*; salinity tolerances of dominant plants), tidal creeks (fish habitat value; maintenance of low salinity SAV habitat), and oyster reefs and bars (spat settlement in spring/summer; mortality at high salinity). Subsequent monitoring and research is undertaken to evaluate the effectiveness of the river flow criteria in protecting the estuarine resource targets.

The inflow standard for San Francisco Bay was developed to ensure that water of a specific salinity (2 PSU, Practical Salinity Units) is not allowed to encroach too far upstream in the estuary. Maintaining this isohaline downstream positions the salinity gradient of the estuary in such a way as to provide suitable habitat for many organisms, and investigators have found significant statistical relationships between the longitudinal position of this isohaline and numerous estuarine resources, including the total input of organic carbon; the supply of phytoplankton and phytoplankton-derived detritus; the abundance of mysids and shrimp; the survival of striped bass and striped bass year class strength; the survival of salmon smolts; and the abundance of planktivorous, piscivorous, and bottom-foraging fish (Kimmerer and Schubel 1994; Jassby et al. 1995). The process for developing this standard is summarized in Kimmerer and Schubel (1994), and Jassby et al. (1995) detail the relationships between 2 PSU and other estuarine characteristics. Further information on potential causal mechanisms for these relationships can be found in Kimmerer (2002).

The approach used to set inflow standards for the Texas Bays and Estuaries is through the use of the Texas Estuarine Mathematical Programming (TxEMP) model, which utilizes a series of relationships between historic monthly inflow and the catch of various fish (black drum, red drum, sea trout), crustaceans (blue crab, white shrimp, brown shrimp) and mollusks (clams, eastern oyster) (Matsumoto et al. 1994; Powell et al. 2002). The salinity ranges of each organism are considered, and if information on nutrients and sediments is available, it can be added as well (Matsumoto et al. 1994). Running the model requires input from managers in terms of which species are included, the relative weighting of the species, fishery harvest targets, and constraints on inflow, salinity, nutrient loading, and sediment loading (Powell and Matsumoto 1994). The model itself is a nonlinear, stochastic, multi-objective model of salinity-inflow and inflow-fishery harvest equations. Model results are in the form of a performance curve, which is a series of solutions that seeks to optimize inflow/harvest relationships. Variability in the inflow/salinity relationship is used to set statistical bounds on salinity.

One technique for ameliorating the effects of reduced inflow is through a targeted diversion. Ward et al. (2002) describe a demonstration project done by the U.S. Bureau of Reclamation in the Nueces River in Texas. The Nueces River is the primary source of freshwater inflow to Corpus Christi Bay and virtually the only source of freshwater inflow to the Nueces Delta. Reservoir development and operation in the Nueces Basin has greatly reduced freshwater inflow to the Delta, causing increased salt concentrations in the soil and water. The Bureau excavated two overflow channels, significantly lowering the minimum threshold for flooding to the upper Delta without having to increase total flow through the main channel. As a consequence of the excavation, the amount of freshwater diverted to the upper Nueces Delta increased by a factor of seven and average salinity was greatly decreased, leading to a corresponding improvement in abundance and diversity of both intertidal vegetation and benthic communities. This study demonstrates that small changes in overflow can result in large changes in local salinity, and exploiting this might be an effective management strategy. Additional information can be found in Montagna et al. (2002) and Palmer et al. (2002).

Most of the rivers described above do not have the magnitude of flow or degree of perturbation seen in the Savannah River, and some examples such as the Nile River are too extreme to apply here. Nevertheless, many of the same concepts illustrated in these examples may be applicable to the Savannah River estuary and the regulation of flow via Thurmond Dam. A resource-based approach, such as that used in the Caloosahatchee River estuary (Doering et al. 2002), may work in the Savannah River estuary provided that suitable indicator species and associated conditions can be identified. The indicator species they used, seagrasses, are not found in Georgia, and indeed no benthic organism would be useful in the Savannah because the channel is dredged periodically. However, maintaining freshwater marsh species above specified locations may be a suitable goal (see marsh habitat discussion below). Freshwater marsh is dependent on maintaining a suitable salinity distribution, so this approach would converge with that used in San Francisco Bay (Kimmerer and Schubel 1994; Jassby et al. 1995). Many of these concepts are brought together in the approach used in the Suwannee River estuary (Mattson 2002). The Appalachicola River estuary example (Livingston et al. 1997) demonstrates that the effects of inflow changes on trophic structure can be complex, and any changes may need to be evaluated several years later to make sure that effects have stabilized.

In contrast, the percent-of-flow approach (Flannery et al. 2002), although appealing from the standpoint of maintaining natural variability, may be difficult to apply to a multi-reservoir system such as the Savannah, where flow upstream of Thurmond Dam is also regulated. The TxEMP model (Matsumoto et al. 1994; Powell and Matsumoto 1994; Powell et al. 2002), with its emphasis on optimizing fisheries, would probably be difficult to apply to the Savannah River estuary as well.

CHARACTERISTICS OF THE SAVANNAH RIVER ESTUARY

This section focuses on the Savannah River estuary and the available information for linking estuarine characteristics with inflow. Specific areas of concern for the Savannah include loss of freshwater marsh and its accompanying biotic diversity, and alteration of the availability of suitable habitat for several fish species including striped bass and shortnose sturgeon. The effects of changing freshwater inflow on these components of the estuarine system will be primarily due to changes in the salinity distribution within the estuary. Additionally, a proposal to deepen the Savannah River harbor will also affect the salinity distribution, as well as other aspects of water quality. Any proposed changes in flow regulation at Thurmond Dam should be evaluated in concert with potential changes due to harbor deepening.

Relationship of inflow to salinity

As part of their Savannah Harbor Expansion Feasibility Study, the Georgia Ports Authority (GPA) contracted with Applied Technology and Management, Inc. (ATM) to develop a 3-dimensional numerical hydrodynamic and water quality model of the Savannah River estuary. Preliminary results from this model, based on the most extreme deepening option under consideration, were summarized in their Tier I Environmental Impact Statement (EIS) (Georgia Ports Authority 1998) and accompanying report on Hydrodynamic and Water Quality Modeling of the Lower Savannah River Estuary (Applied Technology & Management Inc. 1998). The option evaluated, extending the harbor depth from the current 42 ft to 50 ft, is more severe than the currently proposed

48-ft option but represents a reasonable maximum-impact scenario for projecting the scale of any likely effects on the estuary. Reported results included the projected locations of several oligohaline salinity contours (0.5, 1.0, 2.0 and 5.0 PSU) under three river flow scenarios (ranging from near critical low flow to average flow) and three estuarine geometries (current, 50-ft deep, and 50-ft deep plus a closure to restrict salinity intrusion into the Middle River to protect the Savannah National Wildlife Refuge). The 0.5 PSU high tide surface contour is particularly critical for freshwater marsh species, and the 0.5 PSU tidally averaged bottom contour is critical for freshwater aquatic species. We used these results to evaluate both how changes in flow affect the salinity distribution in the estuary and whether any flow scenario changes at Thurmond Dam can affect the estuary as much as the proposed harbor deepening. Since the release of the Tier I EIS, the ATM model has been updated and recalibrated and will be linked to dissolved oxygen (water quality) and marsh succession models (see harbor deepening project documents available at http://www.sysconn.com/harbor/). The analyses that follow should be re-evaluated after results of the updated model become available.

The model's boundary input conditions include freshwater inflow at the Clyo gage plus 10% to allow for additional inflow between Clyo and the head of the modeled region. The flow scenarios evaluated in the EIS were 5,300, 8,200, and 11,000 cfs, which span a range of low to average conditions (critical low flow is 4,000 cfs, growing season average flow is 9,500 cfs, and 11,000 cfs is a typical spawning season flow and is near the post-impoundment mean annual flow). Model output from these three inflow values can thus be used to evaluate the effect of changes ranging from 2,800 to 5,700 cfs, at low to average flows. In comparison, the mean annual flow at Clyo after impoundment (11,928 cfs, 1954-2000) is only 401 cfs below the mean annual flow before impoundment (12,329 cfs, 1929-1949). However, differences in mean monthly flow, post- minus pre-impoundment, range from –3,824 to +2,020 cfs (R. Jackson, pers. comm.).

Relevant model results from the EIS and report are summarized in Table 20 and include predictions of median high tide salinities in surface water and median tidally averaged ("all tide") salinities in bottom water. Where selected values given in the text differed from the contour plots presented in figures, we used values estimated from the figures (to the nearest 0.1 mile) for consistency. (Differences were usually 0.3 miles or less but in one case was 1.3 miles where apparently the wrong contour was reported in the EIS.)

We first used these results to estimate the rates of change in the location of the salinity contours in the estuary under existing conditions. High tide surface salinity contours move in different patterns than all tide bottom salinity contours as flow increases: at low flows, surface and bottom contours move similar distances with changes in flow, but at intermediate flows, surface salinity contours move more drastically than bottom salinity contours (Fig. 33). As flow increases from 5,300 to 8,200 cfs, surface and bottom contours move 0.1-0.9 miles downstream for every 1,000 cfs increase in flow, except for the 5.0 PSU surface contour in the Front River, which moves 1.4 miles. As flow increases from 8,200 to 11,000 cfs, high tide surface contours move 0.5-1.0 miles downstream for every 1,000 cfs increase in flow, and all tide bottom contours move 0.0-0.3 miles. If we use the overall range of 0.0-1.0 mile per 1,000 cfs, then an increase of 400 cfs at Clyo (the difference in average annual flow between pre- and post-impoundment) would result in a predicted downstream shift in salinity contours of only 0.4 miles or less. More extreme seasonal changes in flow (on the order of +/- a few thousand cfs) may move salinity contours up- or downstream approximately 1-2 miles from their current seasonal positions.

The impact of the proposed harbor deepening on salinity distribution in the various branches of the upper Savannah River estuary will depend strongly on whether the option to close the lower Middle River and reopen New Cut is implemented (Table 20). In the Front River, deepening alone is projected to cause the 0.5 PSU salinity contour to move upstream 0.7-2.2 miles in high tide surface water and 1.0-2.8 miles in bottom water. The higher salinity contours in the Front River may move upstream 0.0-0.9 miles in surface water and 0.2-1.4 miles in bottom water. In the Middle River, deepening alone is projected to cause the 0.5 PSU salinity contour to move upstream approximately half as far: 0.2-1.1 miles in high tide surface water and 0.5-1.4 miles in bottom water. The higher salinity contours in the Middle River may move upstream 0.1-2.2 miles in surface water and 0.2-1.9 miles in bottom water. In the Back River, deepening alone is projected to cause less extreme changes, with contours moving up to 0.6 miles upstream. In contrast, harbor deepening with the closure option is projected to cause the 0.5 PSU contours in both the Back and Middle Rivers to move *downstream* from their current positions. However, this option would force more seawater into the Front River at low flows, causing the 0.5 PSU salinity contour to move 0.8-1.5 miles upstream from its current position in surface water and 1.7-3.9 miles upstream in bottom water, which is more than the effect of deepening alone. At average flow, the closure option is expected to cause salinity contours in the Front River to move upstream from their current positions in bottom water but downstream in high tide surface water.

We combined the estimated rate of change in the location of the salinity contours in response to changes in discharge (from above) with the projected positions of the various contours under the 50-ft deep scenario to express the effect of harbor deepening as an equivalent change in discharge at Clyo. In terms of bottom salinity, deepening the harbor to 50 ft without the closure option will move the 0.5 PSU tidally averaged bottom salinity contour in the Front River 2.1 miles upstream at average flow (11,000 cfs). Given that under present conditions this contour moves approximately 0.3 miles per 1,000 cfs down to 8,200 cfs and 0.9 miles per 1,000 cfs below that, the effect of the harbor deepening is equivalent to reducing the average river flow at Clyo by 4,300 cfs. Applying this calculation to the other bottom salinity contours at average flow indicates that, depending on the contour of interest, the deepening would have the same effect as reducing the average flow at Clyo by 2,800-4,700 cfs except for a few contours in the Back River. In terms of surface salinity, harbor deepening is projected to cause the 0.5 PSU high tide surface salinity contour in the Front River to move 2.2 miles upstream at average flow. Given that this contour moves approximately 1.0 mile per 1,000 cfs near average flow under present conditions, deepening the harbor is equivalent to reducing the average river flow at Clyo by 2,200 cfs. For the other surface salinity contours at average flow, harbor deepening would have the same effect as reducing the average flow at Clyo by 800-2,600 cfs with the exception of a few of the Back River contours.

As described above, deepening the harbor with the closure option is projected to have very different effects in the Front vs. Middle and Back Rivers. In cases where this option would cause further salinity intrusion into the Front River, the equivalent flow effects are large: movement of the 0.5 PSU bottom salinity contour would be equivalent to reducing the average flow at Clyo by 4,500 cfs. The 0.5 PSU high tide surface salinity contour at 8,200 cfs would move1.5 miles upstream, equivalent to reducing flow at Clyo by 2,000 cfs during the growing season, which may be critical for the freshwater marsh. In cases where closure would cause salinity contours to move downstream relative to their current positions, primarily in the Middle and Back Rivers, this would be equivalent to flow increases on the order of 700-10,000 cfs.

Given the magnitude of salinity changes predicted in the event of harbor deepening, it is unlikely that any change in the releases at Thurmond Dam toward pre-impoundment conditions would be large enough to completely overcome the effects of harbor deepening. The average flow that would be necessary to ameliorate even the weaker effects of the deepening, at least 13,200 cfs (the current average of 11,000 plus 2,200 to counteract the movement of the 0.5 PSU high tide surface contour), is more than the pre-impoundment annual average flow at Clyo. Seasonal changes in flow of a larger magnitude, on the order of several thousand cfs, might just counteract the deepening during some times of the year, but only if the change is toward more flow. As potential seasonal flow scenarios are developed for this project, it may be possible to make a rough determination of how their effects would interact with the effects of harbor deepening.

Relationship of inflow to marsh habitat

Changes in freshwater inflow, and consequent changes in the salinity distribution in the estuary, may affect the distribution of habitat types important for estuarine biota. Specifically, the distribution of freshwater marsh in the Savannah National Wildlife Refuge has been a concern, especially since previous alterations to the estuary, such as harbor deepening and the installation and removal of a tide gate, have affected the amount and distribution of freshwater marsh (Latham et al. 1993; Pearlstine et al. 1993). If the salinity distribution is altered (either through changes in freshwater inflow or through upstream intrusion of saltwater as the result of harbor deepening), it will likely result in a shift in the distribution of vegetation. The downstream limit of freshwater marsh in the Savannah National Wildlife Refuge is determined primarily by the location of the 0.5 PSU salinity contour at high tide, especially during the lower flow periods of the year (see Georgia Ports Authority 1998 and Pearlstine et al. (1990) referenced within). The current downstream limits of freshwater vegetation were identified in

Enclosure G of the EIS as Steamboat River and Rifle Cut, which correspond to River Mile 22.8 (km 36.8) in the Front River and River Mile 21.0 (km 33.9) in the Back River. For comparison, the locations of the 0.5 PSU high tide surface contours at 8,200 cfs were identified in the ATM model as River Mile 23.0 (km 37.1) in the Front River and 21.0 (km 33.9) in the Back River.

In addition to salinity, another consideration for predicting the effect of changing inflow on marsh vegetation is the fact that the extent of the intertidal habitat varies along the length of the estuary. In some regions the edge of the estuary has a low slope and the area subject to tidal inundation is much greater than in regions with steeper slopes. This means the effects of changing the location of a given salinity contour could be uneven in terms of the loss or gain of intertidal habitat (i.e. if the 0.5 PSU contour is pushed upstream to a location with less intertidal inundation, it could result in a greater loss of freshwater marsh than if it were positioned where there was greater intertidal area). The relationships between flow and salinity distribution represented in the ATM model, along with estimates of tidally inundated area, could be used to determine how much intertidal area might be affected by critical changes in salinity if flow were altered. We anticipate that this type of information will result from the linkage of the updated ATM model to a marsh succession model.

Effects of inflow on striped bass (*Morone saxatilis*)

Striped bass *Morone saxatilis* and striped bass hybrids (i.e., cross with the white bass, *M. chrysops*) are highly popular fisheries in reservoirs, rivers, and estuaries across Georgia and account for a significant portion of the $448 million in annual angler expenditures (Carl Hall, GA-DNR, personal communication). Historically, the Savannah River hosted Georgia's most important striped bass fishery and was the source of brood fish for the Georgia Department of Natural Resources (GA-DNR) *Morone* stocking program.

Striped bass in the south Atlantic region are predominantly riverine and spend their entire life cycle in the same river (Hill et al. 1989). In the Savannah River estuary, the Back River area has been vital to all life history stages of the endemic striped bass population. The majority of striped bass spawning has occurred in the Back River

(Dudley and Black 1979), and young-of-year stripers have used the Back and Middle Rivers as nursery grounds (Wallin et al. 1995). Adult striped bass use the Back and Middle Rivers to over-winter and spawn, and smaller fish remain there throughout the year (Mooneyhan and Van Den Avyle 1995).

The population suffered a severe decline in the 1980s concurrent with conversion of tidal freshwater marsh to brackish marsh. The decline in the striped bass population was attributed to increased salinity in spawning and nursery grounds and transport of eggs and larvae to areas of toxic salinity (Van Den Avyle et al. 1990). In hopes of restoring the freshwater marsh and suitable spawning habitat, mitigation efforts began in 1991 with the removal of the tide gate from operation and filling of the diversion canal in 1992.

Striped bass studies have indicated that a maximum salinity of 1.5 PSU or less is optimal for spawning and subsequent egg development (Bain and Bain 1982) and that exposure to salinity greater than 15.0 PSU was toxic to eggs (Winger and Lasier 1989). In the Savannah River, striped bass have spawned almost exclusively in areas where maximum salinity near the surface was less than 1.0 PSU (Van Den Avyle et al. 1990; Reinert and Jennings 1998; Will et al. 2000) from about mid-March to early-May. In laboratory studies at a constant salinity, Savannah River striped bass larvae survived well at 3.0 to 9.0 PSU salinity, but survival decreased at higher salinity. Five-day-old larvae were able to tolerate higher salinity than two-day-old larvae (Winger and Lasier 1989). An average salinity of 3.0 to 7.0 PSU was optimal, but larvae could survive in up to 15.0 PSU salinity (Bain and Bain 1982). The larval development period in the Savannah River can occur from late March through early June.

In addition to salinity, striped bass eggs need a mean current velocity of 30 cm/s or more to keep eggs suspended in the water column and allow normal development (Bain and Bain 1982). A minimum dissolved oxygen level of 5.0 mg/l or more is optimal for egg and larval development. Survival decreases rapidly and habitat becomes unsuitable at about 3.0 mg/l (Bain and Bain 1982).

River discharge can have a significant effect on factors that influence striped bass reproductive success and on the availability of freshwater habitat in the Savannah River estuary. High river discharge (>15,000 cfs) can extend low-salinity habitat down the entire Back River and Middle River reaches and to at least river mile 20 in the main Savannah River channel (Front River). Likewise, low river discharge (<5,000 cfs) can result in high salinity habitat (>10 PSU) in many of these areas (Jennings and Weyers 2003). Historically, river discharge has been high during winter and spring when many oligohaline and tidal freshwater fishes spawn in the upper Savannah River estuary. The availability of these low salinity habitats (< 5.0 PSU) is critical for egg and larval survival for striped bass and some other important estuarine-dependent fishes. Therefore, river discharge can play a critical role in successful reproduction. Without suitable habitat, abundance of many species probably will decline, further stressing the Savannah River estuary ecosystem.

(5) Conceptual Models of Effects of Flow Regulation on Three Regions of the Lower Savannah River

CONCEPTUAL MODEL OF EFFECTS OF RIVER REGULATION ON BIOLOGICAL PROCESSES IN THE AUGUSTA SHOALS OF THE SAVANNAH RIVER

Relationships of flow regulation to biotic processes in the Augusta Shoals are illustrated in the conceptual model in Figure 34. Similar to the Savannah River floodplain and estuary, multiple anthropogenic factors contribute to an altered flow regime. Hydropower operation at Thurmond Dam and the diversion of water at the Augusta Diversion Dam have significantly altered the flow regime from that of historic conditions in the shoals. Resulting lower base flows (see Part 2, "AUGUSTA SHOALS" for a more thorough description) affect flora and fauna in an array of processes. Apart from that, reservoir operation reduces sediment delivery, reduces inter-annual flow variation, lowers water temperature, and increases daily flow variation.

Lower Base Flows

Lower base flows affect biota in a variety of ways, primarily by changing spawning and foraging habitats. Lower base flows limit the amount of habitat available for mussel foraging. Because of their limited mobility, mussels are restricted to areas that remain inundated for long periods of time. Consequently, base flows define the useable habitat available to mussels and lower baseflows limit that habitat.

For similar reasons, lower base flows reduce the amount of suitable spawning substrate for the robust redhorse *Moxostoma robustum*, Atlantic sturgeon *Acipenser oxyrinchus*[1], and fishes that spawn in shallow-fast water. Low base flows reduce water velocity and the amount of river with flowing water, thereby limiting foraging habitats for some species and spawning habitat for water column spawners, such as the American shad *Alosa sapidissima* and striped bass *Morone saxatilis*. For larger fishes, shallow water impedes movement into spawning habitats. Thus, low base flows result in poor recruitment for some species through a variety of pathways.

---

[1] Although the Atlantic sturgeon does not currently occur in the Augusta Shoals, it is considered here because the shoals may represent historic spawning grounds. This species may occur in the shoals once fish passage at New Savannah Bluff Lock and Dam has been restored.

Although foraging habitat is also reduced for some of the previously mentioned species, foraging habitat increases for the shallow-slow guild. Shallow, slow-moving water habitats are more common during low flow conditions and species that prefer these habitats for foraging and spawning show a corresponding increase in recruitment.

The effects of lower base flows are not limited to fishes. Terrestrial animals, such as the white-tailed deer *Odocoileus virginianus* and raccoon *Procyon lotor* have more access to the shoals during low water periods. Consequently, the endangered shoals spider lily *Hymenocalis coronaria* is grazed heavily, resulting in reduced lily growth and dispersal (Aulbach-Smith, 1998).

Reduced Sediment Delivery

The natural replacement of bed sediments during floods is essential in maintaining mussel and fish habitats. In the case of hydropower dams, however, sediments are moved downstream during high-flow, power generating periods. However, dams trap sediment, preventing renewal of downstream sediment and ultimately resulting in streambed scouring. Thus, habitats that are essential for some mussel species, robust redhorse, Atlantic sturgeon[1], and the shallow-fast guild are gradually lost. Consequently, fish and mussel recruitment decline.

Lower Water Temperatures

In many rivers with cold-water, hypolimnetic discharge, fish spawning is delayed, mussel growth is reduced, and mussel reproduction is prevented (Watters, 2002). Thurmond Dam releases water from the hypolimnion, but the resulting downstream temperature change is not known at this time. Although water probably warms as it moves through the shoals, cold water may be a problem for mussel reproduction in close proximity to the dam.

Higher Daily Fluctuations

Daily flow fluctuations affect fish communities by reducing habitat stability and suitability. Although the daily flow fluctuations resulting from hydropower generation at Thurmond Dam are dampened by the presence of Steven's Creek Dam, the shoals still experience fluctuations that can greatly change instream habitats. The persistence of shallow-water habitats is essential for the development of young-of-year fishes (Freeman et al., 2001). Periodic desiccation of shallow instream habitats may make some habitats unsuitable by eliminating basal resources. Consequently, daily fluctuations alter instream habitats, which in turn alters the fish community.

EFFECTS OF RIVER REGULATION ON BIOLOGICAL PROCESSES IN THE MAIN CHANNEL AND FLOODPLAIN OF THE SAVANNAH RIVER BELOW THURMOND DAM

The hydrology of the Savannah River system from the Augusta Shoals to the estuary has been extensively modified by flow regulation at Thurmond Dam and dredging . The result is a number of effects on floodplain process that result in altered tree, bird, fish, and mussel communities along both the river and its floodplain. The conceptual model illustrating the consequences of river regulation and dredging is shown in Figure 35.

Channel straightening has resulted in fewer channel bends and a loss of spawning habitat for the robust redhorse *Moxostoma robustum*, Atlantic sturgeon *Acipenser oxyrinchus*, and the endangered shortnose sturgeon *A. brevirostrum*. Channel bends frequently have inflowing tributaries that provide pathways for floodplain inundation during high flow events and access points for fishes that spawn in the floodplain. Reservoir operation has reduced the magnitude of floodplain inundation (i.e. the amount of inundated area). Thus, the amount and variety of foraging and spawning habitat is probably limited compared to that of historic conditions. Reduction in the magnitude of floodplain inundation has also potentially resulted in drier overall conditions in the floodplain throughout the growing season for vegetation. This reduced soil moisture could alter tree species composition in the floodplain, increasing the probability of fire and subsequent pine invasion, and the probability of invasion by less flood-tolerant upland species. Changes in tree species composition also results from reduced interannual variability in flooding. Without periodic high magnitude flood events, some shade-intolerant floodplain tree species have few germination and establishment possibilities, increasing the vulnerability of invasion by shade-tolerant exotics such as the

Chinese tallow tree *Sapium sebiferum*. Changes in tree species composition can have an impact on some habitat-specialist floodplain bird species such as the prothonotary warbler *Protonotaria citrea*, and the Swallow-tailed *Elanoides forficatus* and Mississippi kite *Ictinia mississippiensis*.

Earlier minimum flows probably cause drainage of the floodplain during essential periods of larval development (Tables 4-7), resulting in stranding of floodplain larval fishes. Earlier and lower flows in the spring may also have consequences for riverine fishes that spawn in the water column, such as striped bass *Morone saxatilis* and American shad *Alosa sapidissima*. The result is an altered fish community that may impact mussel species that depend on host fish for reproduction and dispersal (Table 12). Lower flows in the winter and early spring can also limit the seed dispersal of some floodplain trees, such as bald cypress *Taxodium distichum* and water tupelo *Nyssa aquatica*, which depend on high winter flows for hydrochory. Floodplain vegetation often depends on high flows in the winter and early spring to resupply floodplain soils with nutrients and moisture. Dampening of these high flows results in both growth reduction and higher mortality for many bottomland hardwood species.

Early floodplain drainage may also affect nesting effort and success of the belted kingfisher *Ceryle alcyon*, bald eagle *Haliaeetus leucocephalus*, the endangered wood stork *Mycteria americana*, and all Ciconiformes by limiting the accessibility to fish prey (Frederick, 1995). Wood stork population numbers, and probably other Ciconiformes, are strongly affected by hydrology. Drying of the land below nest sites has improved accessibility for raccoons, resulting in increased predation and dramatic declines in wood stork nest success in the Savannah River floodplain (USFWS, 2002).

Higher flows during the growing season for vegetation (late spring and early summer) can have dramatic effects on a number of floodplain tree species. Under the stress of prolonged flooding, mature bottomland hardwood and bottomland swamp species suffer reduced growth and higher mortality. Seeds are unable to germinate under flooded conditions, and newly-germinated seedlings demonstrate significant mortality after only a couple weeks of inundation. Higher floods during this time can also have adverse effects on bird species such as the belted kingfisher *Ceryle alcyon* and the prothonotary warbler *Protonotaria citrea*, which build their nests near or in the ground. Nest flooding in these species often results in nest abandonment and death of young.

CONSEQUENCES OF CHANGING SALINITY AND/OR HABITAT IN THE ESTUARY

Many of the relationships among freshwater inflow, estuarine conditions, and estuarine resources that are relevant to the Savannah River estuary are summarized in the conceptual model presented in Fig. 36. The relevant effects of both flow regulation at Thurmond Dam and the proposed harbor deepening are considered because many of the same conditions and resources would be affected, and changes in flow at Thurmond Dam could ameliorate or exacerbate the changes due to harbor deepening.

Most of the important effects of changes in flow at the dam or harbor deepening will probably be related to changes in the salinity distribution in the estuary. Changes due to the dam would affect salinity via changes in the amount and timing of freshwater inflow and could cause seasonal increases or decreases in flow, whereas harbor deepening would increase salinity via greater upstream intrusion of seawater. This means that seasonal changes in salinity from present conditions could be increases (flow decrease with or without harbor deepening), decreases (flow increase without harbor deepening), or neutral (flow increase balancing harbor deepening). An increase in salinity during critical times of the year (marsh growing and fish spawning seasons) seems the most likely effect if the harbor is deepened and/or the flow at the dam is altered toward pre-dam conditions in spring and summer. We therefore describe changes in estuarine resources in terms of a salinity increase, recognizing that opposite effects would occur if salinity were decreased.

If salinity increases over the long term, one of the expected effects would be a gradual encroachment of brackish and salt marsh species into areas of the Savannah National Wildlife Refuge that are now freshwater marsh. Such changes have already occurred due to past harbor deepenings as well as installation of the tide gate on the Back River (Pearlstine et al. 1993). Once freshwater marsh is replaced by more salt-tolerant species, reversal of the effect by increasing freshwater delivery is slow; removal of the tide gate has resulted in some recovery of freshwater marsh but at much slower rates than expected (Latham and Kitchens 1996; Georgia Ports Authority 1998). Loss of freshwater marsh is a concern because of its greater biotic diversity relative to salt marsh. On a seasonal scale, salinity changes can influence the distribution of subtidal, mobile species such as fish. Even though mobile species may move along with water of a preferred salinity, such movement could bring them into habitats with different characteristics in terms of features such as food availability, amount of cover, or water quality.

If freshwater inflow to the estuary is changed substantially, current velocities may also change, although the effects may be complex and hard to predict. The reproductive success of striped bass in the Middle and Back Rivers has been shown to be dependent on current velocities within certain ranges (see Part 4 and references in Georgia Ports Authority 1998). Current velocity may also affect shortnose sturgeon reproduction and survival, although salinity and dissolved oxygen are probably more critical (see references in Georgia Ports Authority 1998). Also, see the discussion of the requirements of these species in Part 2.

Freshwater inflow changes may also affect nutrient loading, sedimentation, and transit time of freshwater and substances carried with it through the estuary, and these in turn may have general but complex effects throughout the estuarine food web. For example, decreased freshwater inflow would likely result in decreased nutrient loading to the estuary, which would be expected to result in lower primary and secondary production. However, decreased freshwater inflow would also increase transit time through the estuary, which could result in higher primary and secondary production by providing more time for nutrient uptake and other processes to occur within the estuary. In many systems, however, increased catches of commercial fishery species are associated with higher freshwater inflow (Alber and Flory 2002). Shrimp and crabs are the two largest commercial fisheries in Georgia. An increase in flow may lead to an increase in the production of these organisms, but the uncertainty regarding the effect of inflow on nutrients coupled with cascading effects through the food web make these relationships complex and difficult to predict. The two freshwater species in our model (striped bass and shortnose sturgeon) are known to be sensitive to salinity and have received a great deal of study in the context of the harbor deepening. The response of these two species to changes in inflow, as well as the other fish that comprise the estuarine community, is a topic that needs further investigation. Information from a recent detailed study of the estuarine fish community in the Savannah River estuary may be useful in this regard (Jennings and Weyers 2003).

Finally, the consequences of any changes in flow at Thurmond Dam on the Savannah River estuary should, if possible, be evaluated in terms of other effects. For example, the level of chloride at the City of Savannah water intake may change if salinity increases. Evaluation of this in connection with the harbor deepening is pending, but the potential for additional changes in chloride levels as a result of flow regulation at the dam must be considered. In addition to harbor deepening, other concurrent changes may also occur. Currently, climate change models are divided as to whether changes in precipitation and temperature will result in more or less freshwater inflow to southeastern estuaries (Wolock and McCabe 1999), but sea level rise would be expected to result in slowly increasing salinities.

OPPORTUNITIES FOR FURTHER RESEARCH

The purpose of this report was to summarize existing data from the Lower Savannah River to provide a background for discussions of ecosystem flow needs in the river. As a result of this summary, the discussions at the April workshop, and reviews of an earlier draft of this summary, several needs for further research and analysis became apparent. The priority research needs identified at the workshop are presented in the final report of the April workshop (Ecosystem Flow Recommendations for the Savannah River below Thurmond Dam available at www.rivercenter.uga.edu). The research needs that have been identified offer opportunities to improve scientific understanding of large rivers as well as to provide data that will be essential for improving management of the Savannah River ecosystems.

ACKNOWLEDGEMENTS

This report was made possible by funding from the US Army Corps of Engineers, U.S. Fish and Wildlife Service, and the Departments of Natural Resources of Georgia and South Carolina through The Nature Conservancy, who provided coordination and guidance. We would like to thank Kim Lutz and Brian Richter for their advice and assistance and John Dowd for making his RiverStat software available to us and providing assistance in its use.

LITERATURE CITED

Aadland, L.P. 1993. Stream habitat types: their fish assemblages and relationship to flow. *North American Journal of Fisheries Management*. 13:790-806.

Alber, M. 2002. A conceptual model of estuarine freshwater inflow management. *Estuaries* 25:1246-1261.

Alber, M. and J. Flory. 2002. The effects of changing freshwater inflow to estuaries: A Georgia perspective. White Paper. Georgia Coastal Research Council, Department of Marine Sciences, University of Georgia, Athens, Georgia.

ALDEN Research Laboratory, Inc. 2002. Fish passage and protection plan for the Augusta Canal hydropower project. FERC Project No. 11810-000.

Aldermain, J.M. 1992. Status survey for the Savannah lilliput *Toxolasma pullus* (Conrad 1938). Report for Cooperative Agreement 14-16-004-89-954, U.S. Fish and Wildlife Service, Asheville NC.

Aleem, A. A. 1972. Effect of river outflow management on marine life. Marine Biology 15:200-208.

American Eel Plan Development Team (AEPDT). 2000. Interstate fishery management plan for American eel (*Anguilla rostrata*). Atlantic State Marine Fisheries Commission, Washington D.C. Fishery Management Report. No. 36, 93 pp.

Applied Technology & Management Inc. 1998. Hydrodynamic and Water Quality Modeling of the Lower Savannah River Estuary. Georgia Ports Authority, Savannah, Georgia.

Ardisson, P.-L. and E. Bourget. 1997. A study of the relationship between freshwater runoff and benthos abundance: a scale-oriented approach. *Estuarine, Coastal and Shelf Science* 45:535-545.

Aulbach-Smith, C., 1998. *Hymenocallis coronaria*, the rocky shoals spider lily; Savannah River, Augusta, Georgia. *In* Augusta Canal Project, FERC Project 11581-000 (ENTRIX, ed.). Augusta, Georgia.

Avise, J.C., G.S. Helfman, N.C. Saunders, and L.S. Hales. 1986. Mitochondrial DNA differentiation in North Atlantic eels: population genetic consequences of an unusual life history pattern. *Proceedings of the National Academy of Science*. U.S.A. 83:4350-4354.

Avondale Mills, Inc. 2001. Final Application for a new license, Sibley Mill Project. FERC No. 5044. Augusta, Georgia, March 2001.

Bailey, H.C., and S.I. Doroshov. 1995. The duration of the interval associated with successful inflation of the swimbladder in larval striped bass (*Morone saxatilis*). *Aquaculture*. 131:135-143.

Bain, K.B. and J.L. Bain. 1982. Habitat suitability index models: Coastal stocks of striped bass. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C. FWS/OBS-82/10.1. 29 pp.

Baker, J.A., K.J. Killgore, and R.L. Kasul. 1991. Aquatic habitats and fish communities in the lower Mississippi River. *Reviews in Aquatic Sciences*. 3: 313-356.

Batzer, D. P. and S. A. Wissinger 1996. Ecology of insect communities in nontidal wetlands. *Annual Review of Entomology* 41: 75-100.

Benke, A. C. 2001. Importance of flood regime to invertebrate habitat in an unregulated river-floodplain ecosystem. *Journal of the North American Benthological Society* 20(2): 225-240.

Bjorgo, K.A., J.J. Isley, C.S. Thomason. 2000. Seasonal movement and habitat use by striped bass in the Combahee River, South Carolina. *Transactions of the American Fisheries Society*. 129:1281-1287.

Bowen, Z.H., M.C. Freeman, K.D. Bovee. 1998. Evaluation of generalized habitat criteria for asesing impacts of altered flow regimes on warmwater fishes. *Transactions of the American Fisheries Society* 127: 455-468.

Bowers, C., H. Hanlin, et al. 2000. Herpetofaunal and vegetational characterization of a thermally-impacted stream at the beginning of restoration. *Ecological Engineering* 15(supplement 1): S101-S114.

Brown, G.W. 1888. Map of the Savannah River from Andersonville, S.C. to Augusta, GA. U.S. Engineer Office Savannah, GA.

Brown, S., 1981. A comparison of the structure, primary productivity, and transpiration of cypress ecosystems in Florida. *Ecological Monographs* 51: 403-427.

Bruce, K.A., G.N. Cameron, P.A. Harcombe and G. Jubinsky, 1997. Introduction, impact on native habitats, and management of a woody invader, the Chinese tallow tree, *Sapium sebiferum* (L.) Roxb. *Natural Areas Journal* 17: 255-260.

Chamberlain, R. H. and P. H. Doering. 1998. Preliminary estimate of optimum freshwater inflow to the Caloosahatchee Estuary: a resource-based approach. In *Proceedings of the Charlotte Harbor Public Conference and Technical Symposium*. Charlotte Harbor National Estuary Program.

Chapman, F.A., and S.H. Carr. 1995. Implications of early life stages in the natural history of the Gulf of Mexico stugeon, *Acipenser oxyrinchus desotoi*. *Environmental Biology of Fishes*. 43:407-413.

Collins, M. R., and T. I. J. Smith. 1995. Characteristics of the adult segment of the Savannah River population of shortnose sturgeon. *Proceedings of the Annual Conference of Southeastern Association of Fish and Wildlife Agencies*. 47(1993):485-491.

Collins, M. R., W. C. Post, D. C. Russ, and T. I. J. Smith. 2002. Habitat use and movement patterns of juvenile shortnose sturgeon in the Savannah River, Georgia-South Carolina. *Transactions of the American Fisheries Society*. 131:975-979.

Collins, M.R., S.G. Rogers, T.I.J. Smith, and M.L. Moser. 2000a. Primary factors affecting sturgeon populations in the southeastern United States: fishing mortality and degradation of essential habitats. *Bulletin of Marine Science*. 66:917-928.

Collins, M.R., T.I.J. Smith, W.C. Post, and O. Pashuk. 2000b. Habitat utilization and biological characteristics of adult Atlantic sturgeon in two South Carolina rivers. *Transactions of the American Fisheries Society*129: 982-988.

Conner, W.H. 1994. The effect of salinity and waterlogging on growth and survival of baldcypress and Chinese tallow seedlings. *Journal of Coastal Research* 10: 1045-1049.

Conner, W.H., K.W. McLeod and J.K. McCarron. 1998. Survival and growth of seedlings of four bottomland oak species in response to increases in flooding and salinity. *Forest Science* 44: 618-624.

Conner, W.H., L. Mihalia and J. Wolfe. 2002. Tree community structure and changes from 1987 to 1999 in three Louisiana and three South Carolina forested wetlands. *Wetlands* 22: 58-70.

Conner, W.H., L.W. Inabinnette and C.A. Lucas. 2001. Effects of flooding on early growth and competitive ability of two native wetland tree species and an exotic. *Castanea* 66: 237-244.

Copeland, B. J. 1966. Effects of decreased river flow on estuarine ecology. *Journal Water Pollution Control Federation* 38:1831-1839.

Crance, J.H. 1986. Habitat suitability index models and instream flow suitability curves: shortnose sturgeon. *U.S. Fish and Wildlife Service Biological Report*. 82(10.129). 31 pp.

Dadswell, M.J., B.D. Taubert, T.S. Squires, D. Marchette, and J. Buckley. 1984. Synopsis of biological data on shortnose sturgeon, *Aciperser brevirostrum* Lesueur

1818. NOAA Tech. Rep. NMFS 14 (FAO Fish. Synopsis 140). U.S. Dep. Commerce. iv + 45 pp.

Deiller, A.F., J.M.N. Walter and M Tremoilieres. 2001. Effects of flood interruption on species reichness, diversity and floristic composition of woody regeneration in the upper Rhine alluvial hardwood forest. *Regulated Rivers: Resource Management* 17: 393-405.

Demaree, D. 1932. Submerging experiments with *Taxodium*. *Ecology* 13: 258-262.

Dirr, M.A., 1998. *Manual of Woody Landscape Plants: Their Identification, Ornamental Characteristics, Culture, Propagation and Uses.* Fifth Edition. Stipes Publishing L.L.C., Champaign, Illinois.

Doering, P. H., R. H. Chamberlain, and D. E. Haunert. 2002. Using submerged aquatic vegetation to establish minimum and maximum freshwater inflows to the Caloosahatchee Estuary, Florida. *Estuaries* 25:1343-1354.

Drinkwater, K. F. and K. T. Frank. 1994. Effects of river regulation and diversion on marine fish and invertebrates. *Aquatic Conservation: Freshwater and Marine Ecosystems* 4:135-151.

Dudley, R.G., A.W. Mullis, and J.W. Terrell. 1977. Movement of Adult Striped Bass (*Morone saxatilis*) in the Savannah River, Ga. *Transactions of the American Fisheries Society* 106:314-322.

Dudley, R.G., and K.N. Black. 1979. *Effects of the Savannah River Tidegate on Striped Bass Eggs and Larvae*. Final Report to the U.S. Army Corps of Engineers on contract DACW21-78-C-0073, 46 pp.

Eager, R. 1987. *Central Savannah River American Shad Study: 1986-1987*. Draft Report. U.S. Fish and Wildlife Service.

ENTRIX, Inc. 2002. Savannah River Instream Flow Study for the Augusta Canal Hydropower Project. FERC No. 11810, September 2002.

Facey, D.E., and M.J. Van Den Avyle. 1986. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North Atlantic)—American shad. *U.S. Fish and Wildlife Service Biological Report*. 82(11.45) *U.S. Army Corps of Engineers*, TR EL-82-4. 18 pp.

Facey, D.E., and M.J. Van Den Avyle. 1987. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (North Atlantic)—American eel. *U.S. Fish and Wildlife Service Biological Report*. 82(11.74) *U.S. Army Corps of Engineers*, TR EL-82-4. 28 pp.

Finger, T.R., and E.M. Stewart. 1987. Response of fishes to flooding regime in lowland hardwood wetlands. Pages 86-92. in W.J. Matthews and D.C. Heins, eds. *Community and evolutionary ecology of North American stream fishes*. University of Oklahoma Press.

Flannery, M. S., E. B. Peebles, and R. T. Montgomery. 2002. A percent-of-flow approach for managing reductions of freshwater inflows from unimpounded rivers to southwest Florida estuaries. *Estuaries* 25:1318-1332.

Flint, R. W. 1985. Long-term estuarine variability and associated biological response. *Estuaries* 8:158-169.

Frederick, P.C. 1995. Wading vird nesting success studies in the Water Conservation Areas of the Everglades, 1992-1995. South Florida Water Management District, Final Report.

Freeman, B.J. and M.C. Freeman. 2001. Criteria for Suitable Spawning Habitat for the Robust Redhorse *Moxostoma robustum*. A Report to the U.S. Fish and Wildlife Service, January 2001.

Freeman, M. C., Z. H. Bowen, K. D. Bovee, E. R. Irwin. 2001. Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes. *Ecological Applications*. 11: 179-190.

GDNR (Georgia Department of Natural Resources). 1998. Draft Savannah River stocking evaluation, 1996-1997. GDNR-WRD, June 1998.

Georgia Ports Authority. 1998. Environmental Impact Statement: Savannah Harbor Expansion Feasibility Study. Savannah, Georgia.

Gilbert, C.R. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic Bight) – Atlantic and shortnose sturgeons. U.S. fish and Wildlife Service Biological Report 82(11.122). U.S. Army Corps of Engineers TR EL –82-4. 28 pp.

Godfrey, R.K., 1988. *Trees, shrubs and woody vines of northern Florida and adjacent Georgia and Alabama.* University of Georgia Press, Atlanta, Georgia.

Goodwin, W.F., and J.G. Adams 1969. Young Clupeids of the Altamaha River, Georgia. Georgia Game and Fish Division. Marine Fisheries Division. Brunswick, Georgia.

GPC (Georgia Power Company). 1998. The Conservation and Restoration of the Robust Redhorse Moxostoma robustum. Report to the Federal Energy Regulatory commission, FERC Project No. 1951, Atlanta, Georgia.

Grossman, G.D., R.J. Ratajczak, Jr., M. Crawford, and M.C. Freeman. 1998. Assemblage organization in stream fishes: effects of environmental variation and interspecific interactions. *Ecological Monographs*. 68: 395-420.

Guillory, V. 1979. Utilization of an inundated floodplain by Mississippi River fishes. *Florida Scientist*. 42: 222-228.

Hale, V.C. and C.R. Jackson, 2003. Hydrologic modifications to the lower Savannah River. *Proceedings of the 2003 Georgia Water Resources Conference*, Kathryn Hatcher, ed. Athens, Georgia.

Halim, Y. 1991. The impact of human alterations of the hydrological cycle on ocean margins, p. 301-327. In R. F. C. Mantoura, J.-M. Martin, and R. Wollast (eds.), Ocean Margin Processes in Global Change. John Wiley & Sons, Chichester, England.

Hall, W. J., T. I. J. Smith, and S. D. Lamprecht. 1991. Movement and habitats of shortnose sturgeon *Acipenser brevirostrum* in the Savannah River. *Copeia*. 1991:695-702.

Hamas, M.J., 1994. Belted kingfisher (*Ceryle alcyon*). *In* The Birds of North America, no. 84 (A. Poole and F. Gill, eds.). Philadelphia: The Academy of Natural Sciences; Washington, D.C.: The American Ornithologists' Union.

Heinricher, J.R. and J.B. Layzer. 1999. Reproduction by individuals of a nonreproducing population of *Megalonaias nervosa* (Mollusca: Unionidae) following translocation. *American Midland Naturalist*. 141: 140-148.

Hill, J.E., J.W. Evans, and M.J. Van Den Avyle. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (South Atlantic)-striped bass. *United States Fish and Wildlife Service Biological Report* 82 (11.118), *U.S. Army Corps of Engineers* TR EL-82-4.

Hillman, T. J. and G. P. Quinn. 2002. Temporal changes in macroinvertebrate assemblages following experimental flooding in permanent and temporary wetlands in an Australian floodplain forest. *River Research and Applications* 18(2): 137-154.

Hochman, E.R., 1999. Lower Roanoke River Hydroperiods: Parts I & II. Report for The Nature Conservancy, North Carolina, U.S.A.

Jassby, A. D., W. J. Kimmerer, S. G. Monismith, C. Armor, J. E. Cloern, T. M. Powell, J. R. Schubel, and T. J. Vendlinski. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5:272-289.

Jennings, C. A. and R. S. Weyers. 2002. Spatial and Temporal Distribution of Estuarine-Dependant Species in the Savannah River Estuary. Annual Report prepared for Georgia Ports Authority.

Jennings, C. A. and R. S. Weyers. 2003. Temporal and spatial distribution of estuarine-dependent species in the Savannah River Estuary. Final report. Georgia Ports Authority, Savannah, Georgia. 179 pp.

Jones, R.H. and R.R. Sharitz. 1990. Effects of root competition and flooding on growth of Chinese tallow tree seedlings. *Canadian Journal of Forest Research* 20: 573-578.

Jones, R.H. and R.R. Sharitz. 1998. Survival and growth of woody plant seedlings in the understorey of floodplain forests in South Carolina. *Journal of Ecology* 86: 574-587.

Jones, R.H., R.R. Sharitz, S.M. James and P.M. Dixon. 1994. Tree population dynamics in seven South Carolina mixed forests. *Bulletin of the Torrey Botanical Club*, 121: 360-368.

Jowett, I. G. 1997. Instream Flow Methods: A comparison of approaches. *Regulated Rivers: Research and Management*. 13:115-127.

Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems, p. 110-127. *In* D.P. Dodge [ed.] Proceedings of the International Large River Symposium. *Canadian Special Publication of Fisheries and Aquatic Sciences*:106.

Keeland, B.D. and R.R. Sharitz, 1995. Seasonal growth patterns of *Nyssa sylvatica* var. *biflora*, *Nyssa aquatica*, and *Taxodium distichum* as affected by hydrologic regime. *Canadian Journal of Forest Research*, 25: 1084-1096.

Keeland, B.D. and R.R. Sharitz, 1997. The effects of water level fluctuations on weekly tree growth in a southeastern USA swamp. *American Journal of Botany*, 84: 131-139.

Keeland, B.D., W.H. Conner and R.R. Sharitz, 1997. A comparison of wetland tree growth response to hydrologic regime in Louisiana and South Carolina. *Forest Ecology and Management*, 90: 237-250.

Kennamer, R. 2001. Relating climatological patterns to wetland conditions and wood duck production in the southeastern Atlantic coastal plain. *Wildlife Society Bulletin* 29: 1193-1205.

Killgore, K.J., and J.A. Baker. 1996. Patterns of larval fish abundance in a bottomland hardwood wetland. *Wetlands*. 16:288-295.

Kimmerer, W. J. 2002. Physical, biological, and management responses to variable freshwater flow into the San Francisco estuary. *Estuaries* 25:1275-1290.

Kimmerer, W. J. and J. R. Schubel. 1994. Managing freshwater flows into San Francisco Bay using a salinity standard: results of a workshop, p. 411-416. In K. R. Dyer and R. J. Orth (eds.), *Changes in Fluxes in Estuaries: Implications from Science to Management*. Olsen & Olsen, Fredensborg, Denmark.

King, S.L. 1995. Effects of flooding regimes on two impounded bottomland hardwood stands. *Wetlands* 15: 272-284.

Kingsford, R. T. 1999. Aerial survey of waterbirds on wetlands as a measure of river and floodplain health. *Freshwater Biology* 41(2): 425-438.

Kozlowski, T.T. 2002. Physiological-ecological impacts of flooding on riparian forest ecosystems. *Wetlands* 22: 550-561.

Krueger, W.H., and K. Oliveira. 1999. Evidence for environmental sex determination in the American eel, *Anguilla rostrata*. *Environmental Biology of Fishes*. 55:381-389.

Kynard, B. 1997. Life history, latitudinal patterns, and status of the shortnose sturgeon, *Acipenser brevirostrum*. *Environmental Biology of Fishes*. 48:319-334.

Kynard, B., and M. Horgan. 2002. Ontogenetic behavior and migration of Atlantic sturgeon *Acipenser oxyrinchus oxyrinchus*, and shortnose sturgeon, *A. brevirostrum*, with notes on social behavior. *Environmental Biology of Fishes*. 63:137-150.

Kynard, B., M. Horgan, M.Kieffer, D. Seibel. 2000. Habitats used by shortnose sturgeon in two Massachusetts rivers, with notes on estuarine Atlantic sturgeon: A hierarchical approach. *Transactions of the American Fisheries Society.* 129:487-503.

Lackly, M. and J. McArthur. 2000. Macroinvertebrate recovery of a post-thermal stream: habitat structure and biotic function. *Ecological Engineering* 15: S87-S100.

Latham, P. J. and W. M. Kitchens. 1996. Changes in vegetation and interstitial salinities in the lower Savannah River: 1986-1994. Final Report. U.S. Fish and Wildlife Service, Charleston, South Carolina.

Latham, P. J., L. G. Pearlstine, and W. M. Kitchens. 1993. Species association changes across a gradient of fresh, oligohaline, and mesohaline tidal marshes along the lower Savannah River. *Wetlands* 14:174-178.

Layzer, J.B. 1996. The importance of habitat hydraulics in the restoration of native freshwater mussels. *Journal of Shellfish Research*. 15:485.

Light, H.M., M.R. Darst, and J.W. Grubbs. 1995. Hydrologic conditions, habitat characteristics, and occurrence of fishes in the Apalachicola River Floodplain, Florida: Second Annual Report of Progress, October 1993- September 1994. U.S. Geological Survey, Open-File Report 95-167.

Liu, E.H., E.M Iglich, R.R. Sharitz and M.H. Smith, 1990. Population genetic structure of baldcypress (*Taxodium distichum*) in a thermally affected swamp forest. *Silvae Genetica*, 39: 129-133.

Livingston, R. J., X. Niu, F. G. Lewis III, and G. C. Woodsum. 1997. Freshwater input to a gulf estuary: long-term control of trophic organization. *Ecological Applications* 7:277-299.

Maddock, T. 1976. A primer on floodplain dynamics. *Journal of Soil and Water Conservation* 31(2): 44-47.

Martin, M.H. 1995. The effects of temperature, river flow, and tidal cycles on the onset of glass eel and elver migration into fresh water in the American eel. *Journal of Fish Biology* 46: 891-902.

Matsumoto, J., G. L. Powell, and D. A. Brock. 1994. Freshwater-inflow need of estuary computed by Texas Estuarine MP Model. *Journal of Water Resources Planning and Management* 120:693-714.

Mattson, R. A. 2002. A resource-based framework for establishing freshwater inflow requirements for the Suwannee River Estuary. *Estuaries* 25:1333-1342.

McCleave, J.D., R.C. Kleckner, and M. Castonguay. 1987. Reproductive sympatry of American and European eels and implications of migration and taxonomy. pp. 9-13. *In*: M.J. Dadswell, R.J. Klauda, C.M. Moffit, R.L. Saunders, R.A. Rulifson and J.E. Cooper (ed.) Common Strategies of Anadromous and Catadromous Fishes, *American Fisheries Society Symposium*. 1, Bethesda,

McDonald, M. 1884. The shad- *Clupea sapidissima in* Goode, G.B. The fisheries and fishery industries of the United States. United States Commission of Fish and Fisheries.

McLeod, K.W., M.R. Reed and E.A. Nelson. 2001. Influence of a willow canopy on tree seedling establishment for wetland restoration. *Wetlands* 21: 395-402.

McLeod, K.W., M.R. Reed and L.D. Wike. 2000. Elevation, competition control, and species affect bottomland forest restoration. *Wetlands* 20: 162-168.

Megonigal, J.P. and F.P. Day. 1992. Effects of flooding on root and shoot production of bald cypress in large experimental enclosures. *Ecology*,73: 1182-1193.

Megonigal, J.P., W.H. Conner, S. Kroeger and R.R. Sharitz. 1997. Aboveground production in Southeastern floodplain forests: A test of the subsidy-stress hypothesis. *Ecology*, 78: 370-384.

Meyer, K.D., 1995. Swallow-tailed kite (*Elanoides forficatus*). *In* The Birds of North America, no. 138 (A. Poole and F. Gill, eds.). Philadelphia: The Academy of Natural Sciences; Washington, D.C.: The American Ornithologists' Union.

Mills, M., C. Hudson, et al. 1995. Spatial ecology and movements of the brown water snake (Nerodia taxispilota). *Herpetologica* 51: 412-423.

Mitsch, P.P. and J.G. Gosselink. 1986. *Wetlands*. Van Nostrand Reinhold Company, New York, NY, USA.

Mitsch, W.J., C.L. Dorge and J.R. Wiemhoff, 1979. Ecosystem dynamics and a phosphorus budget of an alluvial cypress swamp in southern Illinois. *Ecology*, 60: 1116-1124.

Montagna, P. A., M. Alber, P. H. Doering, and M. S. Connor. 2002. Freshwater inflow: science, policy, management. *Estuaries* 25:1243-1245.

Montagna, P. A., R. D. Kalke, and C. Ritter. 2002. Effect of restored freshwater inflow on macrofauna and meiofauna in upper Rincon Bayou, Texas, USA. *Estuaries* 25:1436-1447.

Mooneyhan, D.M. and M.J. Van Den Avyle. 1995. Distribution and habitat requirements of adult striped bass in the Savannah River. Final report. Georgia Department of Natural Resources, Atlanta, GA. 36 pp.

Moss, J.L. 1982. Summer selectionof thermal refuges by striped bass in Alabama reservoirs and tailwaters. *Environmental Risks in Fresh and Salt Water Symposium*. 112:77-83.

National Marine Fisheries Service. 2002. Final Essential Fish Management Plan. www.nmfs.noaa.gov/habitat/habitatprotection/essentialfishhabitat8.htm National Oceanic and Atmospheric Administration. Washington D.C.

O'Leary, J.A. 1984. Characteristics of the Downstream Migration of Juvenile American Shad (*Alosa sapidissima*) and Blueback Herring (*Alosa aestivalis*) in the Connecticut River. University of Massachusetts Master's Thesis. 58p.

Paller, M.H. 1987. Distribution of larval fish between macrophyte beds and open channels in a southeastern floodplain swamp. *Journal of Freshwater Ecology* 4:191-200.

Palmer, T. A., P. A. Montagna, and R. D. Kalke. 2002. Downstream effects of restored freshwater inflow to Rincon Bayou, Nueces Delta, Texas, USA. *Estuaries* 25:1448-1456.

Parker, J.W., 1999. Mississippi kite (*Ictinia mississippiensis*). *In* The Birds of North America, no. 402 (A. Poole and F. Gill, eds.). Philadelphia: The Academy of Natural Sciences; Washington, D.C.: The American Ornithologists' Union.

Pearlstine, L. G., W. M. Kitchens, P. J. Latham, and R. D. Bartleson. 1993. Tide gate influences on a tidal marsh. *Water Resources Bulletin* 29:1009-1019.

Petit, L.J., 1999. Prothonotary warbler (*Protonotaria citrea*). *In* The Birds of North America, no. 408 (A. Poole and F. Gill, eds.). Philadelphia: The Academy of Natural Sciences; Washington, D.C.: The American Ornithologists' Union.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. *BioScience* 47:769-784.

Powell, G. L. and J. Matsumoto. 1994. Texas Estuarine Mathematical Programming Model: a tool for freshwater inflow management, p. 401-406. In K. R. Dyer and R. J. Orth (eds.), Changes in Fluxes in Estuaries: Implications from Science to Management. Olsen & Olsen, Fredensborg, Denmark.

Powell, G. L., J. Matsumoto, and D. A. Brock. 2002. Methods for determining minimum freshwater inflow needs of Texas bays and estuaries. *Estuaries* 25:1262-1274.

Probst, W. 1988. Evaluation of Successive Year Class Strength of Juvenile American Shad in the Ogeechee River. Georgia Department of Natural Resources. Game and Fish Division. Altanta Georgia.

Quintrell, R.D. 1980. Effects of hypolimnial oxygenation on the fish populations and the water chemistry of the Clark Hill Reservoir tailwaters. Masters Thesis. University of Georgia. Athens, GA.

Reinert, T.R., K.L. Jefferson, and C.A. Jennings. 1998. Abundance and distribution of striped bass eggs and larvae in the Savannah River estuary-Implications for channel dredging window, 1996-1998. Final Report, U.S. Army Corps of Engineers Savannah District. USGS, Biological Resources Division, Georgia Cooperative Fish and Wildlife Research Unit, Daniel B. Warnell School of Forest Resources, University of Georgia, Athens, Ga. 30602.

Reinert, T. R., and C. A. Jennings. 1998. Abundance and distribution of striped bass eggs and larvae in the Savannah River estuary - implications for channel dredging window. Annual report submitted to U.S. Army Corps of Engineers, Savannah District. 84 pp.

Richter, B. D., J. V. Baumgartner, R. Wigington, and D. P. Braun. 1997. How much water does a river need? *Freshwater Biology* 37:231-249.

Ross, S.T., and J.A. Baker. 1983. The response of fishes to periodic spring floods in a Southeastern stream. *The American Midland Naturalist*. 109:1-14.

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

Rulifson, R. A. and C. S. Manooch III. 1990. Recruitment of Juvenile Striped Bass in the Roanoke River, North Carolina, as Related to Reservoir Discharge._*North American Journal of Fisheries Management*. 10:397-407.

Rulifson, R.A., J.E. Cooper, and D.W. Stanley. 1988. Larval striped bass and the food chain: cause for concern? Pages 213-224 I *in* W.L. Lyke and T.J. Hoban, eds. Symposium on coastal water resources. American Water Resources Association. Technical Publication Series TPS-88-1, Bethesda, Maryland.

Schmidt, D.N., and J.H. Hornsby. 1985. A fisheries survey of the Savannah River. Georgia Department of Natural Resources, Game and Fish Division, Atlanta, Georgia. Federal Aid in Fish Restoration Acts, Dingell- Johnson Project F-30.

Schneider, R.L. and R.R. Sharitz. 1988. Hydrochory and regeneration in a bald cypress-water tupelo swamp forest. *Ecology* 69: 1055-1063.

Schneider, R.L., N.E. Martin and R.R. Sharitz, 1989. Impact of dam operations on hydrology and associated floodplain forest of Southeastern rivers. *DOE Symposium Series No. 61*, Oak Ridge, TN.

Sharitz, R.R. and L.C. Lee, 1985. Limits on regeneration processes in southeastern riverine wetlands. *Riparian Ecosystems and Their Management: Reconciling Conflicting Uses*, U.S. Forestry Service.

Sharitz, R.R., R.L. Schneider and L.C. Lee, 1990. Composition and regeneration of a disturbed river floodplain forest in South Carolina. *Ecological Processes and Cumulative Impacts: Illustrated by Bottomland Hardwood Wetland Ecosystems*, Chelsea, MI.

Simons, D.B. 1979. Effects of stream regulation on channel morphology. In: J.V. Ward and J.A. Stanford (editors). *The Ecology of Regulated Streams*. Plenum Press, New York.

Sklar, F. H. and J. A. Browder. 1998. Coastal environmental impacts brought about by alterations to freshwater flow in the Gulf of Mexico. Environmental Management 22:547-562.

Smith, T. I. J., M. C. Collins, and W. C. Post. 2002. Stock enhancement of shortnose sturgeon: A case study. *American Fisheries Society Symposium*. 28:31-44.

Smith, T.I.J. 1985. The fishery, biology, and management of Atlantic sturgeon, *Acipenser oxyrhynchus*, in North America. *Environmental Biology of Fishes*. 14:61-72.

Smith, T.I.J., and J.P. Clugston. 1997. Status and management of Atlantic sturgeon, *Acipenser oxyrinchus*, in North America. *Environmental Biology of Fishes*. 48:335-346.

South Florida Water Management District (SFWMD). 2001. Draft minimum flows and levels for the Loxahatchee River and estuary, May 22, 2001. South Florida Water Management District, Water Supply Division, West Palm Beach, Florida.

Souther, R.F. and G.P. Shaffer, 2000. The effects of submergence and light on two age classes of baldcypress (*Taxodium distichum* (L.) Richard) seedlings. *Wetlands*, 20: 697-706.

Stier, D.J., and J.H. Crance 1985. Habitat suitability index models and instream flow suitability curves: American Shad. U.S. Fish and Wildlife Service Biological Report. 82(10.88).

Straney, D., L. Briese, et al. 1974. Bird diversity and thermal stress in a cypress swamp. *Thermal Ecology*: 572-578.

Stuart, K.R., A.G. Eversole, and D.E. Brune. 2000. Effect of flow rate and temperature on algal uptake by freshwater mussels. Proceedings of the First Freshwater Mollusk Conservation Society Symposium. 1999: 219-224.

Thomas, R.L., S.L.H. Fuller, R.W. Bouchard, J.W. Littrell, P.F. Overbeck, and R.W. Bouchard, Jr. 2001. A fifty-year history of the mussel fauna of the Savannah River in the vicinity of the U.S. Department of Energy Savannah River Site, Georgia and South Carolina. (Abstract) *North American Benthological Society* Abstracts.

Thorp, J., E. McEwan, et al. 1985. Invertebrate colonization of submerged wood in a cypress-tupelo swamp and blackwater stream. *American Midland Naturalist* 113(1): 56-68.

Townsend, P.A. 2001 Relationships between vegetation patterns and hydroperiod on the Roanoke River Floodplain, N.C. *Plant Ecology* 156: 43-58.

Travnichek, V. H., M. B. Bain, and M. J. Maceina. 1995. Recovery of a warmwater fish assemblage after the initiation of a minimum-flow release downstream from a hydroelectric dam. *Transactions of the American Fisheries Society*. 124:836-844.

Turner, T.F., J.C. Trexler, G.L. Miller, and K.E. Toyer. 1994. Temporal and spatial dynamics of larval and juvenile fish abundance in a temperate floodplain river. *Copeia*. 1994:174-183.

U.S. Army Corps of Engineers, 1992. *Reconnaissance Report: Lower Savannah River Environmental Restoration*. Savannah District, South Atlantic Division.

U.S. Fish and Wildlife Service. 2002. Wood Stork Report. Billy Brooks (ed), Volume1 (No.1).

US Geologic Survey. 1990. Flood Frequency of the Savannah River at Augusta, GA. Water-Resources Investigations Report 90-4024. Columbia, SC.

Van Den Avyle, M. J. and M. A. Maynard. 1994. Effects of saltwater intrusion and flow diversion on reproductive success of striped bass in the Savannah River Estuary. *Transactions of the American Fisheries Society.* 123:886-903.

Van Den Avyle, M. J., M. A. Maynard, R. C. Klinger and V. S. Blazer. 1990. Effects of Savannah Harbor development on fishery resources associated with the Savannah National Wildlife Refuge. Final report to U.S. Fish and Wildlife Service, Atlanta, GA. 109 pp.

Wallin, J. E. and M. J. Van Den Avyle. 1995. Interactive effects of stocking site salinity and handling stress on survival of striped bass fingerlings. *Transactions of the American Fisheries Society.* 124:736-745.

Wallin, J. M.J. Van Den Avyle, and T. Sinclair. 1995. Juvenile striped bass nursery habitat and abundance index in the lower Savannah River. Final report. Georgia Department of Natural Resources, Atlanta, GA. 61 pp.

Ward, G. H., M. J. Irlbeck, and P. A. Montagna. 2002. Experimental river diversion for marsh enhancement. *Estuaries* 25:1416-1425.

Watters, G.T. 2000. Freshwater mussels and water quality: A review of the effects of hydrologic and instream habitat alterations. *Proceedings of the First Freshwater Mollusk Conservation Society Symposium,* 1999. 261-274.

Weber, W.W., C.A. Jennings, and S.G. Rogers. 1998. Population size and movement patterns of shortnose sturgeon in the Ogeechee River System, Georgia. *Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies*. 52:18-28.

Weyers, R.S., C.A. Jennings, M.C. Freeman. 2003. Effects of pulsed, high-velocity water flow on larval robust redhorse and v-lip redhorse. *Transactions of the American Fisheries Society*. In Press

Wiggins, G.B. 1980. Evolutionary and ecological strategies of animals in annual temporary pools. *Arch Hydrobiol., Supplement* 58: 97-206.

Will, T. A., T. R. Reinert and C. A. Jennings. 2000. Spatial assessment of current and historic spawning sites of striped bass, Morone saxatilis, in the Savannah River estuary. Final report for project 10-21-RR 251-131 submitted to Georgia Department of Natural Resources. Social Circle, GA. 81 pp.

Will, T. A., T. R. Reinert, and C. A. Jennings. 2002. Maturation and fecundity of a stock-enhanced population of striped bass in the Savannah River Estuary, USA. *Journal of Fish Biology.* 60:532-544.

Winger, P. V. and P. J. Lasier. 1990. Effects of salinity on striped bass eggs and larvae. Final report to the U.S. Army Corps of Engineers, Savannah District. 31 pp.

Wolock, D. M. and G. J. McCabe. 1999. Simulated effects of climate change on mean annual runoff in the conterminous United States. *Journal of the American Water Resources Association* 35:1341-1350.

LIST OF TABLES

LIST OF FIGURES

21 Peak flow depth above or below flood stage at River Mile52.6.

22 Percent of inundated floodplain assuming water table rise.

23 Percent of inundated floodplain assuming no water table rise.

24 Median monthly discharge in Augusta Shoals before (1884-1954) and after (1984-2001) construction of all mainstem impoundments. Results are from IHA analyses (Appendix 1) and adjusted by mean monthly withdrawal for Augusta Canal.

25 Seasonal flows required by anadromous and riverine fishes in the Savannah River at Augusta Shoals. Values represent 80 - 100% PMWUA.

26 Flow relationships to key aspects of fish population success.

27 Flow relationships to key aspects of Atlantic sturgeon *Acipenser oxyrinchus* population success highlighting known and unknown flow relationships.

28 Flow relationships to key aspects of shortnose sturgeon *Acipenser brevirostrum* population success.

29 Flow relationships to key aspects of robust redhorse *Moxostoma robustum* population success.

30 Flow relationships to key aspects of striped bass *Morone saxatilis* population success.

31 Flow relationships to key aspects of American shad *Alosa sapidissima* population success.

32 Flow relationships to key aspects of American eel *Anguilla rostrata* population success.

33 Locations of salinity contours in the Savannah River estuary under existing conditions.

34 Conceptual model of effects of river regulation on biological processes in the Augusta Shoals of the Savannah River.

35 Conceptual model of effects of river regulation on biological processes in the main channel and floodplain of the Savannah River.

36 Conceptual model of effects of river regulation on biological processes in the Savannah River Estuary.

Table 1. USGS gages on the Lower Savannah River.

USGS Gage #	Gage Name	From	To
2195000	Savannah River near Clarks Hill, SC	5/14/1940	6/30/1954
2196484	Savannah River near North Augusta, SC	10/1/1988	9/30/2001
2197000	Savannah River at Augusta, GA	10/1/1983	9/30/2001
2197320	Savannah River near Jackson, SC	10/1/1971	9/30/2001
2197500	Savannah River at Burtons Ferry Bridge near Millhaven, GA	10/1/1939	9/30/2001
2198500	Savannah River near Clyo, GA	10/1/1929	9/30/2001

Table 2. Cut off bends of the Lower Savannah River.

Cut #	Cut Off Bend Name	R.M.	Yr. Created	Length(ft)
-	Fritz Cut	183.5	Prvt - 1889	8000
-	Bailey's Cut	181.9	Prvt - 1921	7100
24	Beckum's Cut	181.5	1959	3,137*
23	Lower Silver Bluff Landing	173.3	1959	3150
22	Gray's Landing	169.5	1959	3600
21A	Eagle Point	169	1976	8400
21	Cox Point	153.2	1959	4350
20	Cunningham Point	137.5	1959	3100
19C	Sweetwater Cut	136.5	1976	2484
19B	Catfish Hole Point	136	1959	3900
19A	Devil's Elbow	135.5	1959	3500
19	Swift Cut	135.3	1959	2200
-	Little Hell Landing	134.5	Nat Cut-off	4,000*
18B	Little Randall Point	128.5	1960-61	6,275*
18A	Fat Meat Point	120.8	1960-61	4400
18	Green Log (Egg) Point	112.4	1960-61	3000
17	Dick's Lookout Point	107	1960-61	3500
16	Cook's Field Point	102.8	1960-61	3900
15A	Wildcat Point	102.2	1960-61	5359
15	Seven-day Baptist Point	101.1	1960-61	1,438*
14A	Miller's Old Lake	100.2	Nat Cut-off	3,529*
14	Whirligig Point	99.9	1960-61	3000
13	Pfeiffers Landing	93.8	1960-61	3,450*
12	Thompsons Cow Fold Point	92.8	1960-61	6000
11	Mosquito Camp Point	88.8	1960-61	5100
10	Poor Robin Upper Point	87.1	1960-61	2100
9A	Poor Robin Lower Point	85.2	1960-61	2000
9	Ware Creek Cut	85.4	1960-61	2500
8C	Blanket Point	81	1960-61	7600
8B	Wildcat Cut	78.6	1960-61	8100
8A	Duck Cut	65	Natural??	6,536*
8	Hog Nose Point	62.3	1960-61	6100
7A	McKenzie's Camp	59.7	1960-61	2,353*
7	Bowl Maker Point	51.4	1962	3900
6	Big Keiffer Point	43.2	1962	2800
5	Bay Bush Point	41.6	1962	1300
4	Flat Ditch Point	41.3	1962	7,059*
3	Hickory Bend	40.9	1962	2,092*
2	Pine Tree Camp Point	37.2	1962	2800
1	Moody Cut	31.4	1962	6000
			Total (ft)	**139943**
			Total (Miles)	**26.5**

* Lengths found in: US Army Corps of Engineers, Savannah District, South Atlantic Division. April 1992. Lower Savannah River Environmental Restoration: Reconnaissance Report. Appendix A.
All other lengths measured from aerial photography.

Table 3. Evaporative water loss calculations.

Reservoir	Area (Acres)	Est. Mean Annual Evaporation (Ac-ft)	Drainage Area Above Dam (sq. mi.)	Est. Water Loss (In.)
Thurmond	78500	268208.33	6144	0.82
Russell	29340	100245	2890	0.65
Hartwell	55950	191162.5	2088	1.72
TOTALS:	**163790**	**559615.83**	**11122**	**3.19**

Table 4. Peak larval abundance periods for fish species that reproduce or probably reproduce in flowing floodplain habitats.

Common Name	Scientific Name	Reproduce (R) or probably reproduce (PR)	Peak larval abundance season	Source
threadfin shad	*Dorosoma petenense*	R	late spring	Guillory, 1979; Baker et al., 1991; Light et al., 1998
Eastern silvery minnow	*Hybognathus regius*	R	late spring	Guillory, 1979; Baker et al., 1991
dusky shiner	*Notropis cummingsae*	PR	late spring	Paller, 1987; Killgore and Baker, 1996; Schmidt and Hornesby, 1985
spottail shiner	*Notropis hudsonius*	PR	late spring	Paller, 1987; Killgore and Baker, 1996; Schmidt and Hornesby, 1985
bannerfin shiner	*Cyprinella leedsi*	PR	late spring	Paller, 1987; Killgore and Baker, 1996Light et al., 1998; Schmidt and Hornesby, 1985
whitefin shiner	*Cyprinella nivea*	PR	late spring	Paller, 1987; Killgore and Baker, 1996; Schmidt and Hornesby, 1985
coastal shiner	*Notropis petersoni*	PR	late spring	Paller, 1987; Killgore and Baker, 1996Light et al., 1998; Schmidt and Hornesby, 1985
channel catfish	*Ictalurus punctatus*	R	early summer	Killgore and Baker, 1996; Light et al., 1998
Savannah darter	*Etheostoma fricksium*	PR	late spring	Paller, 1987; Schmidt and Hornesby, 1985
tessellated darter	*Etheostoma olmstedi*	PR	late spring	Paller, 1987; Killgore and Baker, 1996; Schmidt and Hornesby, 1985
sawcheek darter	*Etheostoma serriferum*	PR	late spring	Paller, 1987; Schmidt and Hornesby, 1985
blackbanded darter	*Percina nigrofaciata*	R	late spring	Ross and Baker, 1983; Killgore and Baker, 1996; Light et al., 1998

Table 5. Peak larval abundance periods for fish species that reproduce or probably reproduce in lentic floodplain habitats.

Common Name	Scientific Name	Reproduce (R) or probably reproduce (PR)	Peak larval abundance season	Source
gizzard shad	*Dorosoma cepedianum*	R	late spring	Guillory, 1979; Killgore and Baker, 1996; Baker et al., 1991; Light et al., 1998
yellow bullhead	*Ameiurus natalis*	R	early summer	Finger and Stewart, 1987; Guillory, 1979; Killgore and Baker, 1996; Light et al., 1998
brown bullhead	*Ameiurus nebulosus*	R	early summer	Finger and Stewart, 1987; Light et al., 1998
golden topminnow	*Fundulus chrysotus*	PR	summer	Finger and Stewart, 1987; Paller, 1987;Ross and Baker, 1983; Light et al., 1998; Schmidt and Hornesby, 1985
flier	*Centrarchus macropterus*	R	late spring	Finger and Stewart, 1987; Guillory, 1979; Killgore and Baker, 1996; Light et al., 1998
banded pygmy sunfish	*Elassoma zonatum*	R	late spring	Finger and Stewart, 1987; Ross and Baker, 1983; Light et al., 1998
green sunfish	*Lepomis cyanellus*	R	late spring	Ross and Baker, 1983; Killgore and Baker, 1996; Light et al., 1998
white crappie	*Pomoxis annularis*	R	late spring	Guillory, 1979; Killgore and Baker, 1996; Baker et al., 1991; Light et al., 1998

Table 6. Peak larval abundance periods for fish species that reproduce or probably reproduce in flowing or lentic floodplain habitats.

Common Name	Scientific Name	Reproduce (R) or probably reproduce (PR)	Peak larval abundance season	Source
spotted gar	*Lepisosteus oculatus*	R	early summer	Killgore and Baker, 1996; Light et al., 1998
longnose gar	*Lepisosteus osseus*	R	early summer	Killgore and Baker, 1996; Light et al., 1998
bowfin	*Amia calva*	R	spring	Finger and Stewart, 1987; Ross and Baker, 1983; Guillory, 1979; Baker et al., 1991; Light et al., 1998
redfin pickerel	*Esox americanus*	R	late winter	Finger and Stewart, 1987; Ross and Baker, 1983; Light et al., 1998
chain pickerel	*Esox niger*	R	late winter	Ross and Baker, 1983; Light et al., 1998
common carp	*Cyprinus carpio*	R	early summer	Guillory, 1979; Baker et al., 1991; Light et al., 1998
golden shiner	*Notemigonus crysoleucas*	R	late spring	Finger and Stewart, 1987; Ross and Baker, 1983; Guillory, 1979; Killgore and Baker, 1996; Light et al., 1998
pugnose shiner	*Notropis emiliae*	R	late spring	Ross and Baker, 1983; Killgore and Baker, 1996; Light et al., 1998
taillight shiner	*Notropis maculatus*	R	late spring	Guillory, 1979; Light et al., 1998
lake chubsucker	*Erimyzon sucetta*	R	uncertain	Finger and Stewart, 1987; Light et al., 1998
spotted sucker	*Minytrema melanops*	R	uncertain	Guillory, 1979; Killgore and Baker, 1996; Light et al., 1998
tadpole madtom	*Noturus gyrinus*	R	early summer	Ross and Baker, 1983; Killgore and Baker, 1996; Light et al., 1998
speckled madtom	*Noturus leptacanthus*	R	early summer	Ross and Baker, 1983; Light et al., 1998
pirate perch	*Aphredoderus sayannus*	R	late spring	Finger and Stewart, 1987; Ross and Baker, 1983; Killgore and Baker, 1996; Light et al., 1998
mosquitofish	*Gambusia affinis*	R	late spring	Finger and Stewart, 1987; Ross and Baker, 1983; Guillory, 1979; Light et al., 1998
brook silverside	*Labidesthes sicculus*	R	late summer	Paller, 1987; Ross and Baker, 1983; Light et al., 1998
bluespotted sunfish	*Enneacanthus gloriosus*	R	late spring	Paller, 1987; Light et al., 1998
redbreast sunfish	*Lepomis auritus*	R	late spring-late summer	Ross and Baker, 1983; Guillory, 1979; Killgore and Baker, 1996; Light et al., 1998
warmouth	*Lepomis gulosis*	R	late spring-late summer	Finger and Stewart, 1987; Ross and Baker, 1983; Guillory, 1979; Killgore and Baker, 1996; Light et al., 1998
bluegill	*Lepomis macrochirus*	R	late spring-late summer	Finger and Stewart, 1987; Ross and Baker, 1983; Guillory, 1979; Killgore and Baker, 1996; Light et al., 1998
dollar sunfish	*Lepomis marginatus*	R	late spring-late summer	Ross and Baker, 1983; Killgore and Baker, 1996; Light et al., 1998
redear sunfish	*Lepomis microlophus*	R	late spring-late summer	Ross and Baker, 1983; Killgore and Baker, 1996; Light et al., 1998
spotted sunfish	*Lepomis punctatus*	R	late spring-late summer	Ross and Baker, 1983; Killgore and Baker, 1996; Light et al., 1998
largemouth bass	*Micropterus salmoides*	R	late spring	Finger and Stewart, 1987; Paller, 1987; Ross and Baker, 1983; Killgore and Baker, 1996; Light et al., 1998
black crappie	*Pomoxis nigromaculatus*	R	late spring-late summer	Finger and Stewart, 1987; Paller, 1987; Guillory, 1979; Killgore and Baker, 1996; Light et al., 1998
pumpkinseed	*Lepomis gibbosus*	PR	late spring	Finger and Stewart, 1987; Paller, 1987;Killgore and Baker, 1996; Schmidt and Hornesby, 1985

Table 7. Peak larval abundance periods for fish species that reproduce or probably reproduce on floodplains; habitat type uncertain.

Common Name	Scientific Name	Reproduce (R) or probably reproduce (PR)	Peak larval abundance season	Source
ironcolor shiner	*Notropis chalybaeus*	PR	late spring	Paller, 1987; Killgore and Baker, 1996; Schmidt and Hornesby, 1985
yellowfin shiner	*Notropis lutipinnis*	PR	late spring	Paller, 1987; Killgore and Baker, 1996
rosyface shiner	*Notropis rubescens*	PR	late spring	Killgore and Baker, 1996
creek chubsucker	*Erimyzon oblongus*	PR	late spring	Finger and Stewart, 1987; Paller, 1987; Schmidt and Hornesby, 1985
red-eye bass	*Micropterus coosae*	PR	late spring	Finger and Stewart, 1987; Paller, 1987;Killgore and Baker, 1996
smallmouth bass	*Micropterus dolomieui*	PR	late spring	Finger and Stewart, 1987; Paller, 1987;Killgore and Baker, 1996
mummichog	*Fundulus heteroclitus*	PR	summer	Finger and Stewart, 1987; Paller, 1987;Ross and Baker, 1983; Schmidt and Hornesby, 1985
lined topminnow	*Fundulus lineolatus*	PR	summer	Finger and Stewart, 1987; Paller, 1987;Killgore and Baker, 1996; Ross and Baker, 1983 ; Schmidt and Hornesby, 1985
swampfish	*Chologaster cornuta*	PR	unknown	Schmidt and Hornesby, 1985

Table 8. Fish species that occur or probably occur on the floodplain but do not necessarily reproduce there.

Common Name	Scientific Name	Occur (O) or probably occurr (PO) on floodplain	Occur in flowing (F) or lentic (L) water	Source
Florida gar	*Lepisosteus platyrhincus*	PO	unknown	Finger and Stewart, 1987; Paller, 1987; Schmidt and Hornesby, 1985
American eel	*Anguilla rostrata*	O	L	Baker et al., 1991; Light et al., 1998
blueback herring	*Alosa aestivalis*	PO	L	Schmidt and Hornesby, 1985
hickory shad	*Alosa mediocris*	PO	L	Schmidt and Hornesby, 1985
American shad	*Alosa sapidissima*	PO	L	Schmidt and Hornesby, 1985
river carpsucker	*Carpoides carpio*	O	L	Baker et al., 1991; Light et al., 1998
quillback	*Carpiodes cyprinus*	O	FL	Light et al., 1998
highfin carpsucker	*Carpiodes velifer*	O	F	Baker et al., 1991; Light et al., 1998
notched lip redhorse	*Moxostoma collapsum*	PO	FL	Schmidt and Hornesby, 1985
brassy jumprock	*Scartomyzon sp.cf. lachneri*	PO	unknown	Schmidt and Hornesby, 1985
snail bullhead	*Ameiurus brunneus*	O	FL	Light et al., 1998
white catfish	*Ameiurus catus*	O	FL	Light et al., 1998
flat bullhead	*Ameiurus platycephalus*	PO	FL	Finger and Stewart, 1987; ; Schmidt and Hornesby, 1985
blue catfish	*Ictalurus furcatus*	PO	FL	Baker et al., 1991
Atlantic needlefish	*Strongylura marina*	O	F	Light et al., 1998
mosquitofish	*Gambusia holbrooki*	PO	FL	ENTRIX, 2002; ALDEN, 2002
brook stickleback	*Culaea inconstans*	PO	unknown	Schmidt and Hornesby, 1985
striped bass	*Morone saxatilis*	O	F	Baker et al., 1991; Light et al., 1998
white bass	*Morone chrysops*	O	L	Baker et al., 1991; Light et al., 1998
striped bass X white bass Morone chrysops	*Morone hybrid*	PO	F	Schmidt and Hornesby, 1985
Everglades pygmy sunfish	*Elassoma evergladei*	O	L	Light et al., 1998
Okefenokee pygmy sunfish	*Elassoma okeenokee*	O	L	Light et al., 1998
blackbanded sunfish	*Enneacanthus chaetodon*	PO	L	Schmidt and Hornesby, 1985
banded sunfish	*Enneacanthus obesus*	PO	unknown	Light et al., 1998
yellow perch	*Perca flavescens*	PO	FL	Schmidt and Hornesby, 1985
Irish pompano	*Diapterus auratus*	PO	unknown	Schmidt and Hornesby, 1985
spotfin mojarra	*Eucinostomus argenteus*	PO	unknown	Schmidt and Hornesby, 1985
striped mullet	*Mugil cephalus*	O	FL	Light et al., 1998
freshwater goby	*Gobionellus shufeldti*	PO	F	Schmidt and Hornesby, 1985
Southern flounder	*Paralichthys lethostigma*	PO	FL	Schmidt and Hornesby, 1985
hogchoker	*Trinectes maculatus*	O	FL	Light et al., 1998

Table 9. Fish species that occur in the Savannah River mainstem but presence in floodplains has not been confirmed.

Common Name	Scientific Name	Source
grass carp	*Ctenopharyngodon idella*	ENTRIX, 2002
rosyface chub	*Hybopsis rubrifrons*	Quintrell, 1980; Schmidt and Hornesby, 1985
bluehead chub	*Nocomis leptocephalus*	Schmidt and Hornesby, 1985; ENTRIX, 2002; ALDEN, 2002
sailfin shiner	*Pteronotropis hypselopterus*	ENTRIX, 2002; ALDEN, 2002
Northern hogsucker	*Hypentelium nigricans*	Schmidt and Hornesby, 1985; ENTRIX, 2002
notched lip redhorse	*Moxostoma collapsum*	ENTRIX, 2002
brassy jumprock	*Scartomyzon brasseus*	ENTRIX, 2002
margined madtom	*Noturus insignis*	ENTRIX, 2002; ALDEN, 2002
brown trout	*Salmo trutta*	ENTRIX, 2002
walleye	*Stizostedion vitreum*	Quintrell, 1980
mountain mullet	*Agonostomus monticola*	Schmidt and Hornesby, 1985

Table 10. Flows at which 80 and 100% Possible Maximum Weighted Useable Area (PMWUA) are achieved for various fishes and life stages (ENTRIX, 2002).

	Species and life stage	80% PMWUA (cfs)	100% PMWUA (cfs)
Anadromous	American shad (larval/juvenile)*	2200	6500
	American shad (outmigration)*	2400	6500
	American shad (spawning/egg incubation)*	4900	8000
	striped bass (incubation/drift)*	6100	8000
Deep-Fast	northern hogsucker (adult)	1100	7000
	redeye bass (adult)	1100	6100
	robust redhorse	2100	6100
	silver redhorse (adult)	2000	8000
Deep-Slow	largemouth bass (adult)	800	5500
	redbreast sunfish	200	3800
Shallow-Fast	Chub (Nocomis spp.) (spawn)	500	2600
	margined madtom (adult)	400	2300
	Shallow-Swift guild (all)	1400	5000
	striped jumprock (adult)	800	5100
Shallow-Slow	redbreast sunfish	200	1200
	striped jumprock (YOY, edgecover)	200	600
	redeye bass (YOY edgecover)	200	1600

*Weighted useable area increases with flow.

Table 11. Habitat characteristics, flow characteristics, and G-rank of Savannah River mussels.

Common name	Scientific name	G-Rank	Flow characteristics	Substrate characteristics	Source
Appalachian elktoe	*Alasmidonta raveneliana*		moderate to fast	variety of substrates inc. gravel mixed with cobble and boulders, cracks in bedrock, and coarse sand	ncwildlife.org
Southern elktoe	*Alasmidonta triangulata*			large creeks and rivers in sandy mud and rock pools	georgiawildlife.dnr.state.ga.us
triangle floater	*Alasmidonta undulata*		no preference	no habitat preference	ncwildlife.org
brook floater	*Alasmidonta varicosa*[4]		slow	sandy/silty substrate in cracks between boulders along a steep bank	ncwildlife.org; www.biosci.ohio-state.edu
slippershell mussel	*Alasmidonta viridis*		slow to fast	riffle areas with gravel/cobble/boulder substrates; silt and sand to cobble; Justicia americana	ncwildlife.org
barrel floater	*Anodonta couperiana*	G4	slow streams	mud or sand	ncwildlife.org
delicate spike	*Elliptio arctata*		strong	coarse sand and gravel	Parmalee and Bogan, 1998
Eastern elliptio	*Elliptio complanata*[4]				www.biosci.ohio-state.edu
Carolina slabshell	*Elliptio congaraea*[4]	G4			
elephantear	*Elliptio crassidens*[1]		strong	small streams and streams; sand and course gravel with mud	Parmalee and Bogan, 1998
spike	*Elliptio dilatata*[1]		strong	coarse sand and gravel of small streams or large rivers	Parmalee and Bogan, 1998
oval elliptio	*Elliptio errans*				
pod lance	*Elliptio folliculata*[4]				
brother spike	*Elliptio fraterna*[2]				
brown elliptio	*Elliptio hepatica*				
variable spike	*Elliptio icterina*[4]				
sad elliptio	*Elliptio lugubris*[3,4]				
Atlantic spike	*Elliptio producta*				
Carolina spike	*Elliptio raveneli*[4]				
Roanoke slabshell	*Elliptio roanokensis*[4]		fast	deeper channels near shore, coarse to medium sized sand and small gravel	ncwildlife.org
Atlantic pigtoe	*Fusconaia masoni*	G2	swift	stable gravel or sand and gravel;often ds of riffles	ncwildlife.org
yellow lampmussel	*Lampsilis cariosa*[2]	G3G4	fast	many different habitats, but slightly prefers shifting sands ds of lg boulders	ncwildlife.org
rayed pink fatmucket	*Lampsilis splendida*	G3			
	Lampsilis luteola[1]				

Table 11 cont. Flow and substrate characteristics of Savannah River mussels.

Carolina heelsplitter	*Lasmigona decorata*			sand, gravel, cobble; stable stream banks important	ncwildlife.org
green floater	*Lasmigona subviridis*			gravel and sand in pools and eddies; canals	ncwildlife.org; Parmalee and Bogan, 1998
tidewater mucket	*Leptodea ochracea*		no preference	sand/ silt substrates	ncwildlife.org
Eastern floater	*Pyganodon cataracta*	G5			
creeper	*Strophitus undulatus*[2]		no preference but achieves max growth in rivers with current	silt, sand, gravel, and mixed substrates; high gradient-meandering rivers	www.biosci.ohio-state.edu; Illinois natural history survey; www.ncwildlife.org; Parmalee and Bogan, 1998
Savannah lilliput	*Toxolasma pullus*	G3	no preference	silty-sand or mud; near shore	ncwildlife.org
Florida pondhorn	*Uniomerus caroliniana*[4]				
paper pondshell	*Utterbackia imbecillis*		slow	ponds, lakes, sluggish mud-bottomed pools of creeks and rivers, fine sand	Illinois natural history survey; www.biosci.ohio-state.edu; Parmalee and Bogan, 1998
Eastern creekshell	*Villosa delumbis*[4]	G3		mud or soft sand, in small rivers and creeks	ncwildlife.org
Southern rainbow	*Villosa vibex*	G4			www.biosci.ohio-state.edu; Parmalee and Bogan, 1998

[1]Species is not known to occur in the Savannah River system but was included because host fish may be similar within the *Elliptio complex*.

[2]Species was not collected in recent years or has experienced a significant decline (Thomas, 2001).

[3]Possible variant of *E. icterina*.

[4]Found in the Augusta Shoals survey (ENTRIX, 2002)

Table 12. Host fish and breeding season of Savannah River mussels.

Common name	Scientific name	Savannah River host	Gravid/ Breeding period	Source
Appalachian elktoe	*Alasmidonta raveneliana*		Oct-Jan, May	ncwildlife.org
Southern elktoe	*Alasmidonta triangulata*			georgiawildlife.dnr.state.ga.us
triangle floater	*Alasmidonta undulata*		throughout year	ncwildlife.org
brook floater	*Alasmidonta varicosa*[4]	golden shiner *Notemigonus crysoleucas*; margined madtom *Noturus insignis*; pumpkinseed *Lepomis gibbosus*; yellow perch *Perca flavescens*	Aug through May	ncwildlife.org; www.biosci.ohio-state.edu
slippershell mussel	*Alasmidonta viridis*		fall through spring	ncwildlife.org
barrel floater	*Anodonta couperiana*			ncwildlife.org
delicate spike	*Elliptio arctata*		unknown	Parmalee and Bogan, 1998
Eastern elliptio	*Elliptio complanata*[4]	green sunfish *Lepomis cyanellus*; largemouth bass *Micropterus salmoides*; white crappie *Pomoxis annularis*; yellow perch *Perca flavescens*		www.biosci.ohio-state.edu
Carolina slabshell	*Elliptio congaraea*[4]			
elephantear	*Elliptio crassidens*[1]		June and July	Parmalee and Bogan, 1998
spike	*Elliptio dilatata*[1]	gizzard shad *Dorosoma cepedianum*; white crappie *Pomoxis annularis*; black crappie *P. nigromaculatus*; yellow perch *Perca flavescens*	mid-May to Aug (Parmalee and Bogan, 1993) but spawns twice a year at 5 and 19C (Watters and O'Dee, 2000)	Parmalee and Bogan, 1998
oval elliptio	*Elliptio errans*			
pod lance	*Elliptio folliculata*[4]			
brother spike	*Elliptio fraterna*[2]			
brown elliptio	*Elliptio hepatica*			
variable spike	*Elliptio icterina*[4]			
sad elliptio	*Elliptio lugubris*[3,4]			
Atlantic spike	*Elliptio producta*			
Carolina spike	*Elliptio raveneli*[4]			
Roanoke slabshell	*Elliptio roanokensis*[4]	probably anadromous	as early as Mar	ncwildlife.org
Atlantic pigtoe	*Fusconaia masoni*	bluegill sunfish *Lepomis macrochirus*	late Jun to early Jul	ncwildlife.org
yellow lampmussel	*Lampsilis cariosa*[2]	migratory sp.; Must also have freshwater host		ncwildlife.org
rayed pink fatmucket	*Lampsilis splendida*			
	Lampsilis luteola[1]		releases glochidia nearly year round but peaks at 19C in May.	

Table 12 cont. Host fish and breeding season of Savannah River mussels.

Carolina heelsplitter	*Lasmigona decorata*			ncwildlife.org
green floater	*Lasmigona subviridis*		Aug through May	ncwildlife.org; Parmalee and Bogan, 1998
tidewater mucket	*Leptodea ochracea*	unknown but alewife and silverside (*Menidia species*) suggested	Dec to Jun	ncwildlife.org
Eastern floater	*Pyganodon cataracta*			
creeper	*Strophitus undulatus*[2]	river chub *Nocomis micropogon*; yellow bullhead *Ameiurus natalis*; channel catfish *Ictalurus punctatus*; bluegill *Lepomis macrochirus*; green sunfish *Lepomis cyanellus*; pumpkinseed *L. gibbosus*; smallmouth bass *Micropterus dolomieu*; largemouth bass *Micropterus*	July to May	www.biosci.ohio-state.edu; Illinois natural history survey; www.ncwildlife.org; Parmalee and Bogan, 1998
Savannah lilliput	*Toxolasma pullus*			ncwildlife.org
Florida pondhorn	*Uniomerus caroliniana*[4]			
paper pondshell	*Utterbackia imbecillis*	mosquitofish *Gambusia affinis*; green sunfish *Lepomis cyanellus*; pumpkinseed *Lepomis gibbosus*; warmouth *Lepomis gulosus*; Bluegill *Lepomis macrochirus*; dollar sunfish *Lepomis marginatus*; largemouth bass *Micropterus salmoides*; black crappie *Pomoxis nigromacu*	probably Autumn breeder	Illinois natural history survey; www.biosci.ohio-state.edu; Parmalee and Bogan, 1998
Eastern creekshell	*Villosa delumbis*[4]			ncwildlife.org
Southern rainbow	*Villosa vibex*	green sunfish *Lepomis cyanellus*; redeye bass *Micropterus coosae*; largemouth bass *Micropterus.salmoides*	Sep to May	www.biosci.ohio-state.edu; Parmalee and Bogan, 1998

[1]Species is not known to occur in the Savannah River system but was included because host fish may be similar within the *Elliptio complex*.
[2]Species was not collected in recent years or has experienced a significant decline (Thomas, 2001).
[3]Possible variant of *E. icterina*.
[4]Found in the Augusta Shoals survey (ENTRIX, 2002)

Table 13. Area of occurrence and hydroperiod requirements of common tree species on the Savannah River floodplain.

Common Name	Scientific Name	Area on Floodplain[A,C]	Median Annual Optimum Hydroperiod[1]	Median Spring Optimal Hydroperiod[1]
Bald Cypress	*Taxodium distichum*	Bottomland Swamp	198	86
Water Tupelo	*Nyssa aquatica*	Bottomland Swamp	212	all
Swamp Tupelo	*Nyssa sylvatica* var. *biflora*	Bottomland Swamp/ Wet Bottomland Hardwood	167	69
Water Hickory	*Carya aquatica*	Wet Bottomland Hardwood	67	15
Green Ash	*Fraxinus pennsylvanica*	Wet Bottomland Hardwood	53	8
Laurel Oak/ Diamondleaf Oak	*Quercus laurifolia*	Wet Bottomland Hardwood	44	3
Sweetgum	*Liquidambar styraciflua*	Mesic Bottomland Hardwood	33	none
Swamp Chestnut Oak	*Quercus michauxii*	Mesic Bottomland Hardwood	14	none
American Hornbeam/ Ironwood	*Carpinus caroliniana*	Mesic Bottomland Hardwood	30	none
Chinese Tallow	*Sapium sebiferum*	Tends to invade Bottomland Swamp areas first.[B]	NA	NA

[1] From Townsend's study of the Roanoke River system (Townsend 2001).[C] Median annual and spring hydroperiods represent the species optima as identified by ordination analysis. Median hydroperiod refers to the duration of flooding in days experienced by the species during the 50th percentile year for the current hydroperiod regime in the Roanoke system. For further details, see Townsend (2001). NA = Not Available.

Table 14. Relationship between critical life stages and flooding of dominant tree species on the Savannah River floodplain.[1]

Common Name	Scientific Name	Seedfall period[2]	Germination period[3]	Seed buoyancy/ viability	Seedling tolerance to submergence[4]	Seedling tolerance to soil saturation	Waterlogging tolerance (adult trees)	Requirements for competition
Bald Cypress	*Taxodium distichum*	Sept – Nov* [E]	Spring	Seeds capable of remaining buoyant and viable for 2-3 months.[H]	Highly tolerant. Newly-germinated seedlings (<2 wks old) begin to show clear signs of stress after approximately one month and substantial mortality after 45 days.[K]	Highly tolerant.	Highly tolerant. Optimum growth probably achieved by holding water table close to the surface (-20 cm), permitting both adequate aeration and soil moisture.[M]	Intermediate shade tolerance.
Water Tupelo	*Nyssa aquatica*	Oct – Nov*	Spring – Summer	Seeds exhibit dormancy following dispersal, viable for up to 14 months in water.	95% survive 4 wks of spring flooding, however all leaves lost.	No mortality in 60 days. Established seedlings grow better in saturated conditions than undersaturated. 25% reduction in photosynthesis over 32 d. of flooding.	Highly tolerant.	Shade intolerant.
Swamp Tupelo	*Nyssa sylvatica* var. *biflora*	Oct – Nov* [F]	NA	Seeds exhibit dormancy following dispersal.[F]	NA	95% survive > 2 yrs of root flooding.[L]	Highly tolerant.	Shade intolerant.[F]
Water Hickory	*Carya aquatica*	Nov – Dec*	April – Early June	Seeds exhibit dormancy following dispersal; viability in water unknown.	NA	Seedlings probably very tolerant to soil saturation but no data available.	Highly tolerant.	Intermediate in shade tolerance.
Green Ash	*Fraxinus pennsylvanica*	Oct – Spring* [G]	Spring	Seeds dormant for up to several years following dispersal; viability in water unknown.	Height growth halted. 73% survive 20 d, 20% survive 30 d but 66% lose terminal bud. 91% surviving 4 wks of spring flooding, leaves remain. Most killed re-sprout from root collar.	No mortality in 60 d. Some mortality of secondary root tips, but many new tips. Root growth resumes immediately after saturated conditions removed. Photosynthesis reduced during flooding.	Moderately tolerant.	Shade tolerant.
Laurel Oak/ Diamondleaf Oak	*Quercus laurifolia*	Sept – Oct*	Spring	Seeds dormant following dispersal; remain viable in water at least 30 d.	NA	NA	Weakly tolerant. Too much flooding causes reductions in growth.[N]	Shade tolerant.

Table 14 cont.

Common Name	Scientific Name	Seedfall period[2]	Germination period[3]	Seed buoyancy/ viability	Seedling tolerance to submergence[4]	Seedling tolerance to soil saturation	Waterlogging tolerance (adult trees)	Requirements for competition
Sweetgum	*Liquidambar styraciflua*	Oct	Spring	Seeds exhibit dormancy following dispersal; viability in water unknown.	Height growth halted. 75% survive 10 days. None survived 20 days. 68% surviving 4 weeks of spring flooding, leaves remain. Many killed re-sprout from root collar.	No shoot mortality in 60 days; secondary roots die. Root systems take 3 weeks to redevelop. Significant decrease in growth. 5-month-old seedlings survive 2 yrs continuous root flooding. Smaller than seedlings grown under periodically flooded conditions.	Early successional species that tolerates very little growing season flooding. Ubiquitous species from drier floodplain sites and edges of wetlands into upland areas.[N]	Shade intolerant.
Swamp Chestnut Oak	*Quercus michauxii*	Sept – Oct*	Spring	Seeds not dormant following dispersal; viability in water unknown.	Intolerant.	One-year-old seedlings showed signs of leaf necrosis by week 11, 5% mortality by wk 13, and 10% mortality by wk 17. Seedlings had reduced diameter & height growth, and lower root and stem biomass compared to controls.	Weakly tolerant.	Shade intolerant.
American Hornbeam/ Ironwood	*Carpinus caroliniana*	Oct – Spring	Spring	Seeds dormant following dispersal; viability in water unknown.	NA	NA	Moderately tolerant.	Very tolerant.
Chinese Tallow	*Sapium sebiferum*	NA*	NA	Seeds are buoyant, capable of long periods of dormancy throughout extended periods of flooding;[I] also reproduces vegetatively.[J]	NA	NA	Highly tolerant.[B]	Very tolerant. Can also grow rapidly in full sunlight.[O]

[1] Data from Hochman (1999) [D] unless otherwise specified. NA = Not Available. [2] * = Uses hydrochory as a primary mode of dispersal.
[3] Full growing season for all species is roughly April through October. [4] During the growing season. All species able to withstand inundation during the dormant season.

Table 15. Major forest associates and the current status of dominant tree species on the Savannah River floodplain.

Common Name	Scientific Name	Major associates[P]	Status on Savannah River
Bald Cypress	*Taxodium distichum*	**In bottomland swamps:** *Nyssa aquatica*, *N. sylvatica* var. *biflora* **In bottomland hardwood forests:** *Acer rubrum*, *Salix nigra*, *Fraxinus caroliniana*, *F. profunda*, *Populus heterophylla*, *Planera aquatica*, *Gleditsia aquatica*	▪ High discharge floods released by reservoirs upstream in the late spring and summer of 1984 submerged a study population of *Taxodium* and *Nyssa aquatica* seedlings. Each flood lasted for longer than 3 days, and resulted in 88 and 95% mortality, respectively.[E] ▪ Chronic flooding conditions currently present in some cypress-tupelo forests on the Savannah River largely prohibit germination of *Taxodium*, *N. aquatica*, and *N. sylvatica* var. *biflora* seeds. These conditions are believed to be influenced by dam operations upstream, as well as reactor operations along tributary streams.[Q]
Water Tupelo	*Nyssa aquatica*	Same as *Taxodium distichum*	▪ Growing season floods caused by dam releases have resulted in high mortality of *N. aquatica* seedlings (see box above). ▪ Chronic flooding conditions prohibiting germination of *N. aquatica* seeds in some cypress-tupelo forests may be the result of dam operations upstream (see box above). ▪ A series of short-duration floods observed during the growing season of 1994 on the Savannah River floodplain were deep enough to overtop a study population of one-year-old *Nyssa aquatica* seedlings, resulting in a 19% reduction in survival.[R]
Swamp Tupelo	*Nyssa sylvatica* var. *biflora*	**In bottomland swamps:** Same as *N. aquatica* **In bottomland hardwood forests:** *Ilex opaca*, *Liquidambar styraciflua*, *Q. laurifolia*, *Quercus nigra*	
Water Hickory	*Carya aquatica*	*Acer rubrum*, *Fraxinus pennsylvanica*, *F. americana*, *Gleditsia aquatica*, *Liquidambar styraciflua*, *Quercus* spp.	▪ Species has been witnessing a decline in some sites on the Savannah River floodplain where too much growing season flooding occurs.[N] ▪ A series of short-duration floods observed during the growing season of 1994 on the Savannah River floodplain were deep enough to overtop a study population of one-year-old *Carya aquatica* seedlings, but resulted in little mortality (< 10%).[S]
Green Ash	*Fraxinus pennsylvanica*	*Acer negundo*, *A. saccharinum*, *Carya aquatica*, *C. illinoiensis*, *Celtis* spp., *Fraxinus americana*, *Liquidambar styraciflua*, *Nyssa sylvatica*, *Populus* spp., *Quercus* spp., *Salix nigra*	

Table 15 cont.

Common Name	Scientific Name	Major associates[P]	Status on Savannah River
Laurel Oak/ Diamondleaf Oak	*Quercus laurifolia*	*Acer rubrum*, *Nyssa sylvatica*, *Gordonia lasianthus*, *Liquidambar styraciflua*, *Quercus nigra*, *Ilex opaca*	▪ Common species across many sites. Occurs in areas of dormant season inundation and growing season soil saturation.[T] ▪ A series of short-duration floods observed during the growing season of 1994 on the Savannah River floodplain were deep enough to overtop a study population of one-year-old *Quercus laurifolia* seedlings, resulting in 100% mortality.[S]
Sweetgum	*Liquidambar styraciflua*	*Acer rubrum*, *A. saccharinum*, *Carya aquatica*, *C. illinoiensis*, *Celtis* spp., *F. americana*, *Fraxinus pennsylvanica*, *Gleditsia aquatica*, *Gordonia lasianthus*, *Ilex opaca*, *Nyssa sylvatica*, *Populus* spp., *Quercus* spp., *Salix nigra*	▪ Common species across many sites.[G]
Swamp Chestnut Oak	*Quercus michauxii*	*Carya* spp., *Fraxinus pennsylvanica*, *F. americana*, *Nyssa sylvatica*, *Quercus alba*, *Q. shumardii*	▪ Common species.[G]
American Hornbeam/ Ironwood	*Carpinus caroliniana*		▪ Common understory species throughout most somewhat drier sites.[G]
Chinese Tallow	*Sapium sebiferum*		▪ Chinese tallow is an invasive species on the Savannah River floodplain. While tallow has not been found to be more flood tolerant than bottomland swamp canopy dominants (*Taxodium distichum*, *Nyssa aquatica*), it is more tolerant than a number of bottomland hardwood species.[B]

References for Tables 13, 14 and 15.

[A] Mitsch, W.J. and J.G. Gosselink, 2000. Wetlands. Third Edition. John Wiley & Sons, New York.

[B] Conner, W.H., L.W. Inabinette, and C.A. Lucas, 2001. Effects of flooding on early growth and competitive ability of two native wetland tree species and an exotic. *Castanea*, **66**: 237-244.

[C] Townsend, P.A., 2001. Relationships between vegetation patterns and hydroperiod on the Roanoke River floodplain, North Carolina. *Plant Ecology*, **156**: 43-58.

[D] Hochman, E.R., 1999. Lower Roanoke River Hydroperiods: Parts I & II. Report for The Nature Conservancy, North Carolina, U.S.A.

[E] Sharitz, R.R., R.L. Schneider and L.C. Lee, 1990. Composition and regeneration of a disturbed river floodplain forest in South Carolina. *Ecological Processes and Cumulative Impacts: Illustrated by Bottomland Hardwood Wetland Ecosystems*, Chelsea, MI.

[F] Dirr, M.A., 1998. Manual of Woody Landscape Plants: Their Identification, Ornamental Characteristics, Culture, Propagation and Uses. Fifth Edition. Stipes Publishing L.L.C., Champaign, Illinois.

[G] R.R. Sharitz, personal communication.

[H] Schneider, R.L. and R.R. Sharitz, 1988. Hydrochory and regeneration in a bald cypress-water tupelo swamp forest. *Ecology*, 69: 1055-1063.

[I] S. McCormick, personal communication.

[J] Bruce, K.A., G.N. Cameron, P.A. Harcombe and G. Jubinsky, 1997. Introduction, impact on native habitats, and management of a woody invader, the Chinese tallow tree, *Sapium sebiferum* (L.) Roxb. *Natural Areas Journal*, 17: 255-260.

[K] Souther, R.F. and G.P. Shaffer, 2000. The effects of submergence and light on two age classes of baldcypress (*Taxodium distichum* (L.) Richard) seedlings. *Wetlands*, 20: 697-706.

[L] Angelov, M.N., S.J.S. Sung, R.L. Doong, W.R. Harms, P.P. Kormanik and C.C. Black, 1996. Long- and short-term flooding effects on survival and sink-source relationships of swamp-adapted tree species. *Tree physiology*, **16**: 477-484.

[M] Megonigal, J.P. and F.P. Day, 1992. Effects of flooding on root and shoot production of bald cypress in large experimental enclosures. *Ecology*, 73: 1182-1193.

[N] W. H. Conner, personal communication.

[O] Jones, R.H. and R.R. Sharitz, 1990. Effects of root competition and flooding on growth of Chinese tallow tree seedlings. *Canadian Journal of Forest Research*, 20: 573-578.

[P] Sharitz, R.R. and W.J. Mitsch, 1993. Southeastern floodplain forests. *Biodiversity of the Southeastern United States / Lowland Terrestrial Communities*, John Wiley & Sons, Inc.

[Q] Schneider, R.L. and R.R. Sharitz, 1986. Seed bank dynamics in a southeastern riverine swamp. *American Journal of Botany*, **73**: 1022-1030.

[R] McLeod, K.W., M.R. Reed and L.D. Wike, 2000. Elevation, competition control, and species affect bottomland forest restoration. *Wetlands*, **20**: 162-168.

[S] McLeod, K.W., M.R. Reed and E.A. Nelson, 2001. Influence of a willow canopy on tree seedling establishment for wetland restoration. *Wetlands*, 21: 395-402.

[T] R.R. Sharitz, unpublished data.

Table 16. Threatened and endangered species (TES) on the Savannah River floodplain.

Rhapidophyllum hystrix[2]

- Requirements for establishment:
  --Seed production / dispersal period: ?
  --Seed germination time of up to two years.
  --Requires poorly drained soils to perform well.

- Requirements for growth:
  --Growing season: ?
  --Extremely slow growth rate.
  --Requires poorly drained soils to perform well.

Hymenocallis coronaria[3]

- Requirements for establishment:
  --Flowering period: mid-May – early June; Fruiting period: July – August.[4]
  --The presence of riverweed (*Podostemon ceratophyllum*), which requires fairly clear, cool, clean flowing water to thrive, may be an important factor in the successful recruitment of new individual plants by providing safe sites for seed germination.
  --Germination rates are high, and seeds readily germinate within a few days after deposition. Only a small percentage of seedlings survive the first winter, however. Large numbers of seeds are therefore required for successful establishment.

- Requirements for growth:
  --Growing season: ?
  --Requires clear, flowing water and rocky substrates.
  --Plants can be completely submerged during flooding, the bulbs anchored among the rocks.
  --Sensitive to any activity that increases amount of sediment.
  --Cool temperatures may be as important as water depth and flow. Under altered hydrology, temperature may be the key factor controlling vigor and viability. Water temperatures in the Savannah near Augusta are cool throughout the year, including summer.
  --High DO thought to be integral to survival and success.
  --Exotics—Eurasian watermilfoil (*Myriophyllum spicatum*) and Brazilian elodea (*Egeriadensa*)—have the ability to outcompete other submersed species and become dominant. Could compete with *Hymenocallis*, particularly by preventing seedling establishment, where water is sufficiently deep.
- Current status in Savannah River floodplain:
  --Small populations in existence near Augusta
  --During a 1997-1998 study, water conditions including flow, temperature, and DO were well within tolerance ranges. Low – no flow could, however, result in significant impacts due to elevated temperatures and DO. Low flows also result in increased animal grazing, primarily by deer, which tend to eat clumps of the lily down to the tops of the bulbs.

---

[2]Information from USDA Natural Resources Conservation Service website, January, 2003. [2]Data from Aulbach-Smith 1998 unless otherwise specified. [3] U.S. Army Corps of Engineers website, January 2003.

Table 16 cont.

Potential Species of Special Concern
(for possible consideration)

Carex decomposita **(cypress-knee sedge)**
Tufted perennial graminoid species that occurs in swamps, backwaters and floodplains. Often growing on cypress knees, stumps and downed logs. Active growth period during spring and summer. High tolerance of anaerobic conditions. Shade tolerant. Found on Savannah River floodplain on Savannah River Site.

Quercus austrina **(bluff white oak)**
Grows on sandy "ridges" within the Savannah River drainage and is relatively frequent from Aiken to Jasper Counties, probably occurring on relatively infrequently flooded sites. Occurs on Stave Island on the Savannah River floodplain on the Savannah River Site. Probably flooded relatively infrequently.

Macbridea caroliniana **(Carolina bogmint)**
Perennial mint that grows along bases of slopes of tributaries of the Savannah River and the river itself. Reported in Aiken County.

Table 17. Timing of migration and nesting for major bird species occupying the Savannah River floodplain.[1]

Common Name	Scientific Name	Timing of Migration	Timing of Nesting
Woodcock	*Scolopax minor*	In Georgia year-round	~Jan-March
Belted kingfisher	*Ceryle alcyon*	In Georgia year-round	Begins in April
Swallow-tailed kite[2]	*Elanoides forficatus*	In Georgia & South Carolina during breeding season (March – June); leave by mid-Sept	
Mississippi kite	*Ictinia mississippiensis*	In Georgia & South Carolina during breeding season (late April – early Oct)	
Prothonotary warbler	*Protonotaria citrea*	In Georgia & South Carolina during breeding season (late March – late Sept)	
Hooded warbler	*Wilsonia citrina*	In Georgia & South Carolina during breeding season (March – late Oct)	
Sandhill crane	*Grus canadensis pulla*	In Georgia during nonbreeding season? (Oct – March)	

[1] All information on birds from *The Birds of North America* book series (A. Poole and F. Gill, eds.). See references cited.
[2] Listed as endangered in South Carolina.

Table 18. Major bird species occupying the Savannah River floodplain: Habitat and food requirements pertaining to flooding and floodplain vegetation.

Common Name	Scientific Name	Food	Breeding Habitat	Nesting Habitat	Wintering Habitat
Woodcock	*Scolopax minor*	Principally invertebrates, particularly earthworms. Plant foods relatively minor. Feeding activity influenced indirectly by vegetation (leaf litter that earthworms find palatable as food (aspen > other hardwoods > conifers).	Forest openings and old fields provide display area for males.	Nest in mid-aged, open-grown, mixed pine-hardwood forests on lowland floodplains. Nest on ground.	Wide variety of forests used diurnally, including bottomland hardwoods, upland mixed pine-hardwoods, mature longleaf pine recently burned, and shrub land with no overstorey.
Belted kingfisher	*Ceryle alcyon*	Diet mostly fish.	Inhabits streams, rivers, ponds, lakes, and estuaries or calm marine waters in which prey are clearly visible. Prefers running waters that are not obscured by vegetation.	Excavates burrow in earthen banks void of vegetation, generally near water though not necessary. May prefer banks with herbaceous vegetation—tree roots sometimes impede nest excavation.	Migrants are regular inhabitants of coastal swamps, brackish lagoons, oxbows, and bayous. Avoids turbid waters or habitats lacking perches for detecting prey.
Swallow-tailed kite	*Elanoides forficatus*	Mainly insects; also frogs, nestling birds, lizards, and snakes; less frequently bats, fruits, small fish. Forages in branches, foliage, and stems of deciduous trees, shrubs, & emergent vegetation of rivers, lakes, ponds, marshes, and sloughs.	Key feature is association of tall, accessible trees for nesting with open areas that provide sufficient small, easily subdued prey. Includes various combinations of pine (*Pinus elliottii*) forest, hydric pinelands, pine fringe of floodplain and bottomland swamp forests, wet prairies, freshwater & brackish marshes, hardwood hammocks, tall trees edging sloughs and bayous, and mangrove (*Avicennia*) forest.	Prefers woodland with open, uneven structure for nest-tree crown and immediately surrounding canopy. Stand need not be large or contain high density of preferred species. Beyond 50-100 m, density & structure of habitat much less important, ranging from continuous forest to open marsh. All nests studies in South Carolina were in loblolly pine (*Pinus taeda*). Nests made from small sticks of cypress and pine and epiphytes (Florida data).	
Mississippi kite	*Ictinia mississippiensis*	Predominantly insects. Some reptiles, amphibians, birds, and mammals	Mature bottomland forest, including suitable riparian woodland, with moderate or high tree species diversity.	Prefer old-growth trees in stands >80 ha. Nests constructed from twigs of many tree species.	

Table 18 cont.

Common Name	Scientific Name	Food	Breeding Habitat	Nesting Habitat	Wintering Habitat
Prothonotary warbler	*Protonotaria citrea*	Primarily insectivorous. Takes prey from fallen logs, trunks, and branches of trees, foliage of shrubs, and tree subcanopy. Along Tennessee River, primary foraging substrates are foliage and branches on willow, red maple (*Acer rubrum*) and buttonbrush, and surface of fallen woody debris. Often forages from aboveground roots of cypress ("knees") during breeding season.	Exhibits area sensitivity, avoiding forests <100 ha in area and waterways with wooded borders <30 m wide.	Key features: presence of water near wooded area with suitable cavity nest sites. Nest usually placed over or near large bodies of standing or slow-moving water, including seasonally flooded bottomland hardwood forest, bald cypress (*Taxodium distichum*) swamps, and large rivers or lakes. Water depth under nests highly variable. Common understorey tree species in nesting habitat include willows, maples, sweetgum, willow oak, ashes, elms, river birch, black gum (*Nyssa sylvatica*), tupelo, cypress, and other species, and other species associated with wetlands. Often uses cypress knees where available. Also cavities in cypress, willows, and sweetgum. Nest site almost always over or within 5 m of standing water or in low-lying, easily flooded areas.	
Hooded warbler	*Wilsonia citrina*	Insects and other small arthropods.		Patches of shrub within forest and along edge of forest.	
Sandhill crane	*Grus canadensis pulla*	Cultivated grains are major food items whenever possible. Feed primarily on land or in shallow marshes with emergent vegetation.			Freshwater marshes. In Okefenokee swamp, open, less wooded herbaceous marsh areas preferred; little or no use of drier upland habitats.

Table 19. Major bird species occupying the Savannah River floodplain: Habitat / territory requirements and sources of habitat degradation.

Common Name	Scientific Name	Habitat / Territoriality	Degradation of Habitat
Woodcock	*Scolopax minor*	Adjacent young hardwoods and mixed woods with shrubs, particularly alder <20 yrs, provide moist ground for daytime feeding. No minimum individual distances.	Breeding: decline in numbers may be the result of changing forest management practices, increased fire suppression, and urbanization, which do not provide the suitably large areas of shrub land and young forest this species needs to breed successfully (V. VanSant, *personal communication*). Habitat: draining of bottomland hardwoods and swampy areas degrades habitat.
Belted kingfisher	*Ceryle alcyon*		If ground within nest chamber becomes saturated with water, eggs may settle into mud, causing nest abandonment by female. Water quality, cover, and the availability of suitable nesting sites along the stream are essential for breeders.
Swallow-tailed kite	*Elanoides forficatus*	More important than topography or specific vegetation communities is physical structure of the landscape. Small stands or tree islands in prairielike setting; low-density forest of uneven structure interrupted by open areas of shrub, swamp, or marsh vegetation; or denser forest, frequently interspersed with various sorts of openings. Particular selection of hardwood and cypress swamps. Territory usually ~25–100 m around/above nest-tree stand.	Listed as endangered in South Carolina. Greatest threat is loss and degradation of nesting, foraging, and roosting habitat due in part to logging and flood control in gulf-coastal lowlands, altered hydrology, and production forestry. A need to protect large heterogeneous mosaics of vegetation that include such unregulated systems as older hydric pine forest and small seasonal wetlands.
Mississippi kite	*Ictinia mississippiensis*	Catholic in habitat use. Prefer larger, unfragmented forests, but with considerable nearby open habitat, including pasture and cropland, linear waterways, lesser-used roads, levees, and small lakes. Little to no territoriality.	For some eastern and southeastern populations, removal and fragmentation of mature hardwood forest has had recent negative impacts on local populations, and now represent a major threat to some eastern populations.

Table 19 cont.

Common Name	Scientific Name	Habitat / Territoriality	Degradation of Habitat
Prothonotary warbler	*Protonotaria citrea*	Important habitat correlates include in some places the presence of bald cypress. Territory ranges from 0.5–1.5 ha. Size decreases with increase in breeding density, nest-site density, or habitat quality.	Populations are probably regulated mostly by habitat quality and availability. Flooding is a primary source of nest mortality. Alteration of hydrological regime, causing drying of seasonally flooded wetlands, causes severe negative impacts on populations. Channeling of streams also lowers habitat quality. In some regions, creation of reservoirs or other wetland habitats may offset some habitat loss, causing small geographic shifts in local populations rather than overall declines.
Hooded warbler	*Wilsonia citrina*	Inhabit a variety of forested habitats with an area >15 ha. Typically inhabit mature forests where trees are large enough to create significant tree fall gaps. Deciduous forests occupied usually dominated by maple (*Acer*), beech (*Fogus grandifolia*), or oak (*Quercus*). Breeding territories range from ~0.5–0.75 ha in size.	"Area-sensitive," i.e. generally found only in larger tracts of mature forest on breeding grounds. Forest fragmentation reduces availability of nesting habitat.
Sandhill crane	*Grus canadensis pulla*		Wetland conservation important.

Table 20. Locations of salinity contours (in river miles) at three river flow rates (cfs) and under three harbor depth conditions for branches of the upper Savannah River estuary. Contours represent median high tide salinities in surface water and median tidally averaged salinities in bottom water. Values were estimated from figures in Applied Technology & Management Inc. (1998).

Conditions:	**Existing**			**50-ft Deep**			**50-ft Deep+Closure**		
Clyo Flow (cfs):	5300	8200	11000	5300	8200	11000	5300	8200	11000
	Surface Salinity Contour Locations (River Miles)								
Front River									
0.5 ppt	25.1	23.0	20.3	25.8	24.0	22.5	25.9	24.5	20.2
1.0 ppt	24.2	21.8	19.6	25.1	22.7	20.4	25.2	22.8	19.4
2.0 ppt	22.3	20.4	18.1	23.2	21.0	18.8	23.3	20.7	17.7
5.0 ppt	20.8	16.8	14.4	21.0	16.6	14.4	20.9	16	
Middle River									
0.5 ppt	25.0	23.3	21.9	25.2	24.0	23.0	21.6	21.5	20.3
1.0 ppt	24.0	21.9	20.1	24.8	22.8	21.8	21.5	21.3	
2.0 ppt	21.8	19.7		22.1	21.9		21.2	20.8	
5.0 ppt	19.7			19.8					
Back River									
0.5 ppt	21.3	21.0	19.2	21.3	21.0	19.2	20.6	20.7	18.0
1.0 ppt	21.0	20.8	18.6	21.0	20.8	18.6	20.4	20.1	17.3
2.0 ppt	20.5	19.7	17.7	20.5	19.8	17.8	20.0	19.1	16.0
5.0 ppt	18.5	17.0	15.6	19.1	17.2	16.0	17.7	16.6	14.0
	Bottom Salinity Contour Locations (River Miles)								
Front River									
0.5 ppt	24.0	21.4	20.7	25.0	24.2	22.8	25.7	25.3	23.0
1.0 ppt	22.7	21.0	20.4	23.9	22.2	21.6	25.3	22.9	21.8
2.0 ppt	21.5	20.3	19.8	21.9	21.4	20.9	22.8	21.3	20.8
5.0 ppt	20.1	18.8	18.1	20.3	19.8	19.5	21.0	19.8	19.4
Middle River									
0.5 ppt	24.0	21.9	21.5	25.3	23.3	22.0	21.1	20.2	21.0
1.0 ppt	23.0	21.7	21.0	23.5	22.0	21.7	20.2		
2.0 ppt	21.8	19.8	19.8	22.0	21.7	21.3			
5.0 ppt	19.7			20.6	19.8				
Back River									
0.5 ppt	20.3	19.0	18.7	20.4	19.2	19.0	18.6	18.3	18.6
1.0 ppt	19.3	18.5	18.3	19.6	18.5	18.4	18.3	18.0	18.1
2.0 ppt	18.3	17.5	17.4	18.5	17.7	17.4	17.6	17.3	17.2
5.0 ppt	16.1	15.8	15.6	16.3	16.0	16.0	16.0	16.0	15.7

Figure 1. Annual hydrograph for Augusta and Clyo gages.

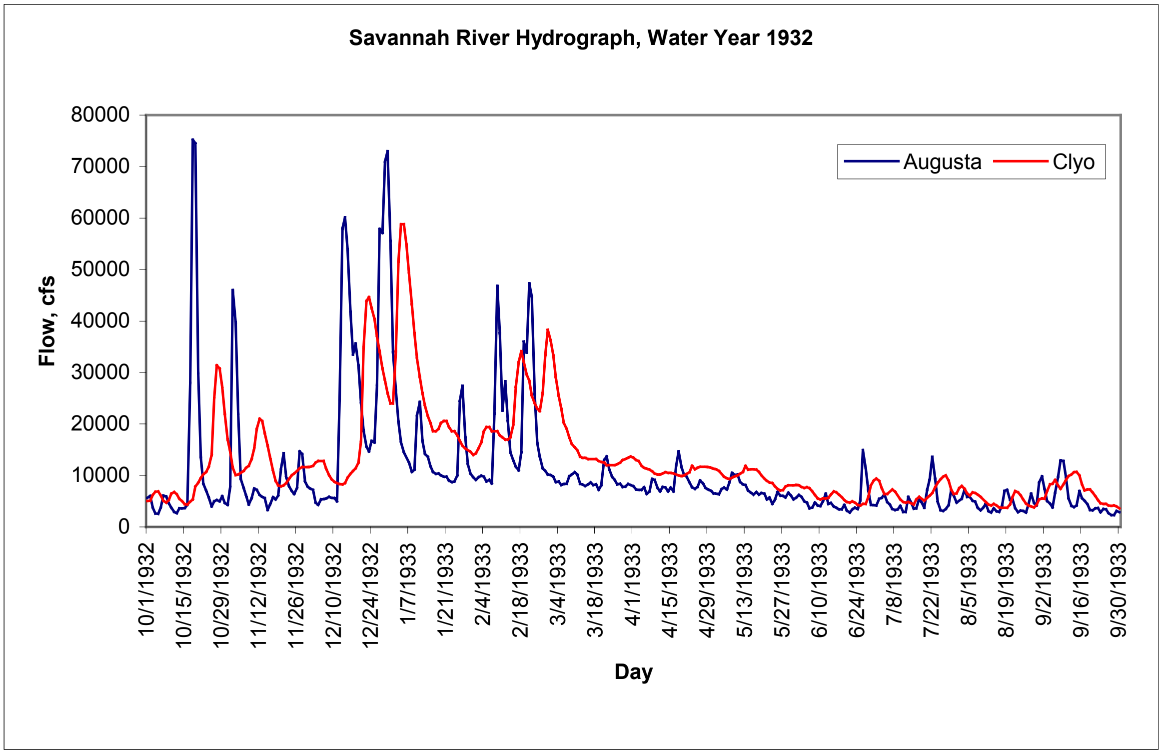


Figure 2. Relationship between flow at Augusta and Clyo gages.

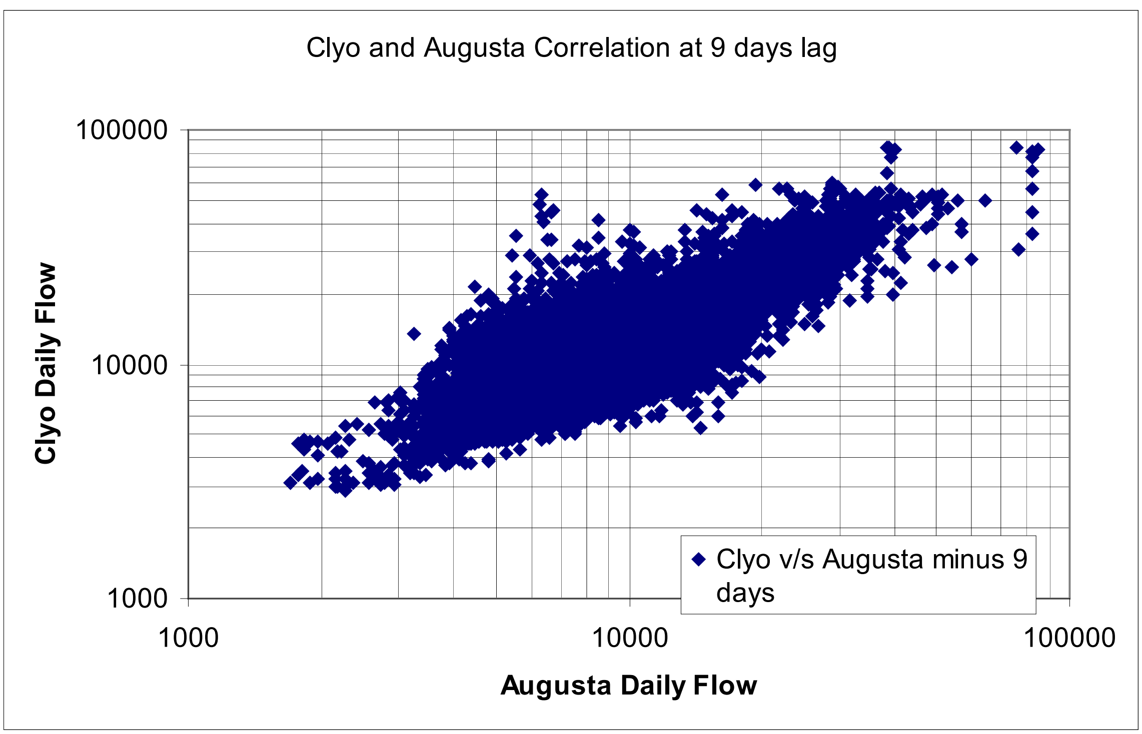


Figure 3. Hydrograph for Water Year 1901.

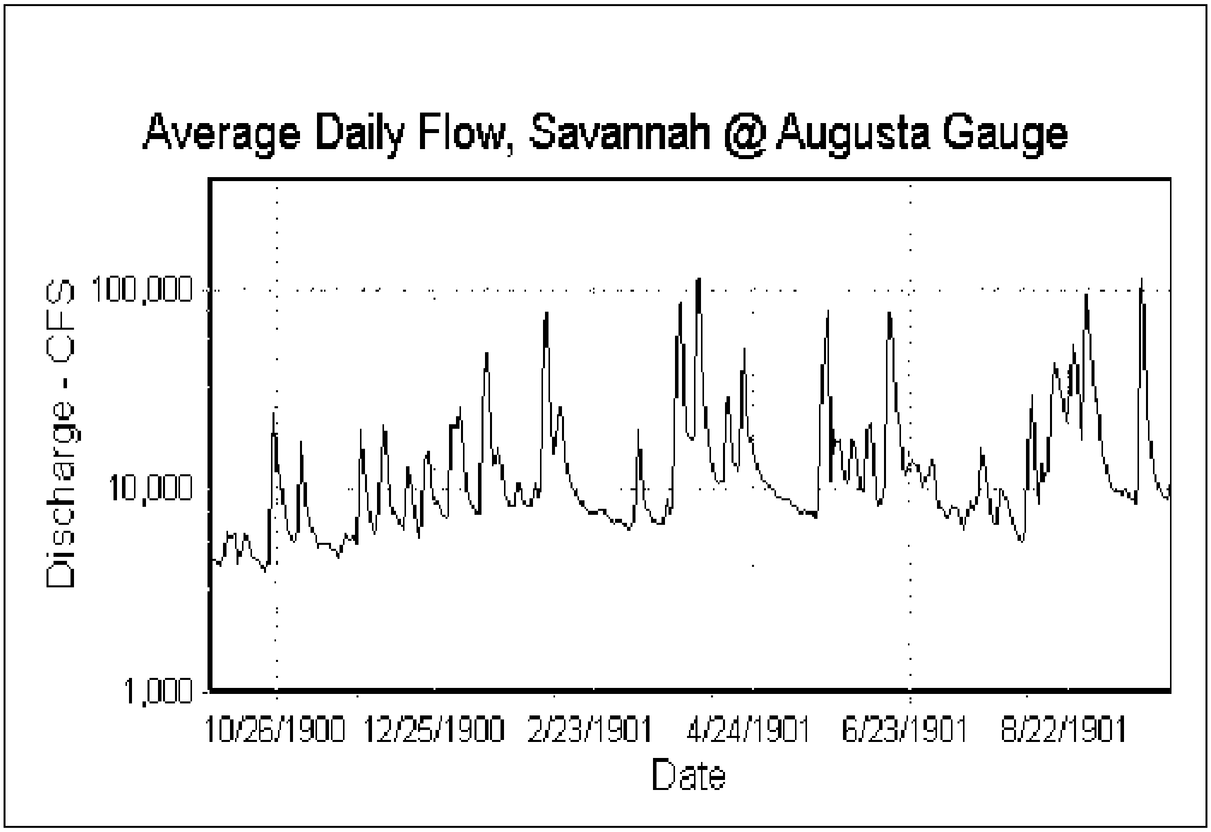


Figure 4. Hydrograph for Water Year 1995.

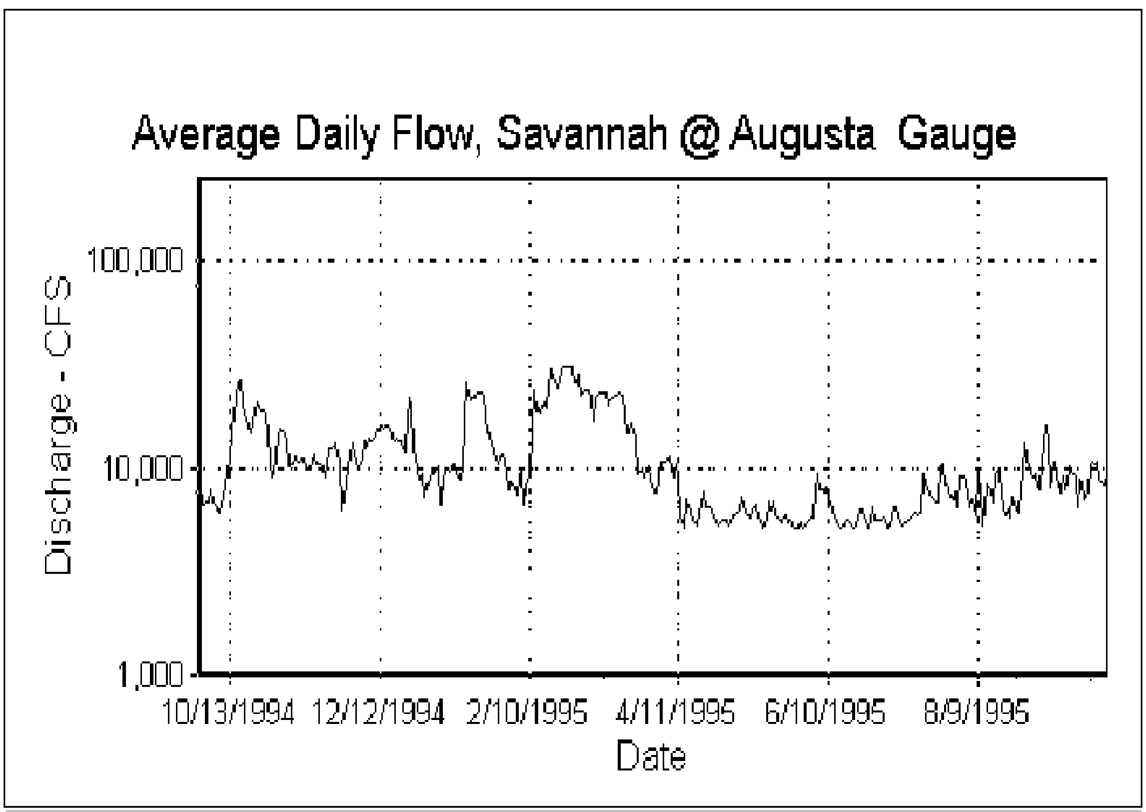


Figure 5. Peak flows for the period of record at the USGS gage #02197000 (Augusta, GA).

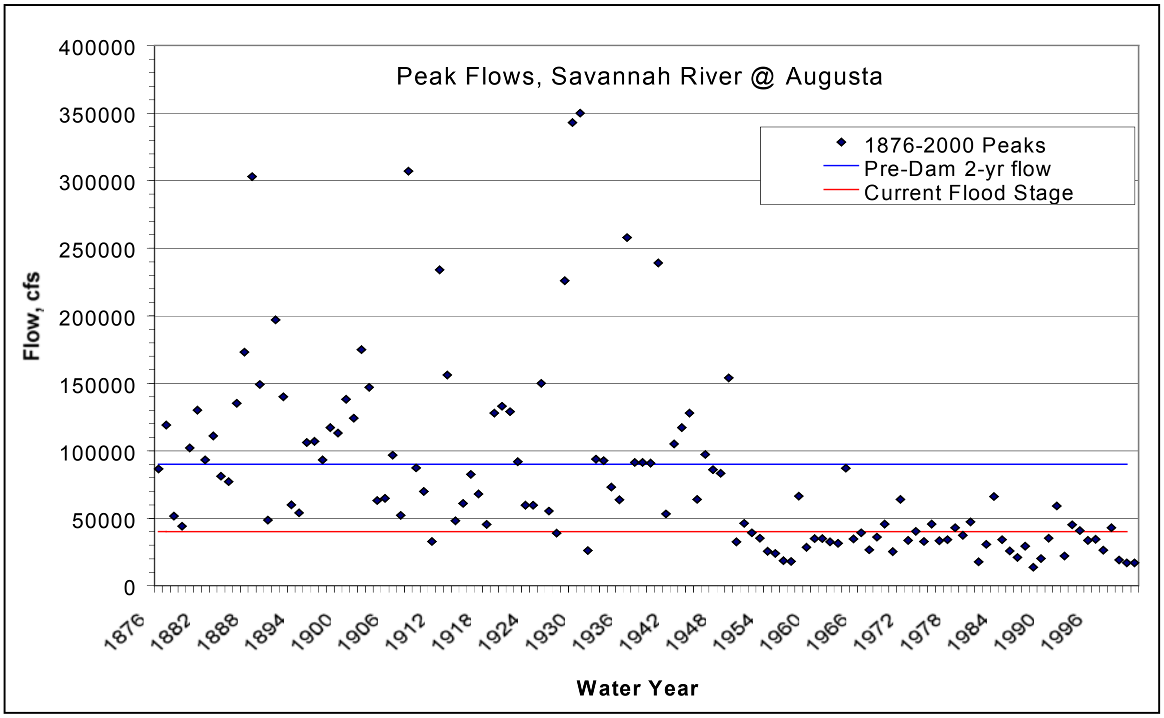


Figure 6. Peak flows for the period of record for the Edisto River.

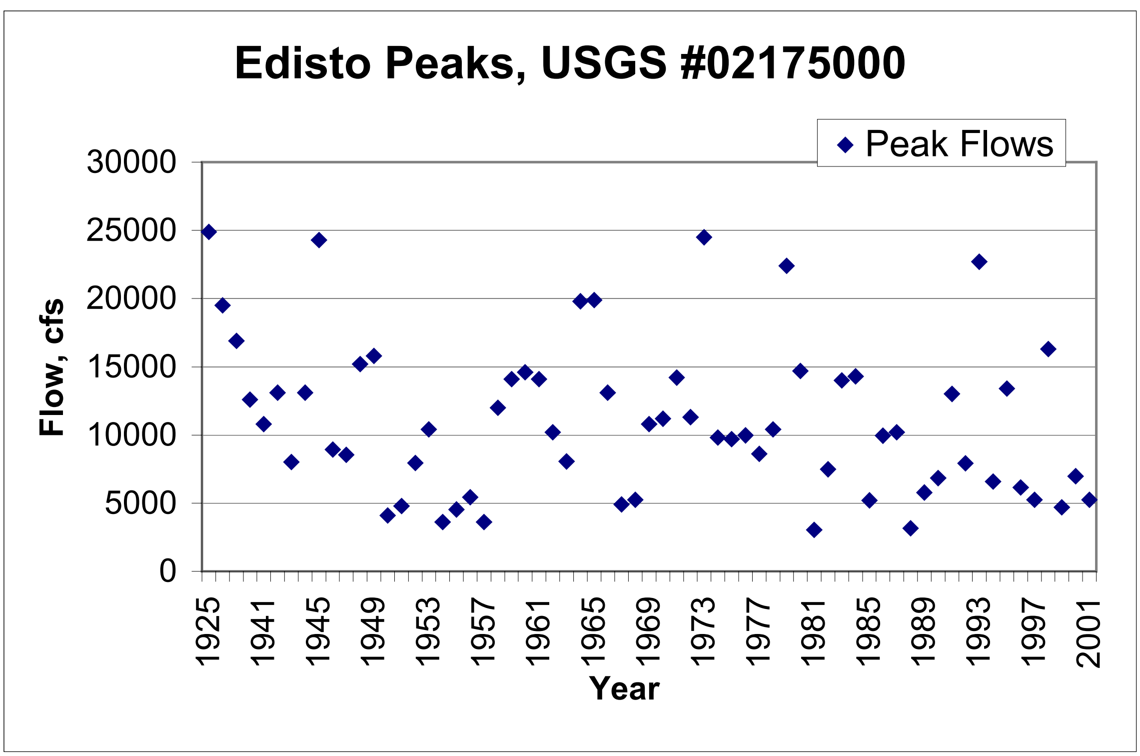


Figure 7. Flow recurrence graph for USGS gage #02197000.

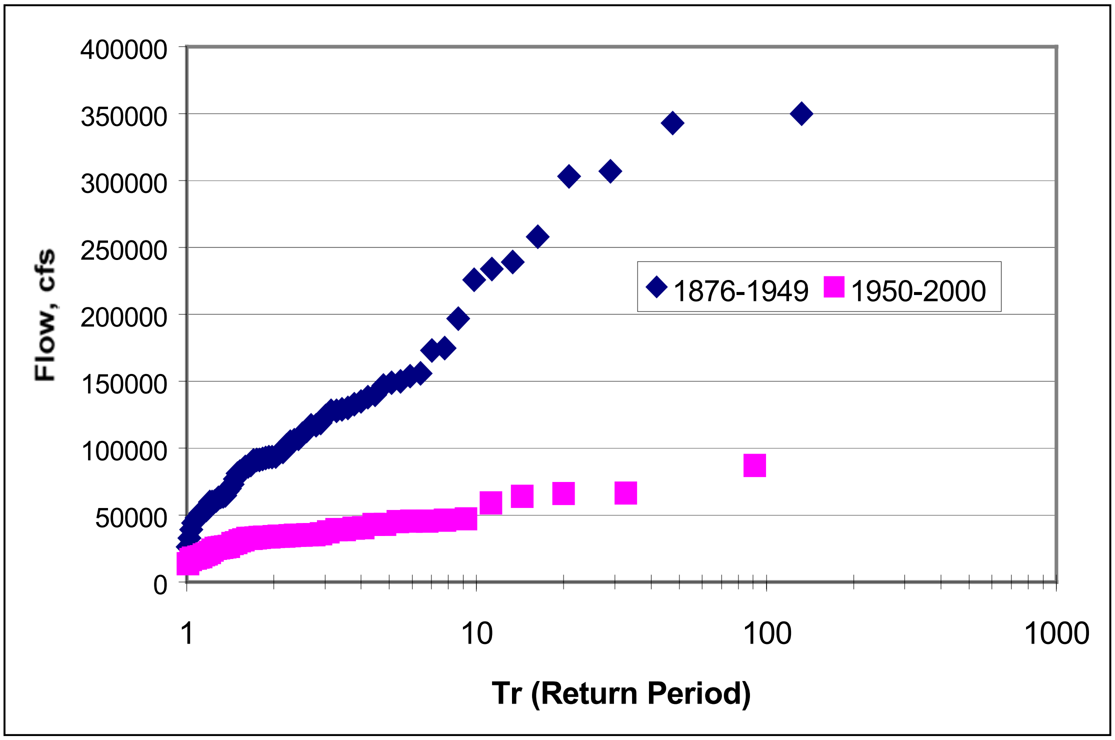


Figure 8. Flow recurrence graph for the Edisto River.

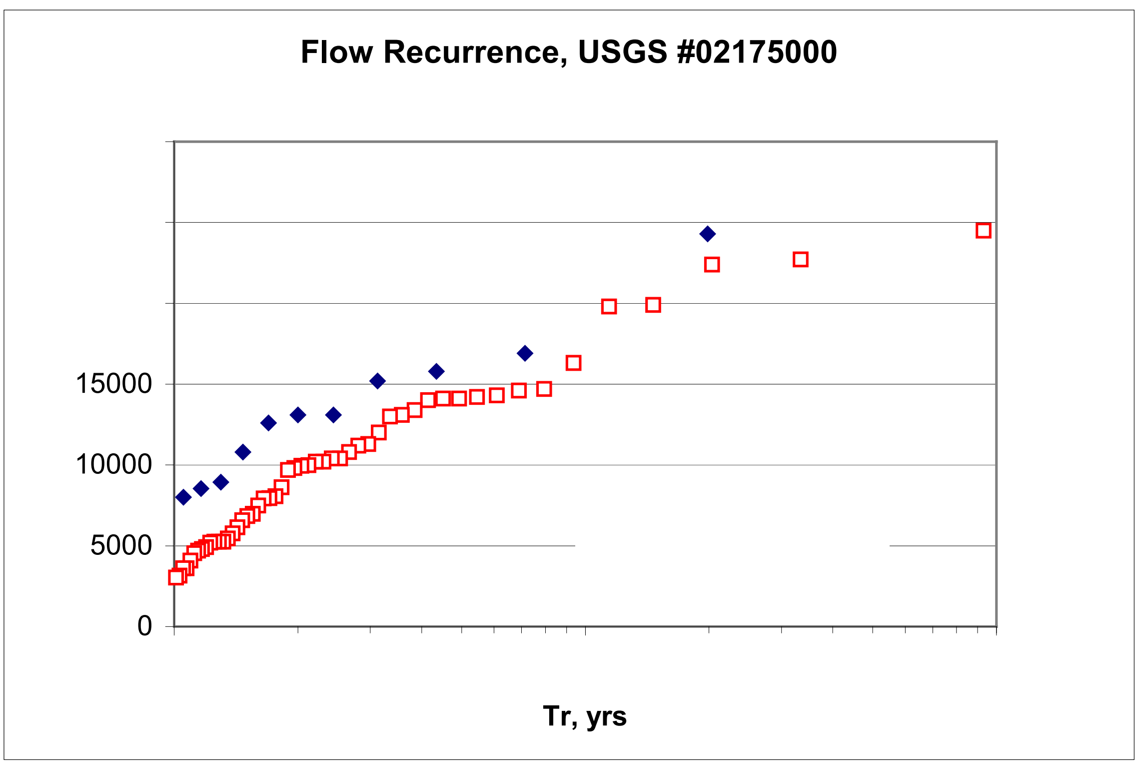


Figure 9. Histogram of peak flow occurrence by month for USGS gage #02197000.

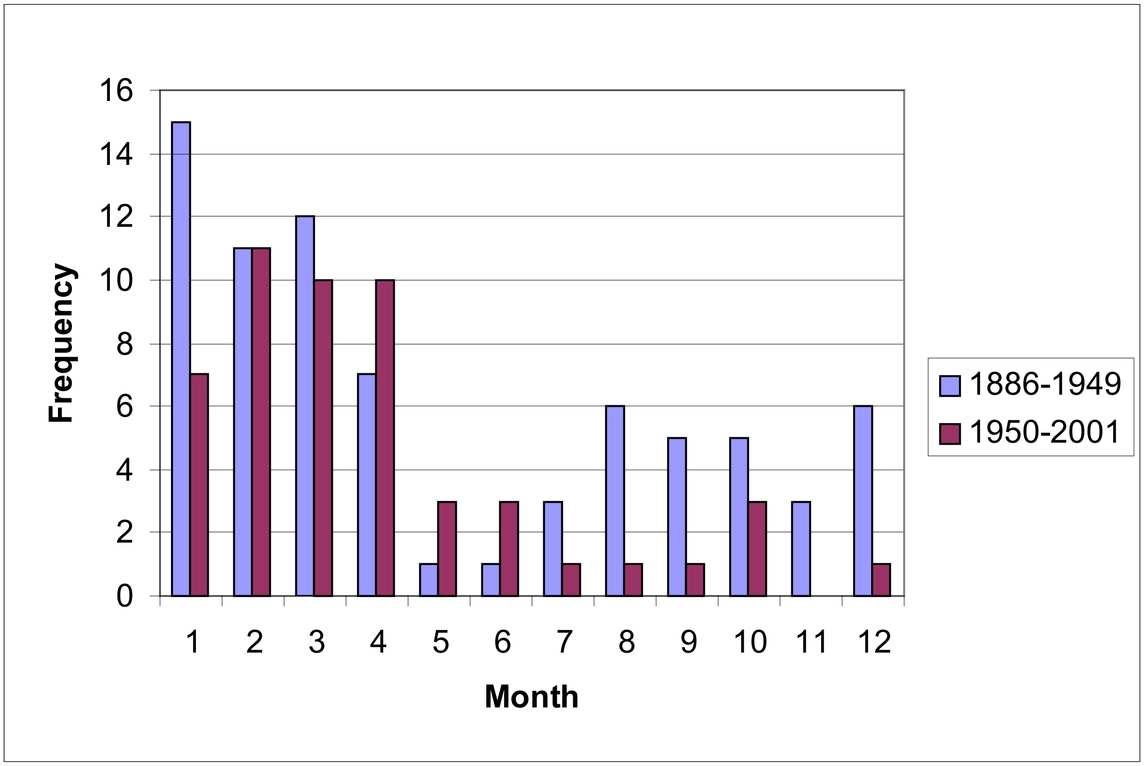


Figure 10. Comparison of pre and post-dam 7-day low flows at the USGS gage #02197000.

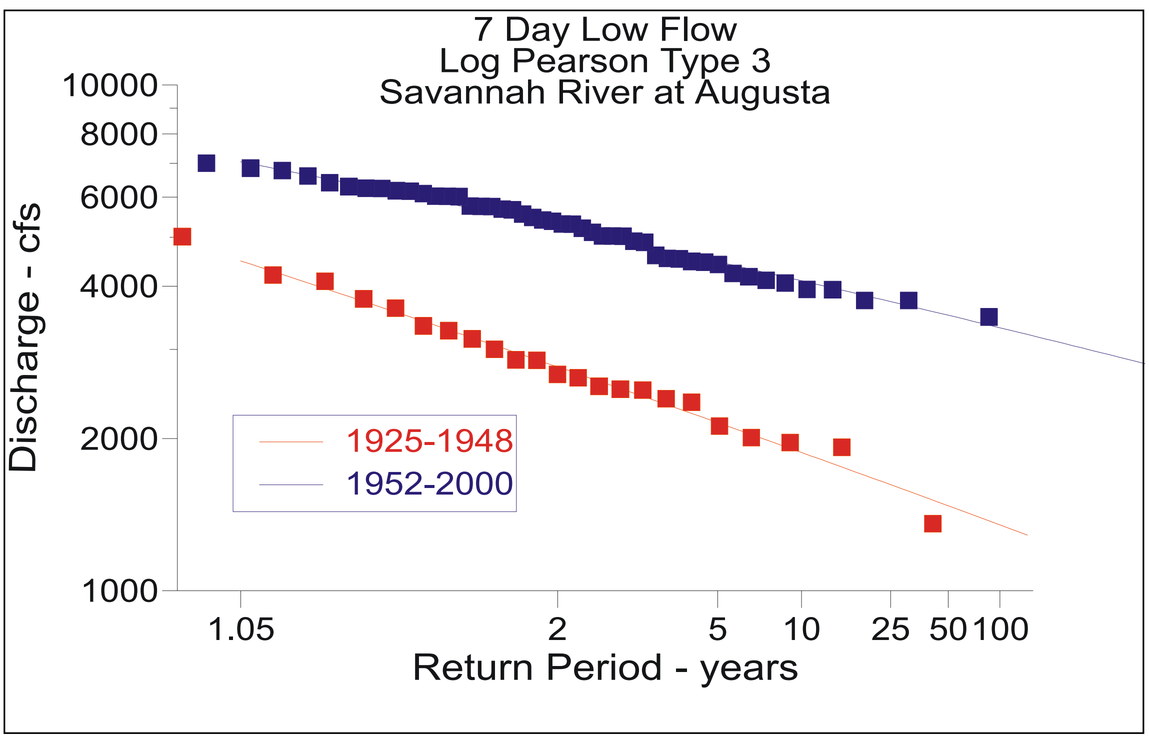


Figure 11. 7-day low flows for USGS gage #02197000.

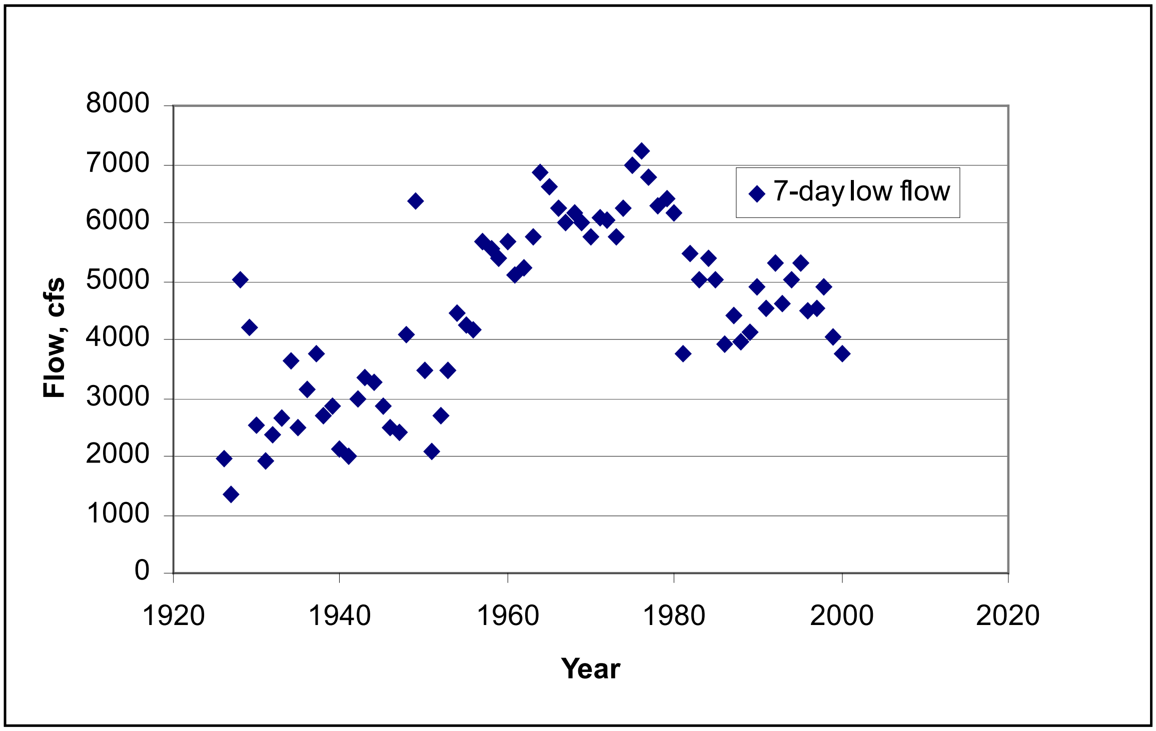


Figure 12. Julian date deviation of the 7-day low flow occurrence from USGS gage #02197000's pre-1950 mean.

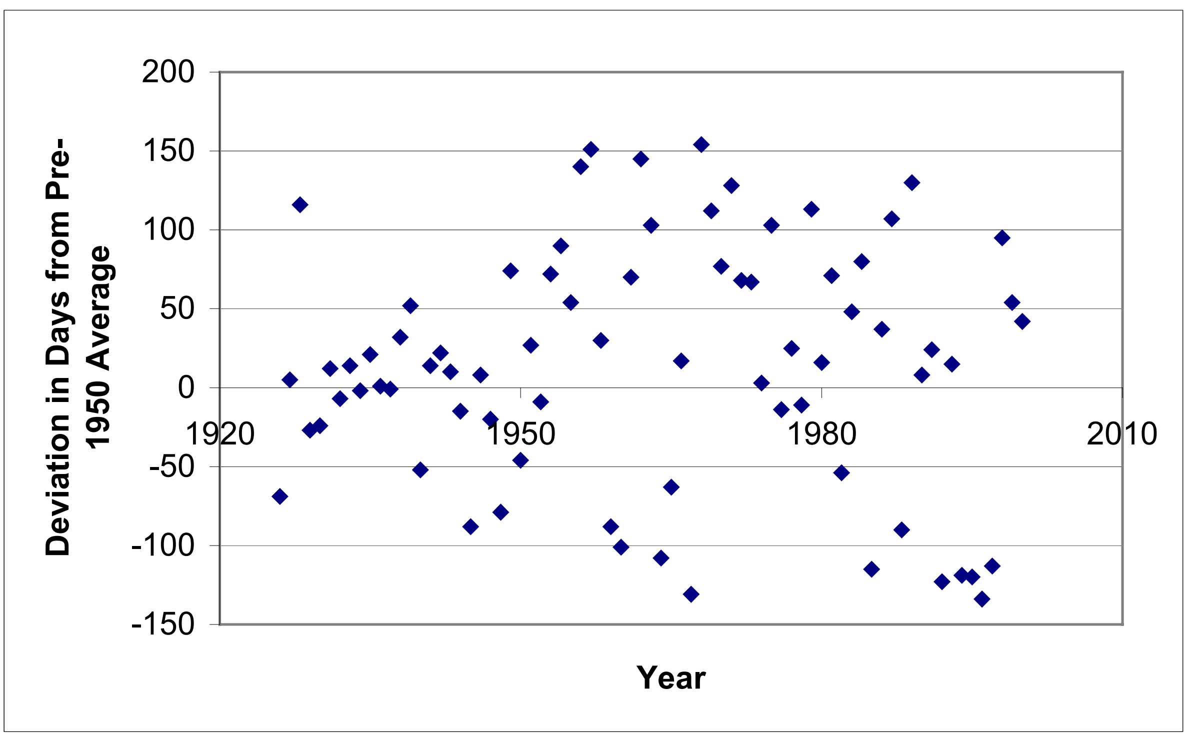


Figure 13a. Pre- and post-dam mean monthly flows for USGS gage #02197000 at Augusta.

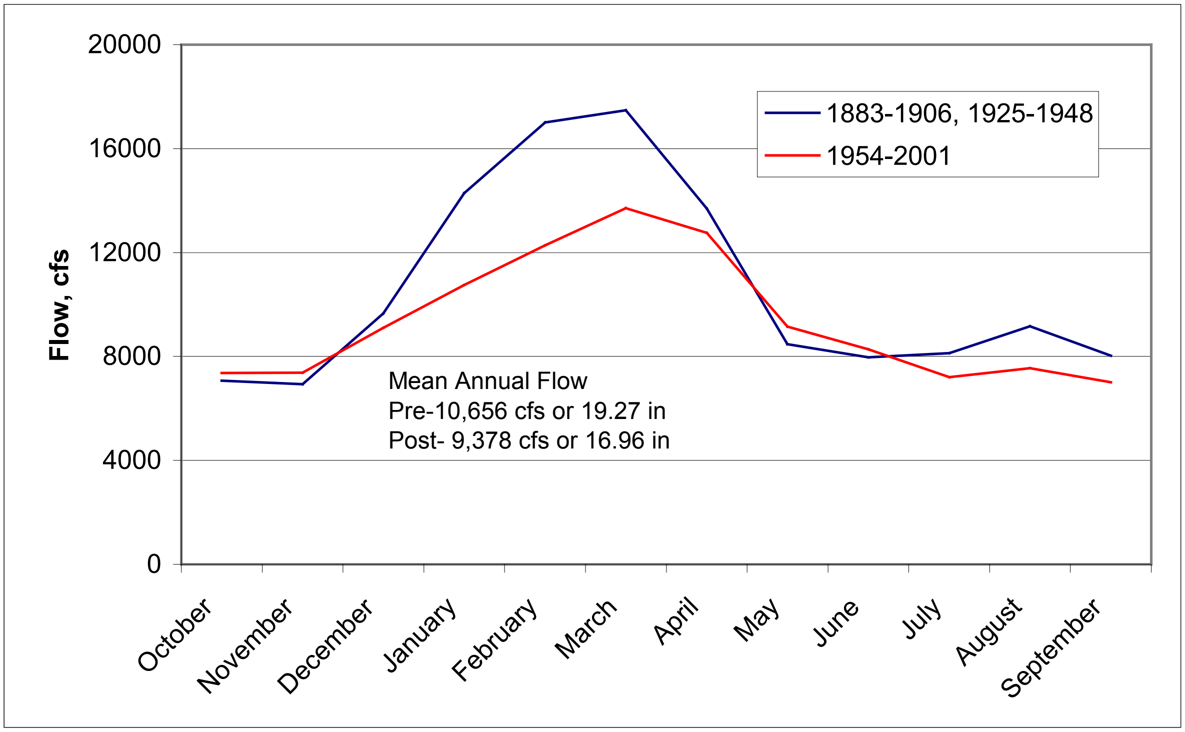


Figure 13b. Pre- and post-dam mean monthly flows for USGS gage #02198500 at Clyo.

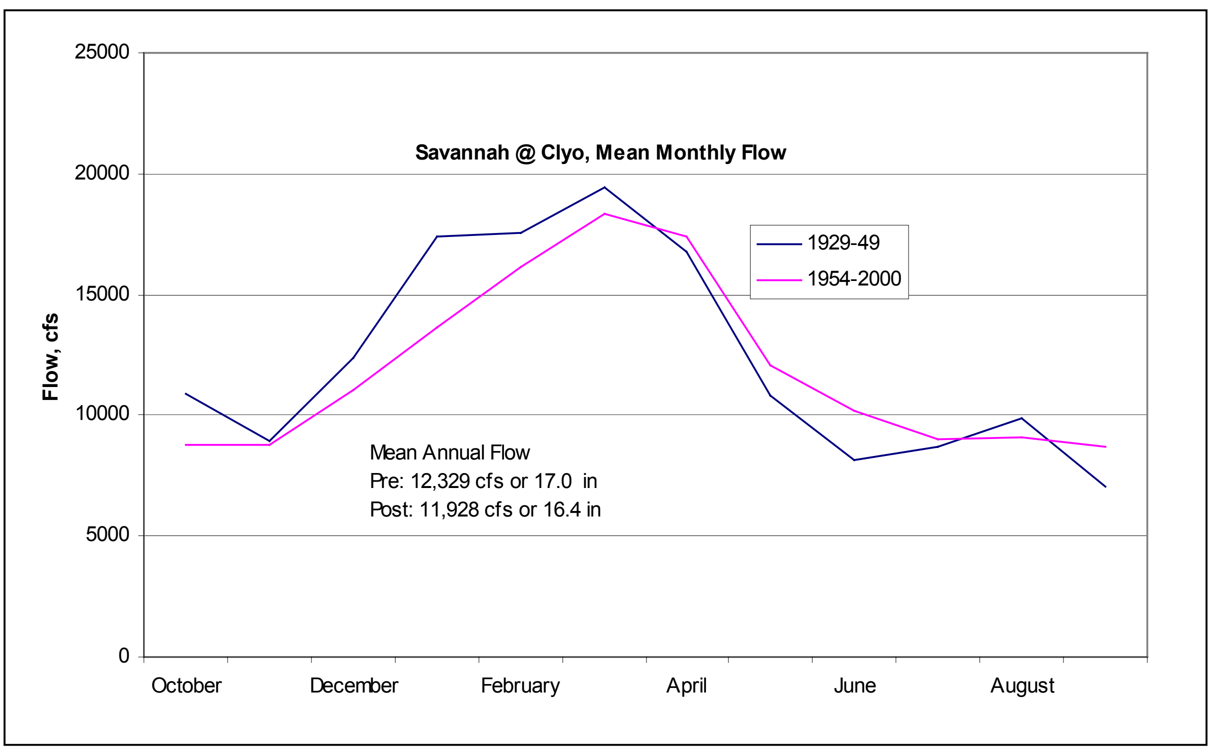


Figure 14. Mean monthly flows for the Oconee River near Greensboro, GA (USGS gage #02218500).

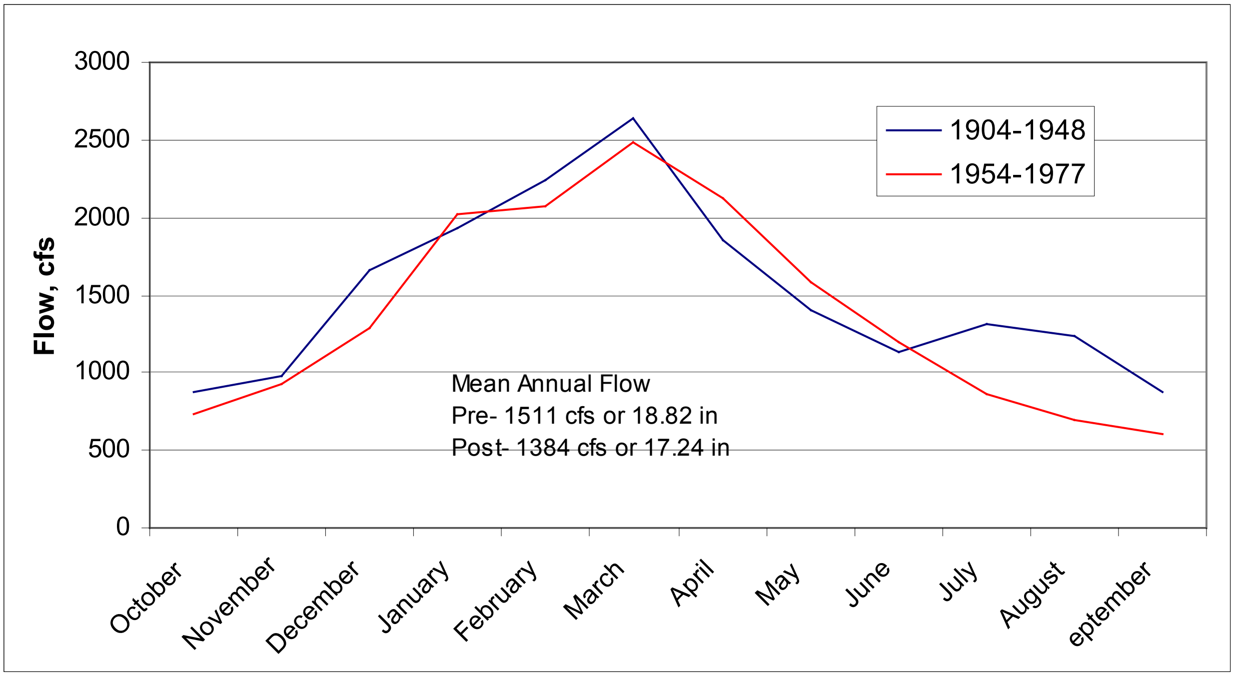


Figure 15. Average baseflow for the month of August at USGS gage #02197000

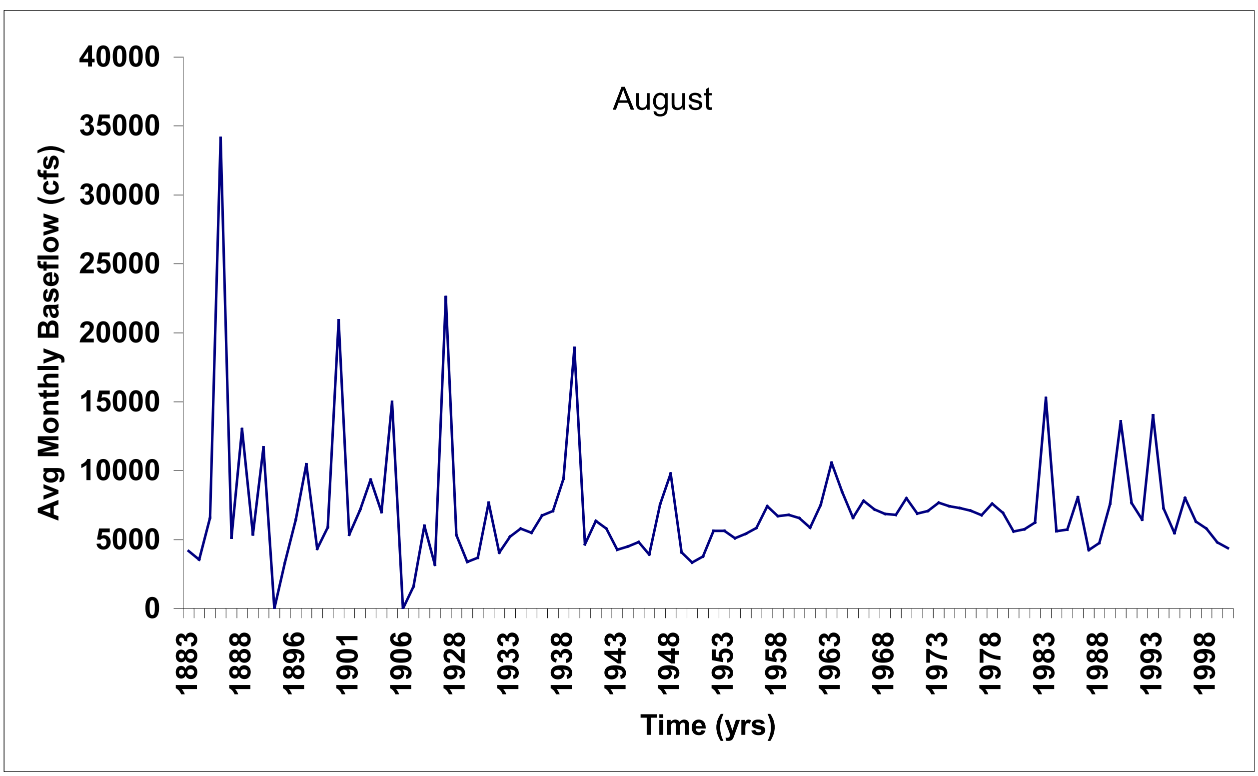


Figure 16. Average baseflow for the month of September at USGS gage #02197000

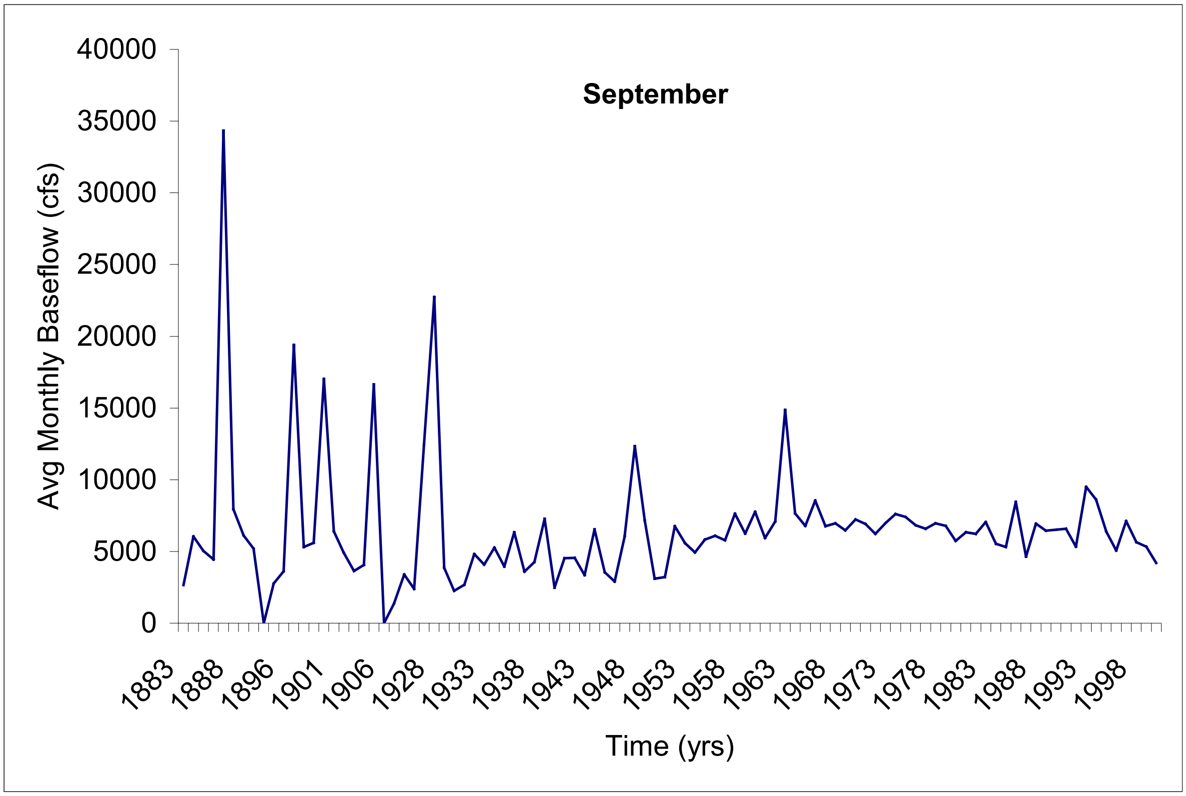


Figure 17. Average baseflow for the month of October at USGS gage #02197000

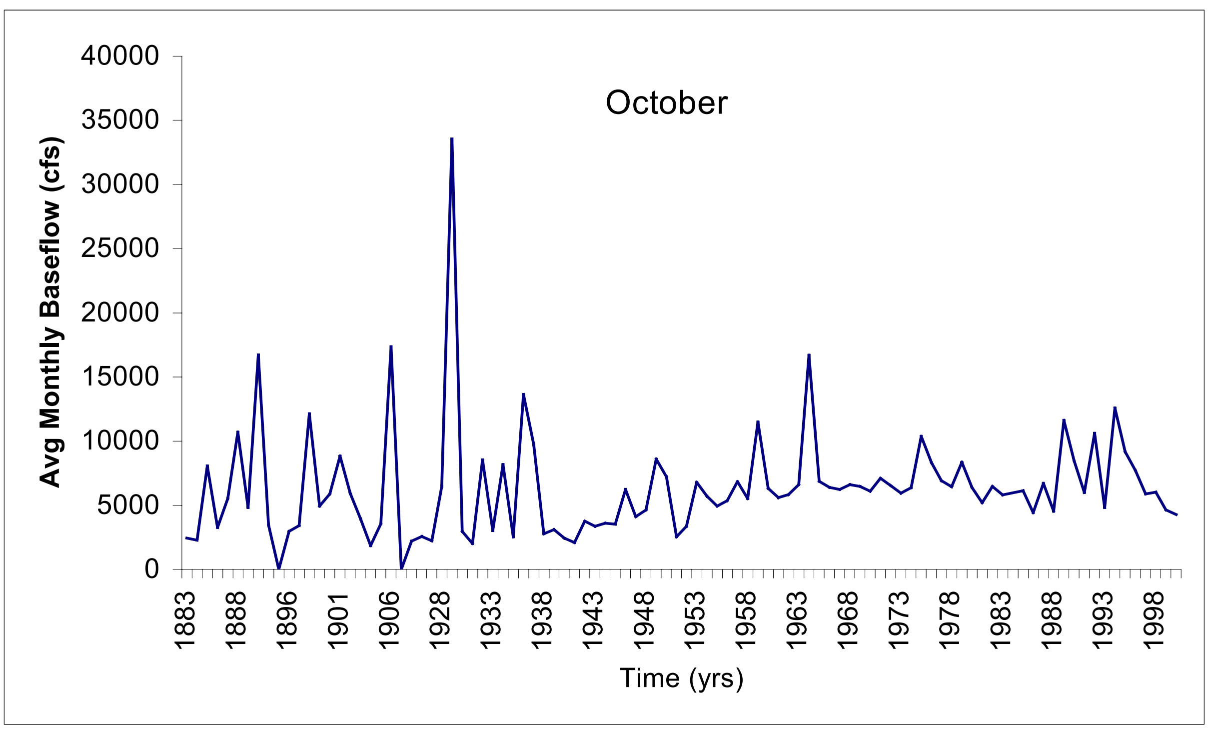


Figure 18. Peak flow depth above or below flood stage at River Mile 179.8.

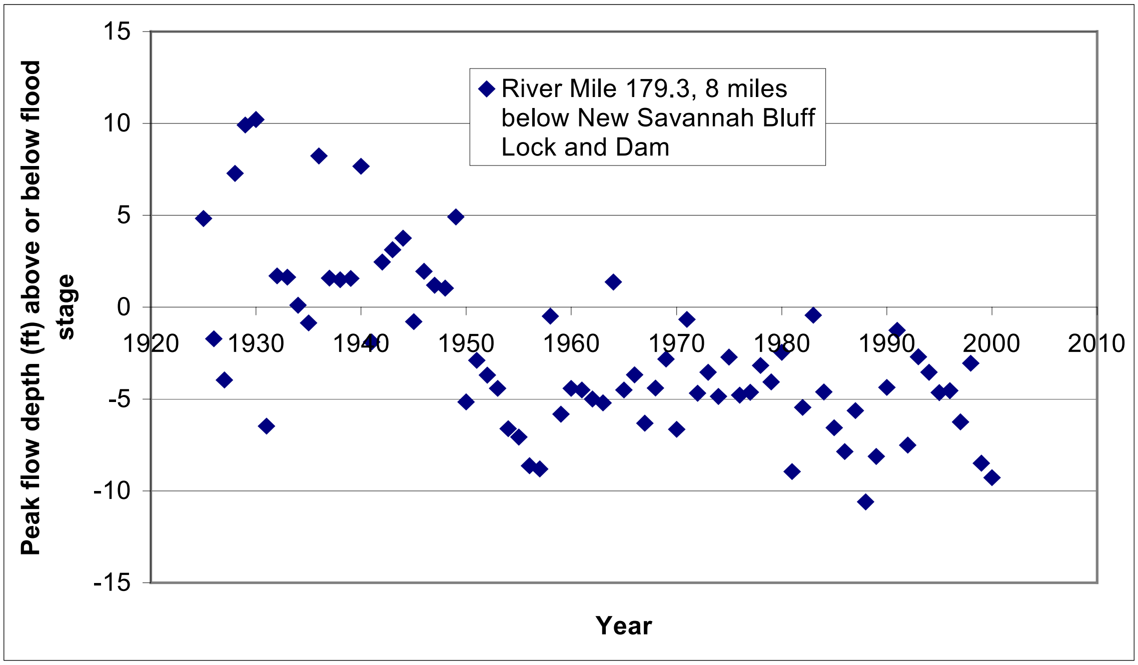


Figure 19. Peak flow depth above or below flood stage at River Mile 128.8.

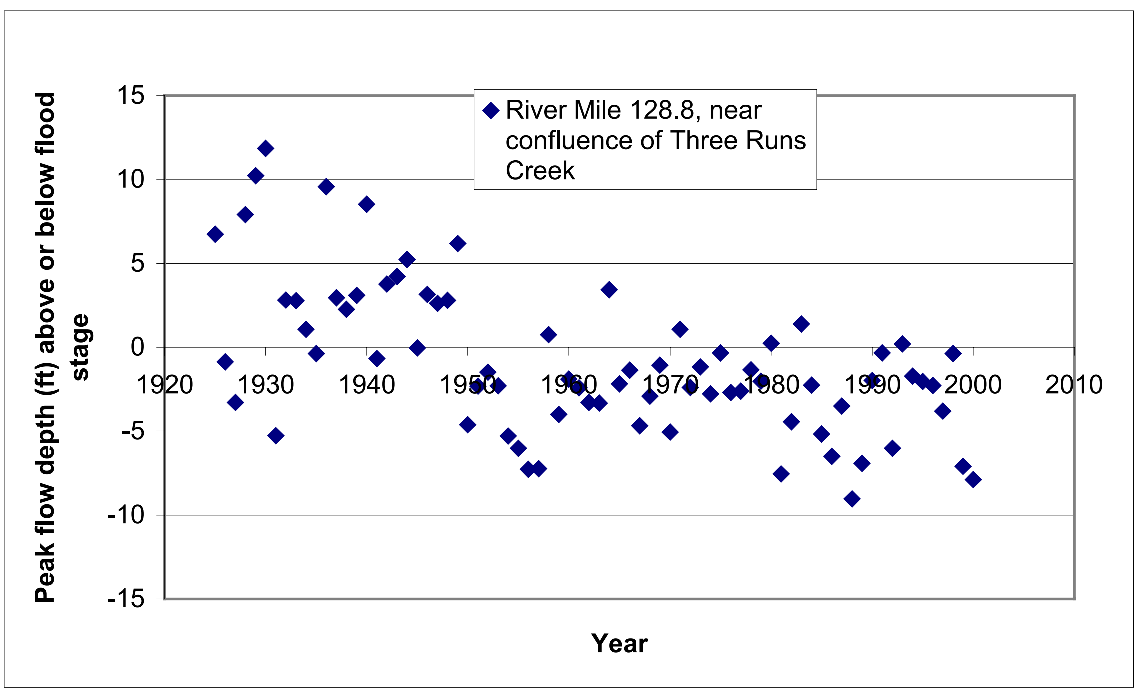


Figure 20. Peak flow depth above or below flood stage at River Mile 96.

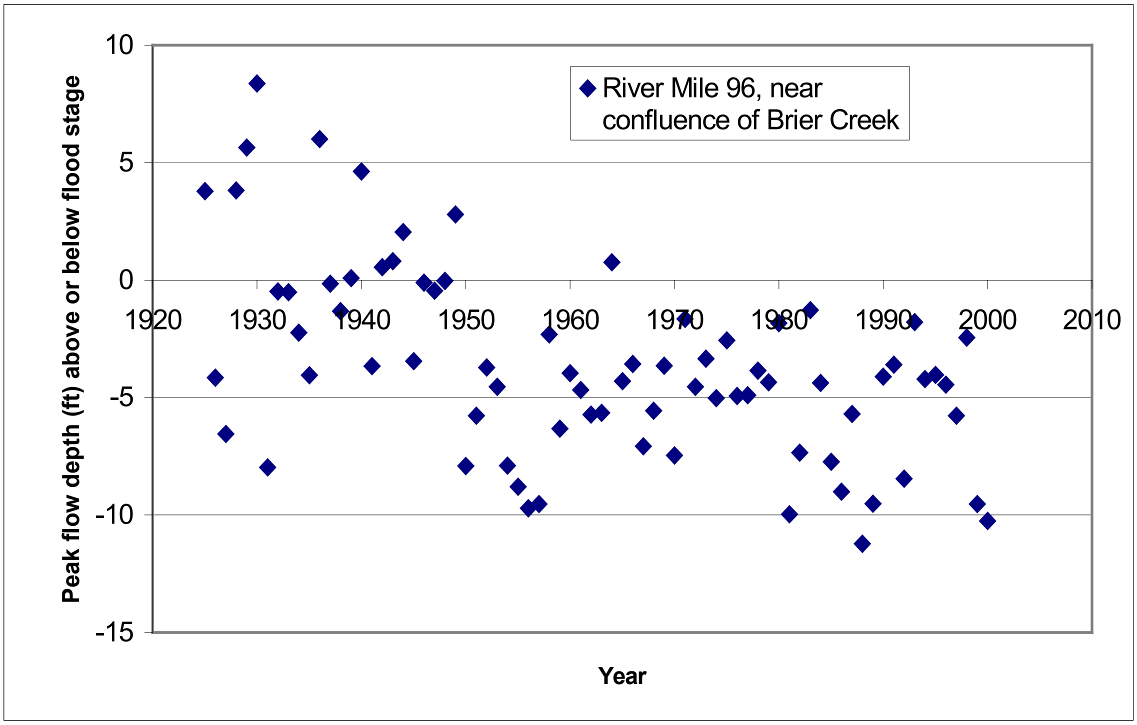


Figure 21. Peak flow depth above or below flood stage at River Mile 52.6.

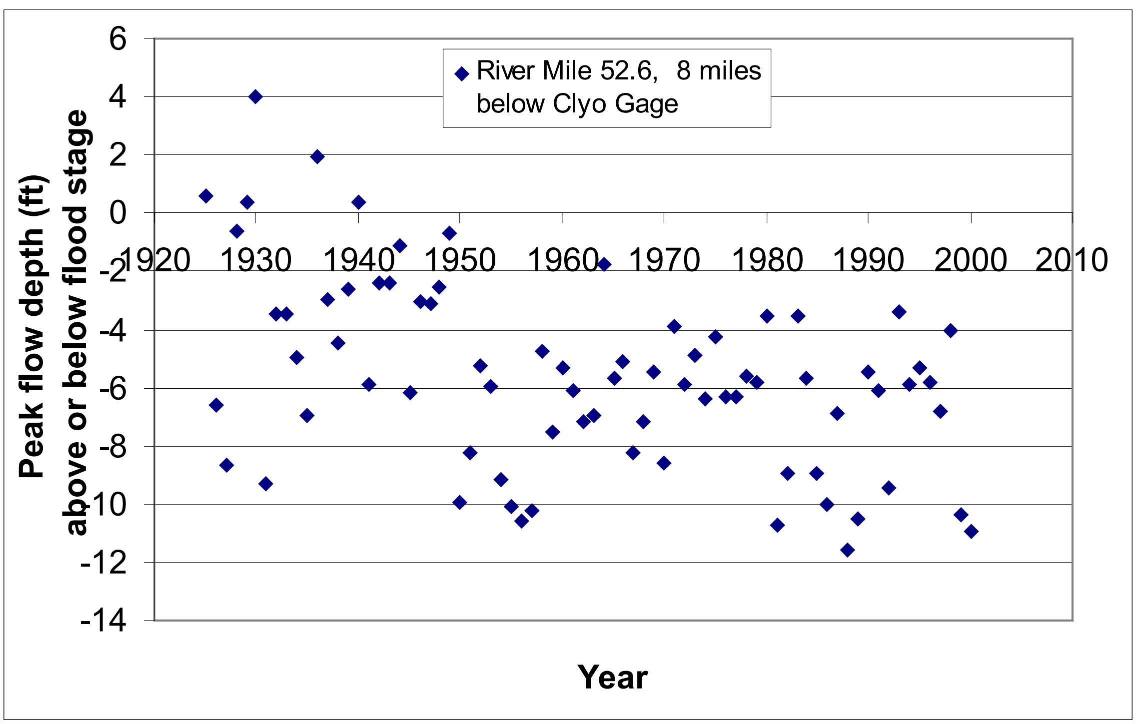


Figure 22. Percent of inundated floodplain assuming water table rise.

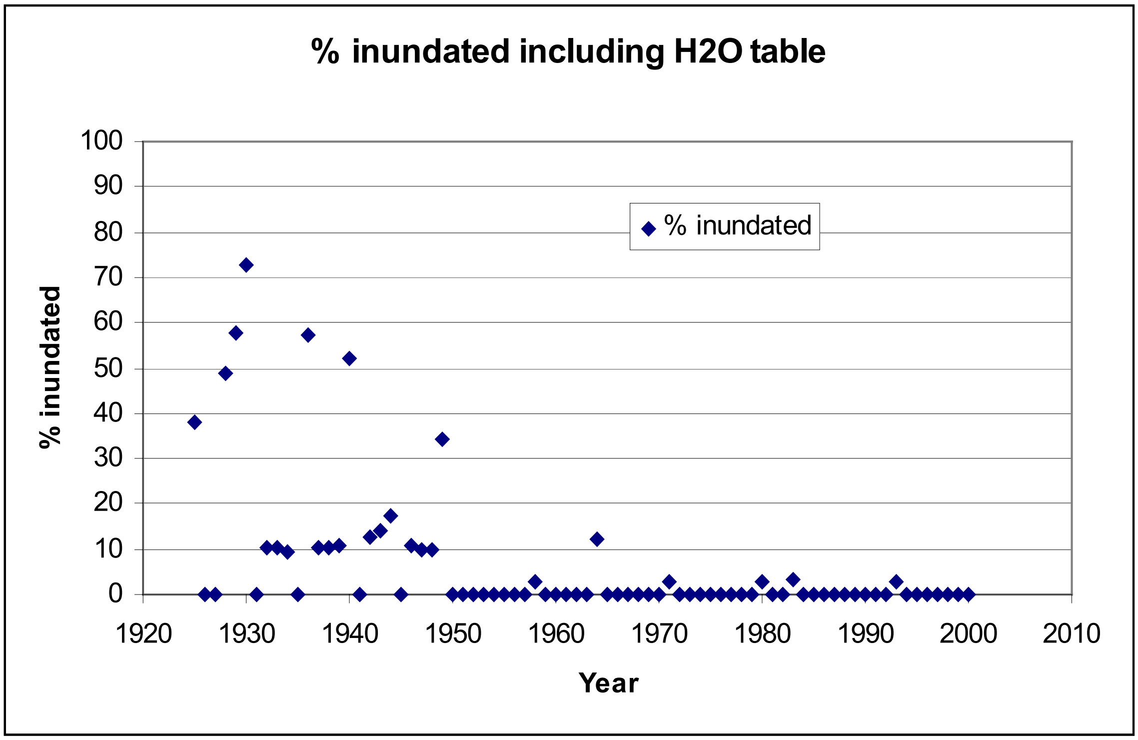


Figure 23. Percent of inundated floodplain assuming no water table rise.

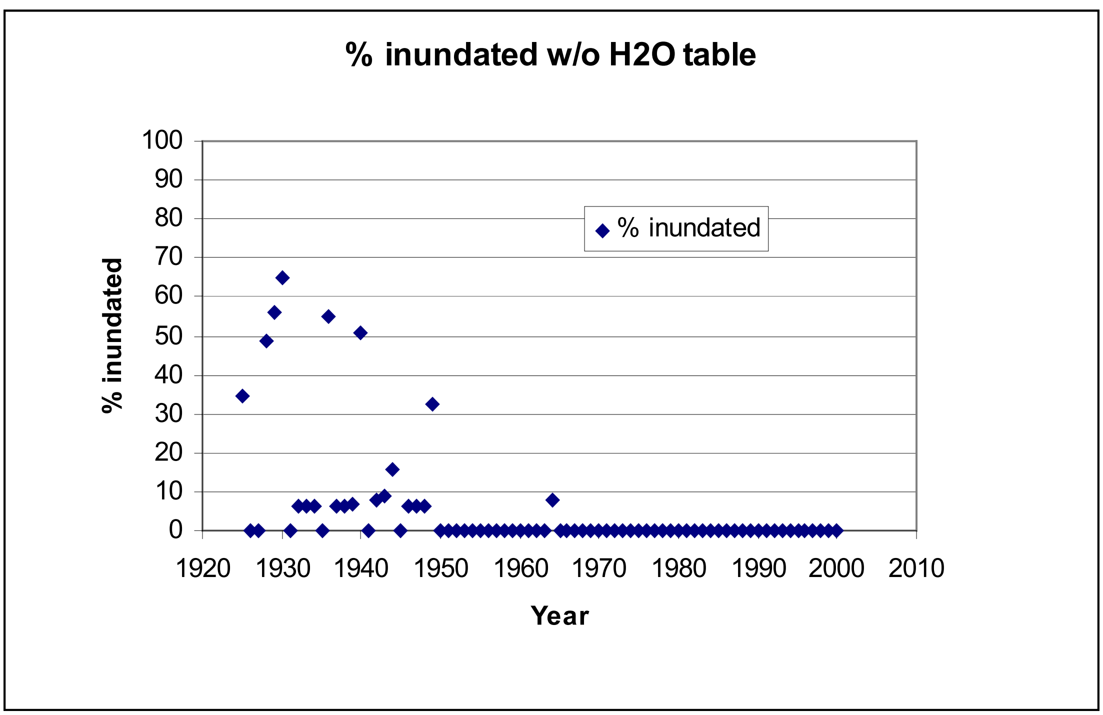


Figure 24. Median flow in the Savannah River at Augusta, GA (Based on the IHA output supplied by B. Richter, TNC).

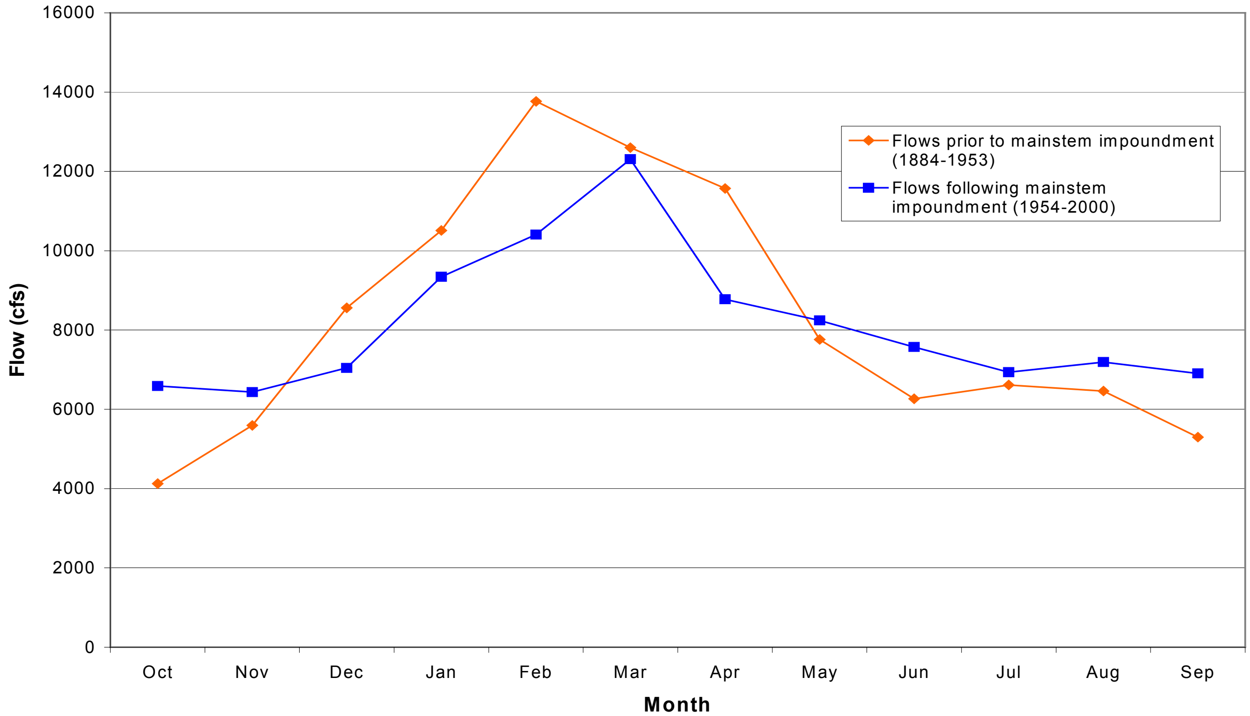


Figure 25. Seasonal flows required by anadromous fishes in the Savannah River at Augusta Shoals. Blue bars represent 80-100% PMWUA.

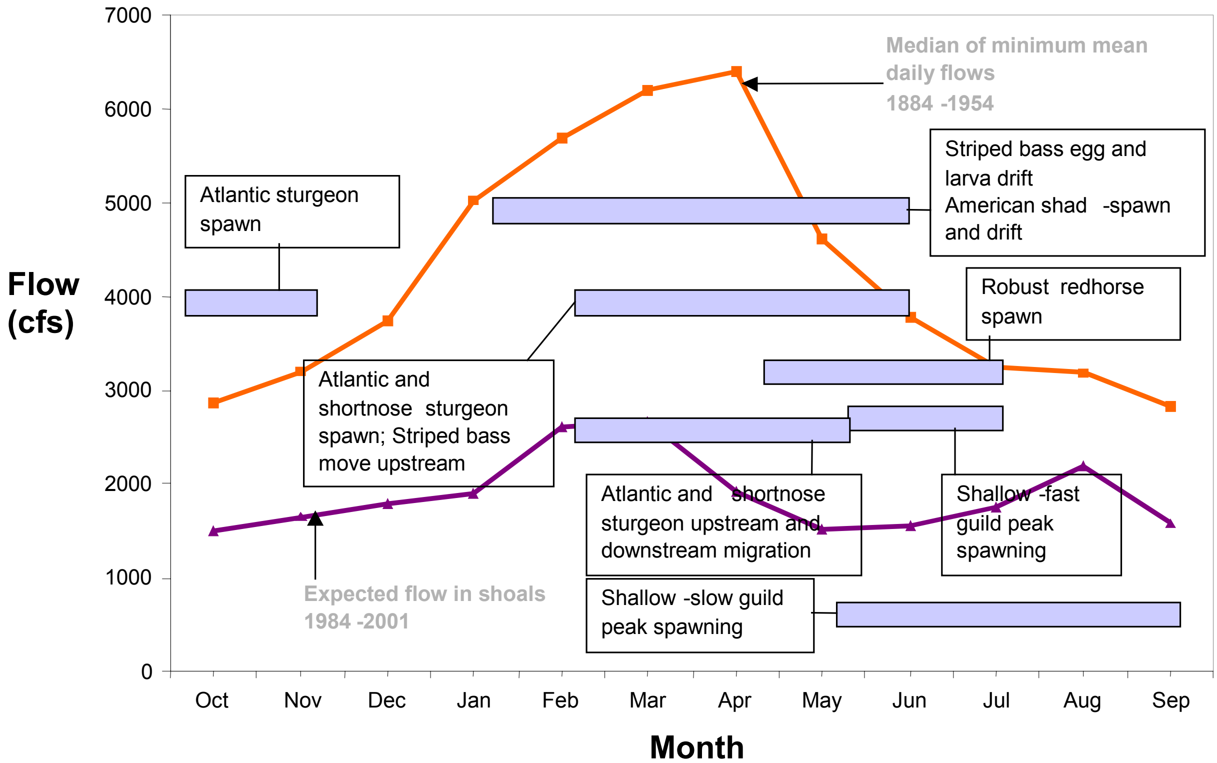


Figure 26. Flow relationships to key aspects of fish population success.

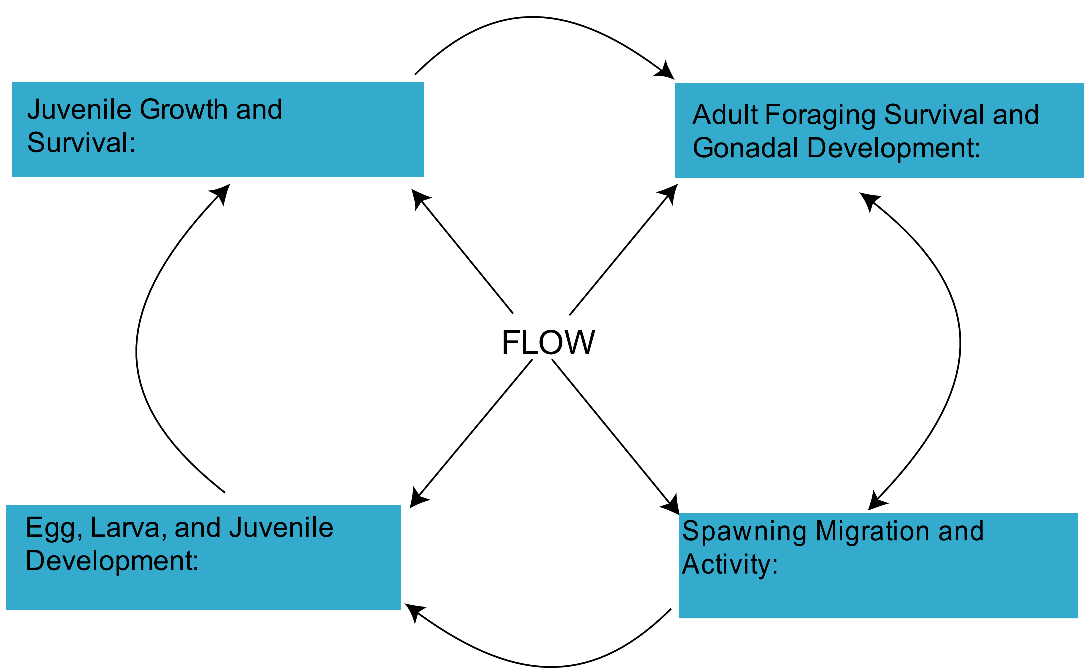


Figure 27. Flow relationships to key aspects of Atlantic sturgeon *Acipenser oxyrinchus* population success highlighting known and unknown flow relationships.

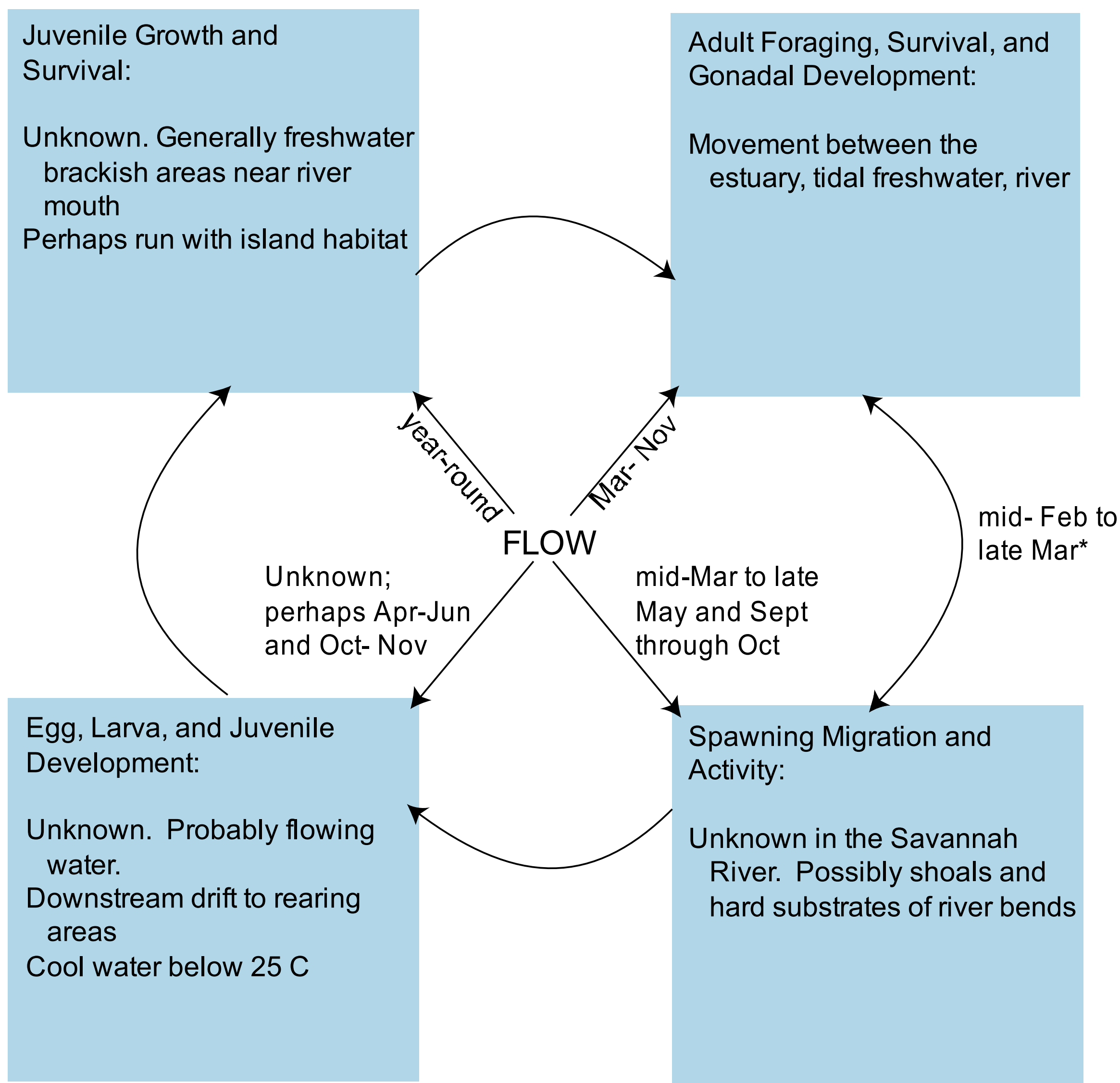


Figure 28. Flow relationships to key aspects of shortnose sturgeon *Acipenser brevirostrum* population success.

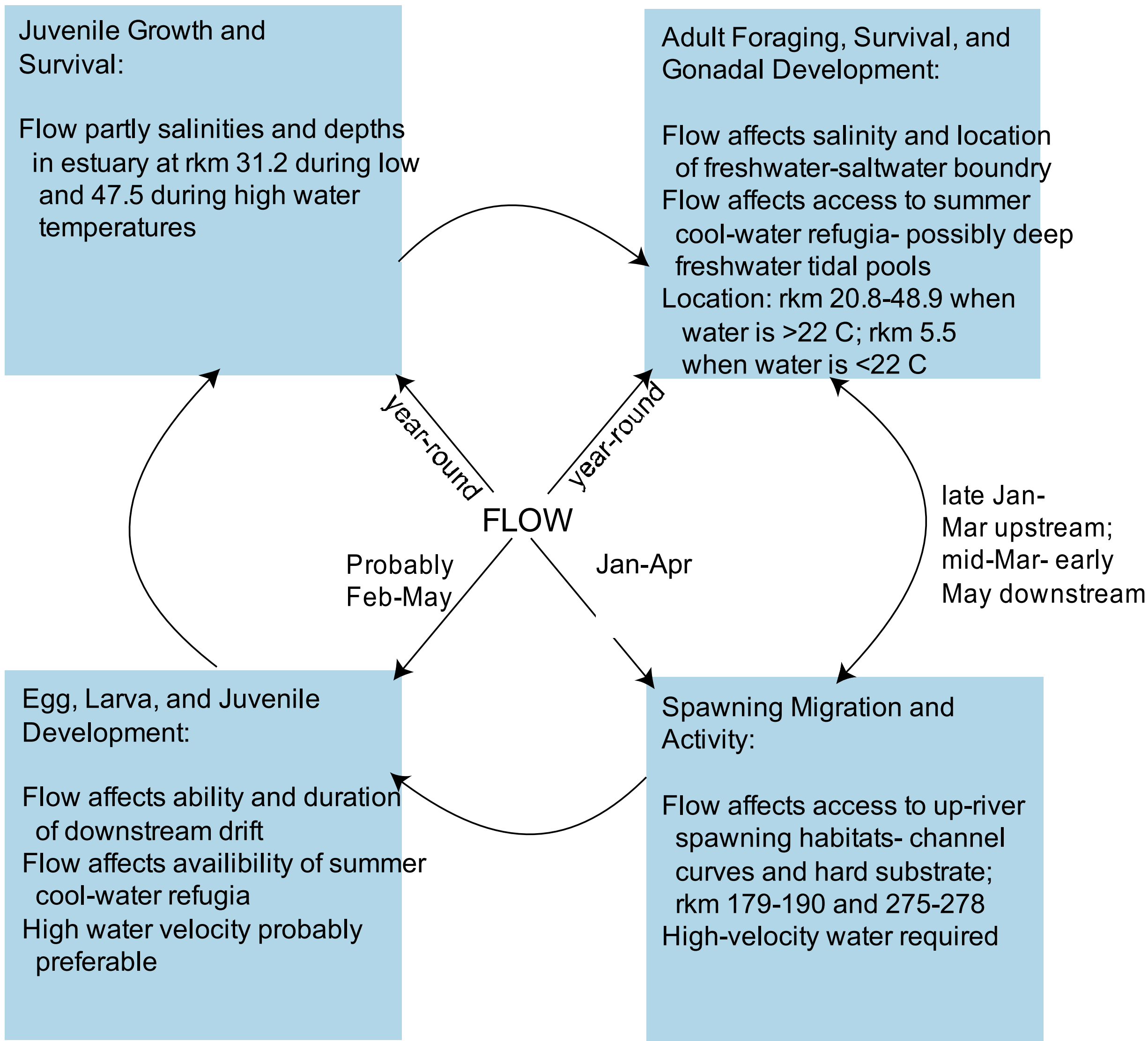


Figure 29. Flow relationships to key aspects of robust redhorse *Moxostoma robustum* population success.

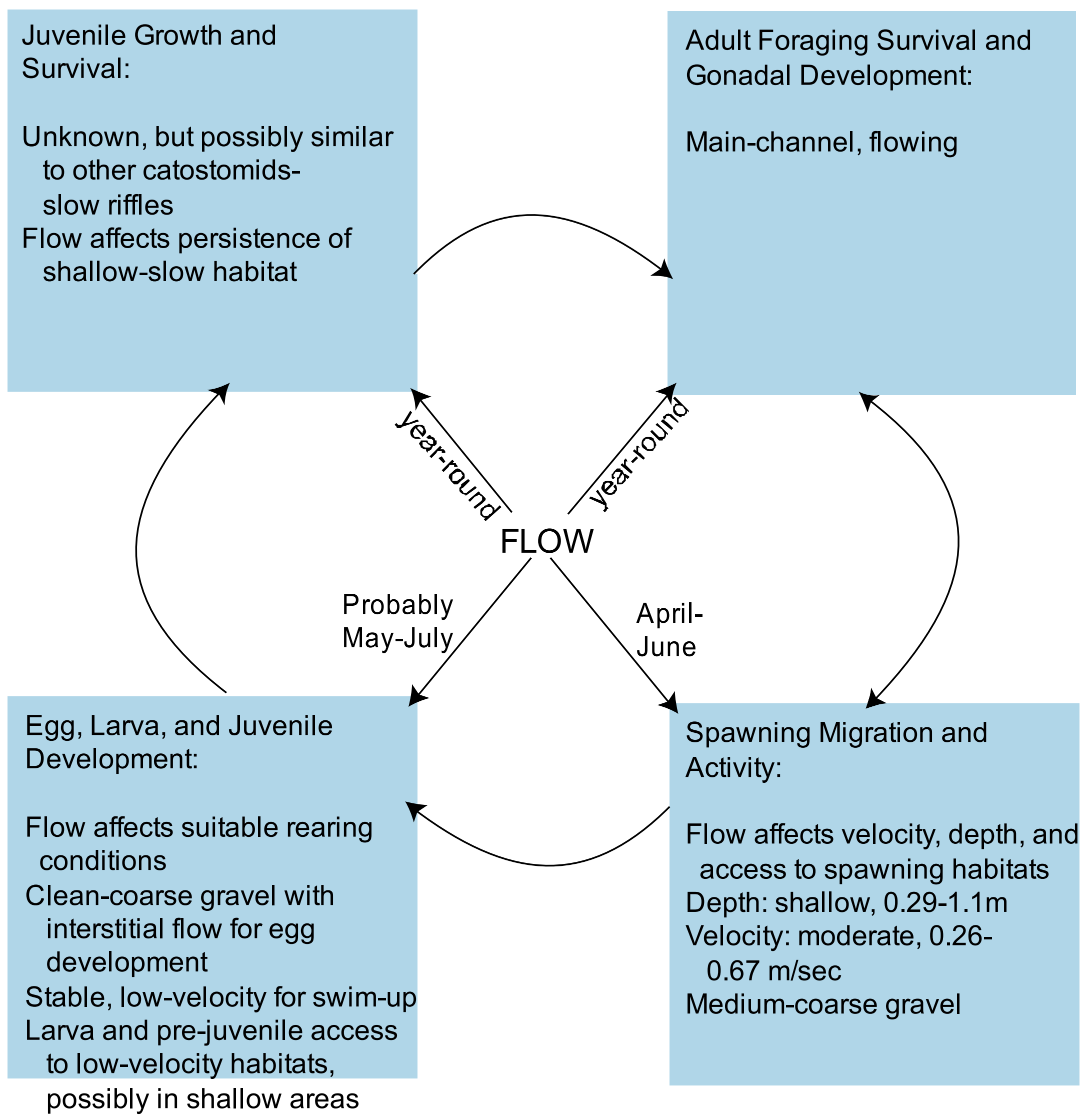
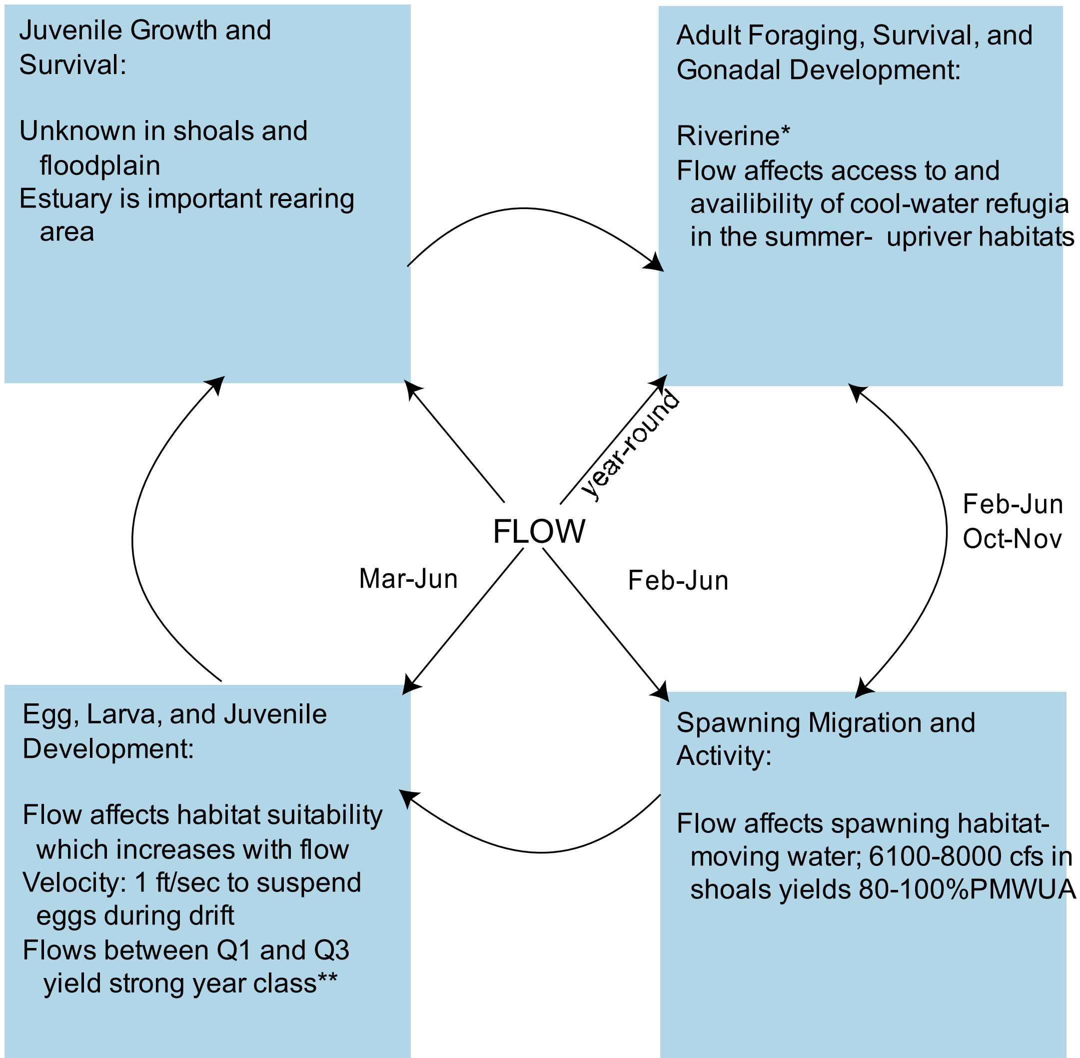


Figure 30. Flow relationships to key aspects of striped bass *Morone saxatilis* population success.



*Possibly ranges throughout the river and estuary.
**Striped bass recruitment in the lower Roanoke River peaks in years with intermediate springtime flows and a spring flood (Rulifson and Manooch, 1990).

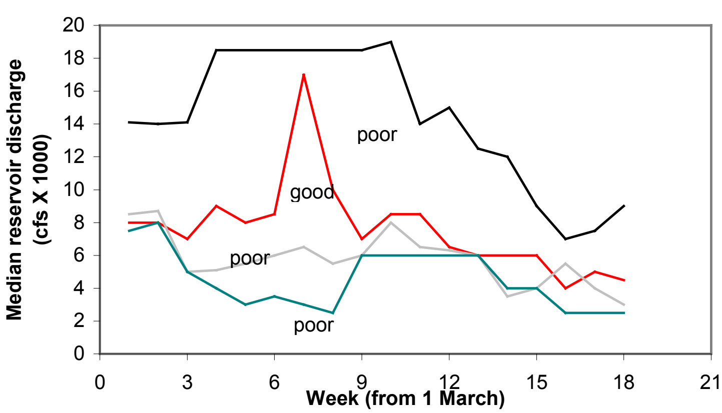


Figure 31. Flow relationships to key aspects of American shad *Alosa sapidissima* population success.

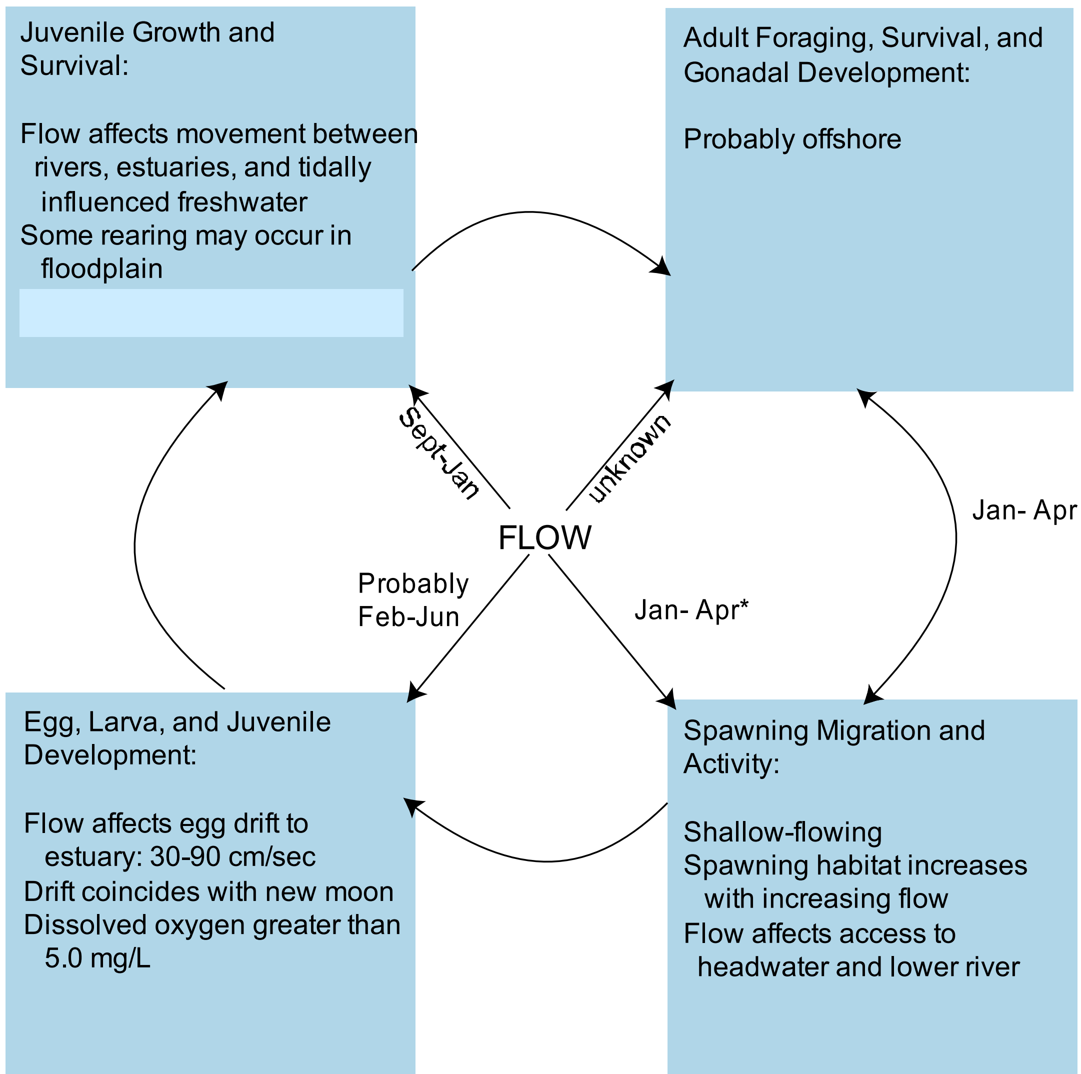
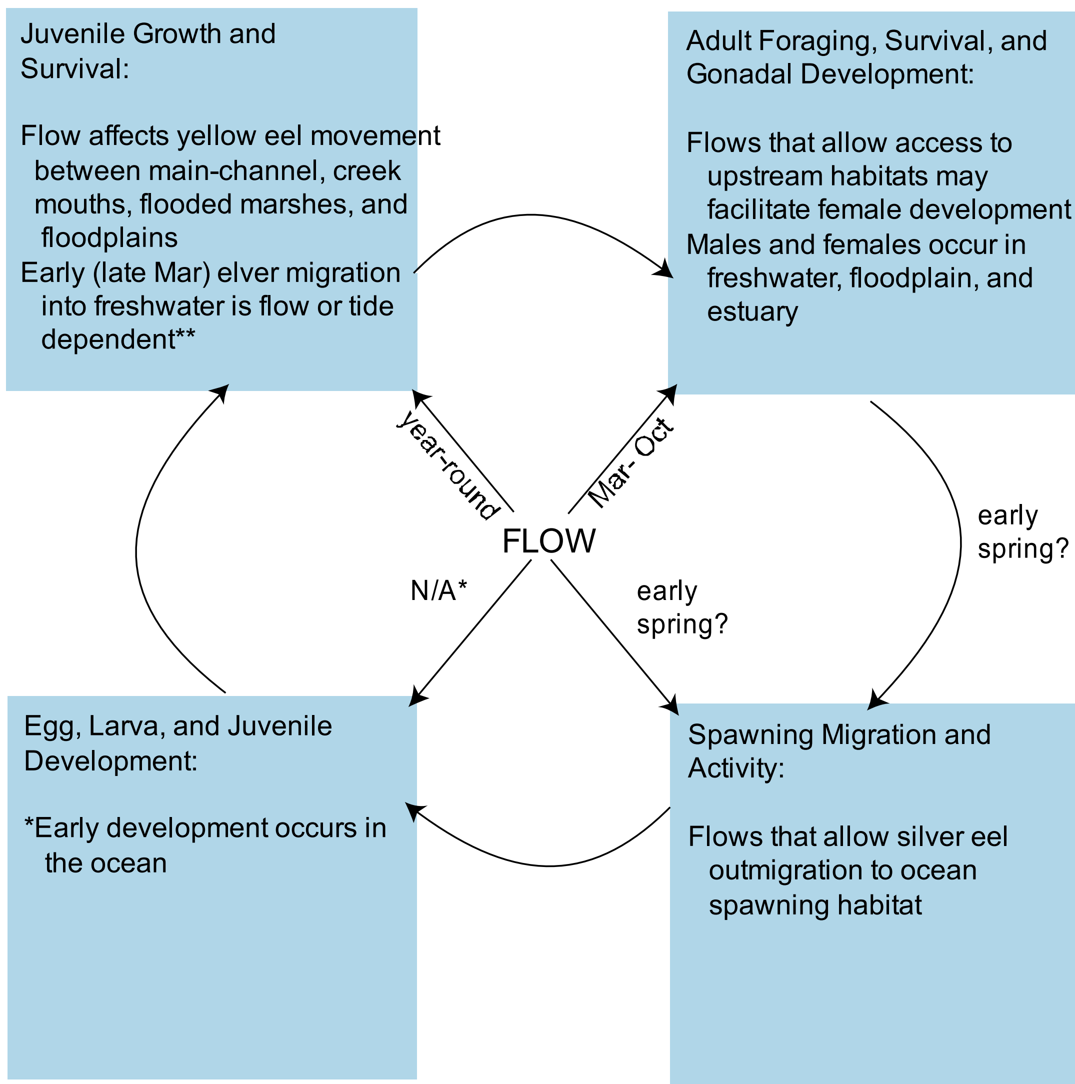


Figure 32. Flow relationships to key aspects of American eel *Anguilla rostrata* population success.



**Early elver migration into freshwater in late March in the North is associated with increased river temperature and decreased flow. In mid-May to mid-June, migration is associated with tide stage.

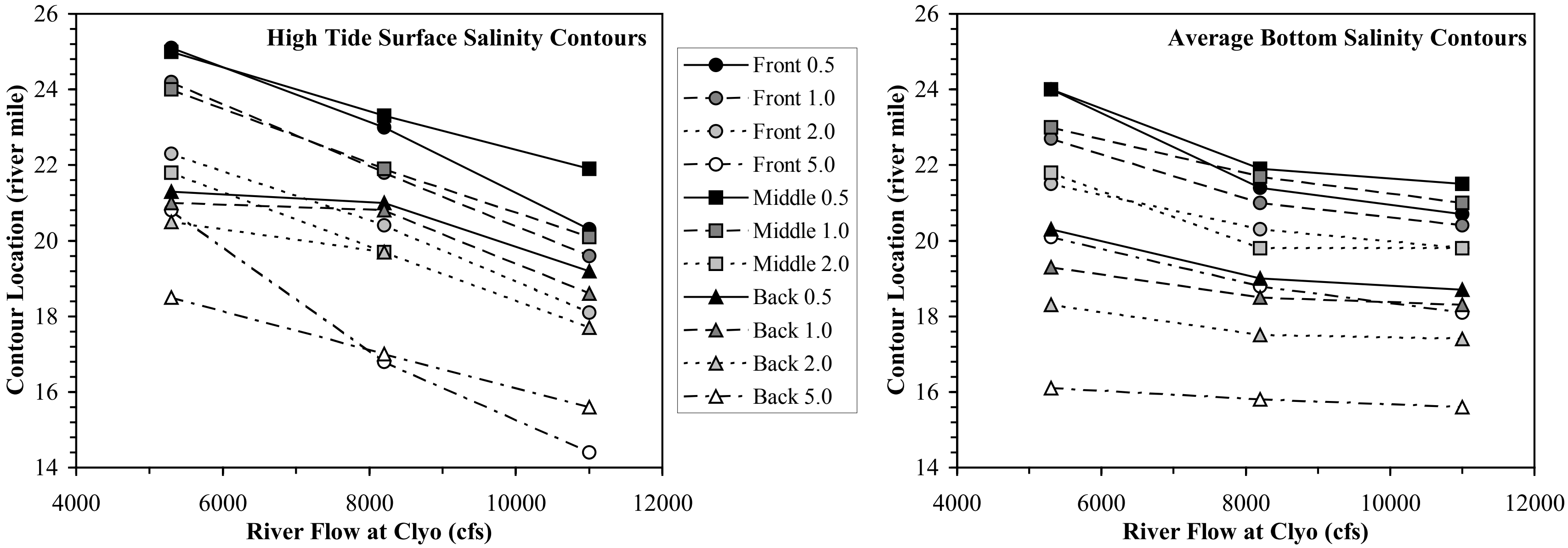


Figure 33. Locations of salinity contours in the Savannah River estuary under existing conditions.

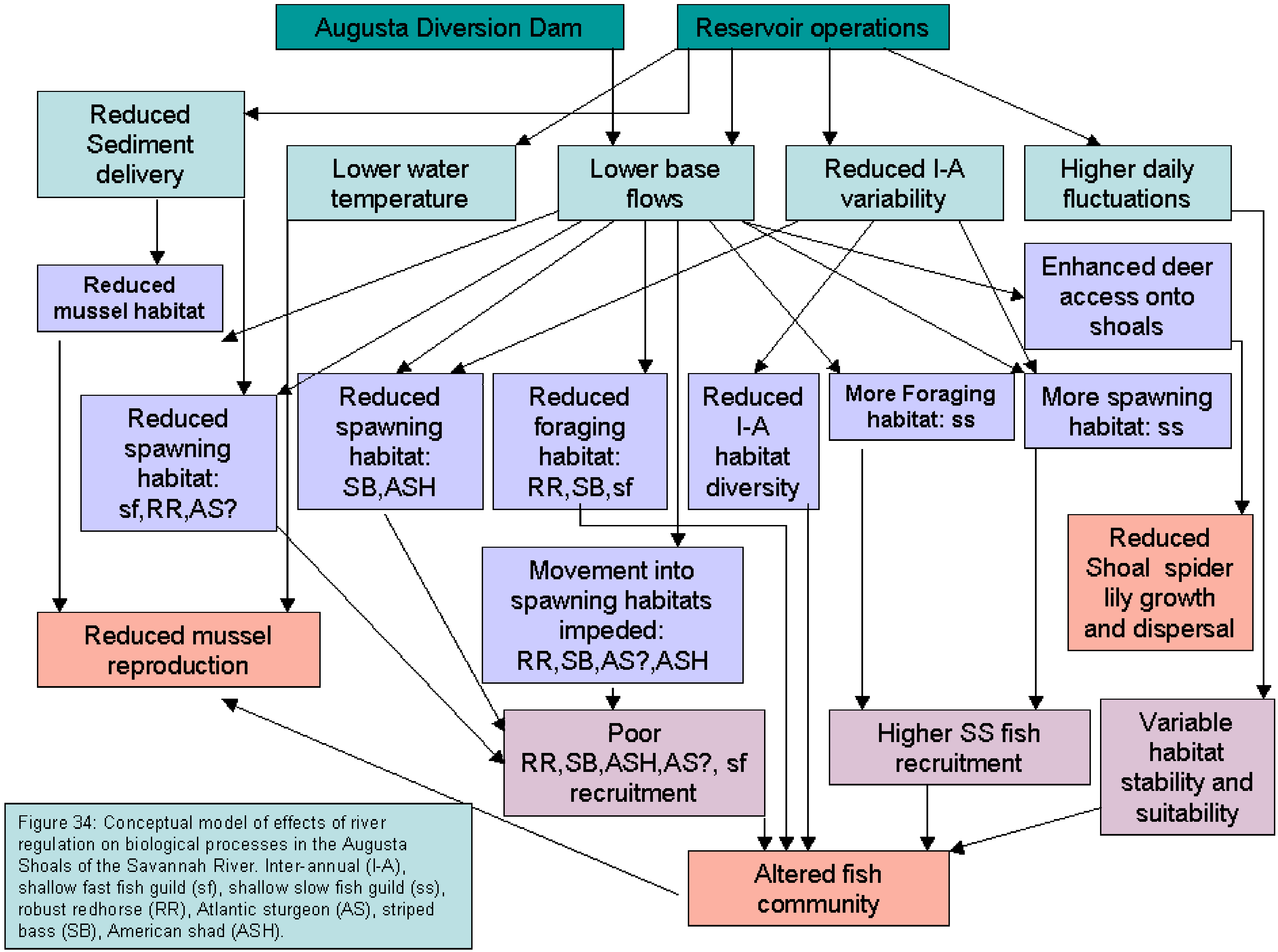


Figure 34: Conceptual model of effects of river regulation on biological processes in the Augusta Shoals of the Savannah River. Inter-annual (I-A), shallow fast fish guild (sf), shallow slow fish guild (ss), robust redhorse (RR), Atlantic sturgeon (AS), striped bass (SB), American shad (ASH).

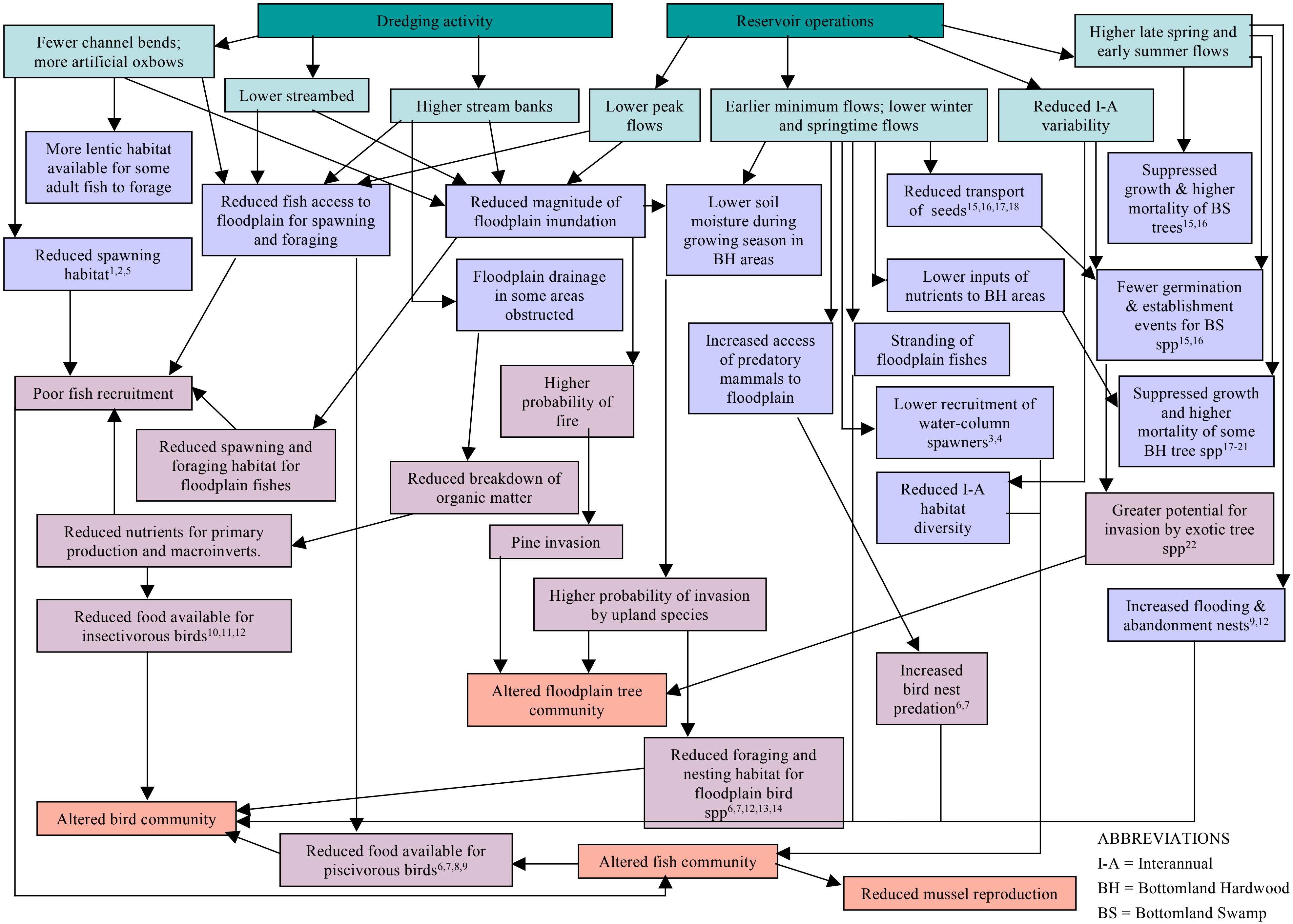


Figure 35. Conceptual model of effects of river regulation on biological processes in the main channel and floodplain of the Savannah River.

Figure 35a. Key for conceptual model of the effects of river regulation on biological processes in the main channel and floodplain of the Savannah River.

[1] Atlantic sturgeon (*Acipenser oxyrhynchus*)

[2] Shortnose sturgeon (*Acipenser brevirostrum*)

[3] Striped bass (*Morone saxatilis*)

[4] American shad (*Alosa sapidissima*)

[5] Robust redhorse (*Moxostoma robustum*)

[6] Whooping crane (*Grus americana*)

[7] Ciconiformes

[8] Bald eagle (*Haliaeetus leucocephalus*)

[9] Belted kingfisher (*Ceryle alcyon*)

[10] Hooded warbler (*Wilsonia citrina*)

[11] Louisiana waterthrush (*Seiurus motacilla*)

[12] Prothonotary warbler (*Protonotaria citrea*)

[13] Swallow-tailed kite (*Elanoides forficatus*)

[14] Mississippi kite (*Ictinia mississippiensis*)

[15] Bald cypress (*Taxodium distichum*)

[16] Water tupelo (*Nyssa aquatica*)

[17] Oak spp. (*Quercus*)

[18] Water hickory (*Carya aquatica*)

[19] Green ash (*Fraxinus pennsylvanica*)

[20] Ironwood (*Carpinus caroliniana*)

[21] Holly (*Ilex*)

[22] Chinese tallow (*Sapium sebiferum*)

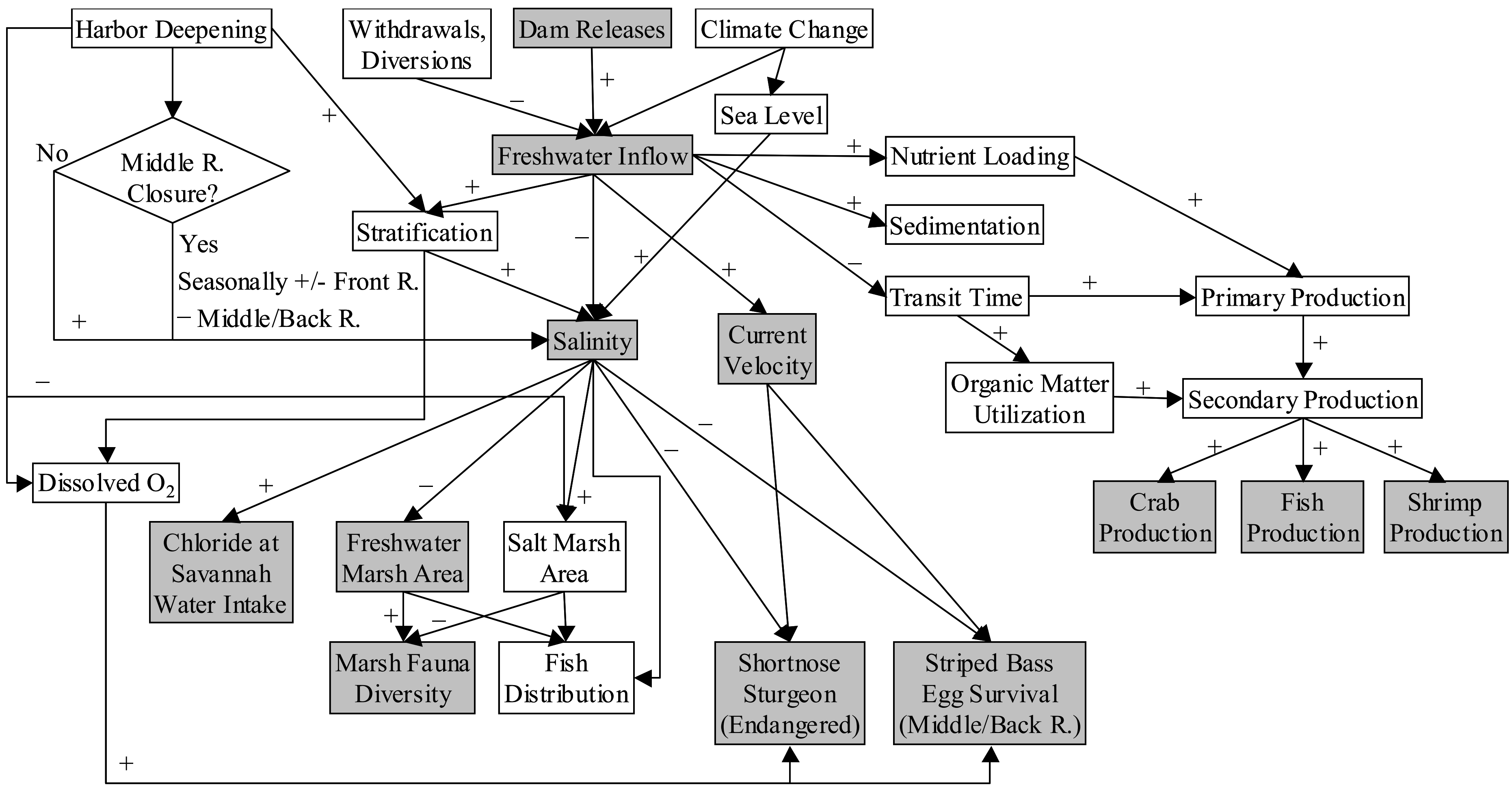


Figure 36. Conceptual model of the effects of flow regulation at Thurmond Dam on the Savannah River estuary. A (+) next to an arrow indicates a change in the same direction, although the change could be positive or negative; a (-) indicates an inverse effect; and neither indicates a more complex effect. Boxes indicating conditions or resources of particular concern are shown in gray.

Appendix 1A. Indicators of Hydrologic Alteration (IHA) scorecard; data from Augusta gage, years 1884-1953 (pre-dam) and 1954-2000 (post-dam).

Non-Parametric IHA Scorecard

Savannah River at Augusta

Pre-impact period: 1884-1953 (50 yrs), Post-impact period: 1954-2000 (47 yrs)

Watershed area	1.00	
Mean annual flow	10392.72	9394.35
Mean flow/area	10392.72	9394.35
Annual C. V.	.39	.34
Flow predictability	.49	.65
Constancy/predictability	.84	.93
% of floods in 60d period	.25	.24
flood-free season	.00	2.00

	MEDIANS		COEFF. of DISP.		DEVIATION FACTOR		SIGNIFICANCE COUNT	
	Pre	Post	Pre	Post	Medians	C.V.	Medians	C.V.
Parameter Group #1								
October	4125.5	6558.7	1.63	.20	.59	.88	.00	.07
November	5597.2	6435.7	.71	.26	.15	.64	.01	.19
December	8560.5	7043.5	.83	.95	.18	.14	.42	.49
January	10513.7	9346.1	1.00	.76	.11	.24	.44	.26
February	13769.3	10407.9	1.00	.90	.24	.10	.23	.68
March	12602.7	12307.4	1.01	.92	.02	.09	.92	.79
April	11573.2	8775.3	.83	1.35	.24	.63	.18	.02
May	7763.4	8241.0	.44	.65	.06	.46	.48	.13
June	6268.2	7570.7	.51	.41	.21	.19	.01	.57
July	6616.8	6938.4	.79	.27	.05	.65	.43	.08
August	6459.4	7195.8	.75	.27	.11	.64	.06	.02
September	5299.8	6908.7	.76	.23	.30	.70	.00	.02

	MEDIANS		COEFF. of DISP.		DEVIATION FACTOR		SIGNIFICANCE COUNT	
	Pre	Post	Pre	Post	Medians	C.V.	Medians	C.V.
Parameter Group #2								
1-day minimum	2160.0	5080.0	.57	.32	1.35	.43	.00	.05
3-day minimum	2428.3	5220.0	.51	.31	1.15	.39	.00	.05
7-day minimum	2725.7	5405.7	.47	.30	.98	.36	.00	.06
30-day minimum	3207.8	5680.7	.44	.21	.77	.53	.00	.01
90-day minimum	4341.0	6068.0	.54	.19	.40	.64	.00	.02
1-day maximum	89950.0	31900.0	.75	.49	.65	.34	.02	.19
3-day maximum	79883.3	30200.0	.75	.49	.62	.35	.01	.16
7-day maximum	52485.7	27471.4	.76	.56	.48	.26	.00	.36
30-day maximum	29860.7	21103.3	.58	.58	.29	.01	.01	.98
90-day maximum	19492.5	14966.4	.64	.55	.23	.13	.03	.50
Number of zero days	.0	.0	.00	.00	999999.00	999999.00	.00	.00
Base flow	.3	.6	.36	.40	1.20	.10	.00	.63
Parameter Group #3								
Date of minimum	274.5	191.0	.14	.36	.46	1.56	.00	.00
Date of maximum	55.5	67.0	.31	.17	.06	.44	.34	.06
Parameter Group #4								
Low pulse count	14.0	.0	.91	.00	1.00	1.00	.05	.05
Low pulse duration	4.8	.0	.86	.00	1.00	1.00	.08	.09
High pulse count	13.5	9.0	.61	.78	.33	.27	.02	.32
High pulse duration	5.3	6.7	.73	.98	.27	.35	.09	.12

The low pulse threshold is 4510.00
The high pulse level is 10800.00

	MEDIANS		COEFF. of DISP.		DEVIATION FACTOR		SIGNIFICANCE COUNT	
Parameter Group #5								
Rise rate	3443.4	1114.1	.74	.56	.68	.24	.01	.33
Fall rate	-2415.3	-1032.6	-.62	-.60	.57	.04	.00	.89
Number of reversals	142.0	142.0	.38	.11	.00	.70	.79	.03

Appendix 1B. Indicators of Hydrologic Alteration (IHA) scorecard; data from Augusta gage, years 1884-1953 (pre-dam) and 1984-2000 (post-dam). Years 1954-1983 are omitted in order to consider the collective effects of all major impoundments on the Savannah River: construction of the first major mainstem dam (Thurmond) on the Savannah River was in 1954, the last major mainstem dam (Hartwell) was constructed in 1984.

Non-Parametric IHA Scorecard

Savannah River

Pre-impact period: 1884-1953 (50 yrs) Post-impact period: 1984-2000 (17 yrs)

	Pre	Post
Watershed area	1.00	
Mean annual flow	10392.72	8839.10
Mean flow/area	10392.72	8839.10
Annual C. V.	.39	.35
Flow predictability	.49	.60
Constancy/predictability	.84	.97

WARNING: Some of the Colwell Parameters are based on < 20 years of data

	Pre	Post
% of floods in 60d period	.25	.24
flood-free season	.00	9.00

	MEDIANS		COEFF. of DISP.		DEVIATION FACTOR		SIGNIFICANCE COUNT	
	Pre	Post	Pre	Post	Medians	C.V.	Medians	C.V.
Parameter Group #1								
October	4125.5	6566.5	1.63	.70	.59	.57	.05	.10
November	5597.2	6183.7	.71	.24	.10	.66	.32	.30
December	8560.5	6595.8	.83	.95	.23	.14	.31	.68
January	10513.7	7825.2	1.00	.71	.26	.29	.21	.59
February	13769.3	10655.0	1.00	1.25	.23	.24	.41	.39
March	12602.7	12307.4	1.01	1.19	.02	.18	.92	.62
April	11573.2	8722.3	.83	.58	.25	.30	.13	.39
May	7763.4	5779.4	.44	.91	.26	1.05	.09	.10
June	6268.2	6450.3	.51	.48	.03	.05	.91	.89
July	6616.8	6523.9	.79	.23	.01	.70	.87	.08
August	6459.4	6884.5	.75	.39	.07	.47	.78	.47
September	5299.8	6982.7	.76	.31	.32	.59	.04	.10

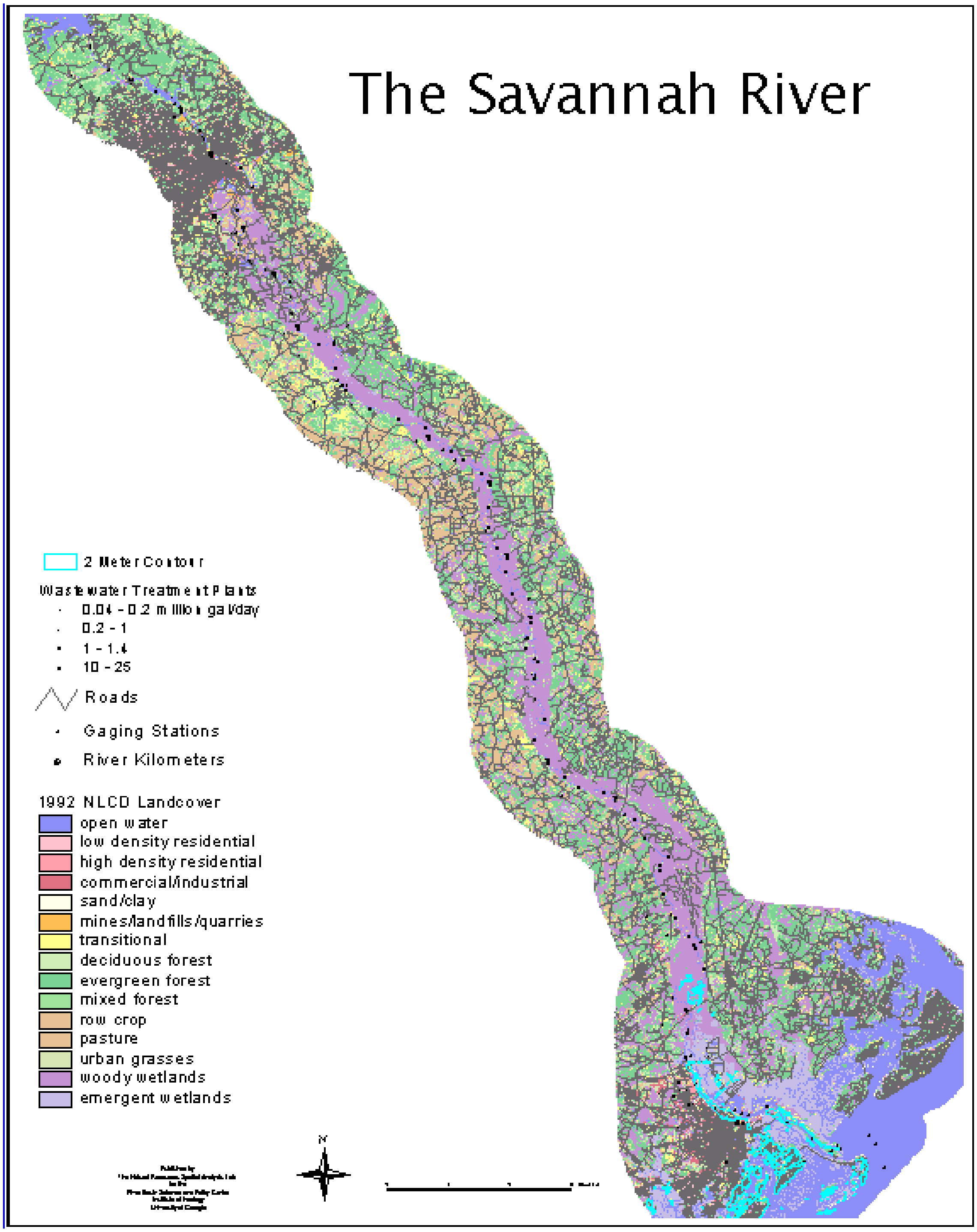
FACTOR	MEDIANS Pre	MEDIANS Post	COEFF. of DISP. Pre	COEFF. of DISP. Post	DEVIATION Medians	DEVIATION C.V.	SIGNIFICANCE COUNT Medians	SIGNIFICANCE COUNT C.V.
Parameter Group #2								
1-day minimum	2160.0	4200.0	.57	.17	.94	.69	.00	.02
3-day minimum	2428.3	4336.7	.51	.22	.79	.56	.00	.04
7-day minimum	2725.7	4540.0	.47	.18	.67	.62	.00	.01
30-day minimum	3207.8	5104.3	.44	.21	.59	.51	.00	.04
90-day minimum	4341.0	5459.9	.54	.27	.26	.49	.06	.03
1-day maximum	89950.0	26800.0	.75	.71	.70	.05	.02	.90
3-day maximum	79883.3	25933.3	.75	.78	.68	.04	.02	.91
7-day maximum	52485.7	23828.6	.76	.79	.55	.04	.02	.93
30-day maximum	29860.7	17003.3	.58	.86	.43	.48	.01	.19
90-day maximum	19492.5	13687.2	.64	.78	.30	.23	.06	.39
Number of zero days	.0	.0	.00	.00	999999.00	999999.00	.00	.00
Base flow	.3	.5	.36	.71	.87	.97	.00	.04
Parameter Group #3								
Date of minimum	274.5	176.0	.14	.41	.54	1.91	.00	.00
Date of maximum	55.5	57.0	.31	.22	.01	.28	1.00	.64
Parameter Group #4								
Low pulse count	14.0	6.0	.91	2.33	.57	1.56	.06	.02
Low pulse duration	4.8	1.4	.86	3.38	.71	2.95	.00	.00
High pulse count	13.5	9.0	.61	1.33	.33	1.18	.05	.02
High pulse duration	5.3	5.3	.73	1.05	.02	.44	.91	.11

The low pulse threshold is 4510.00

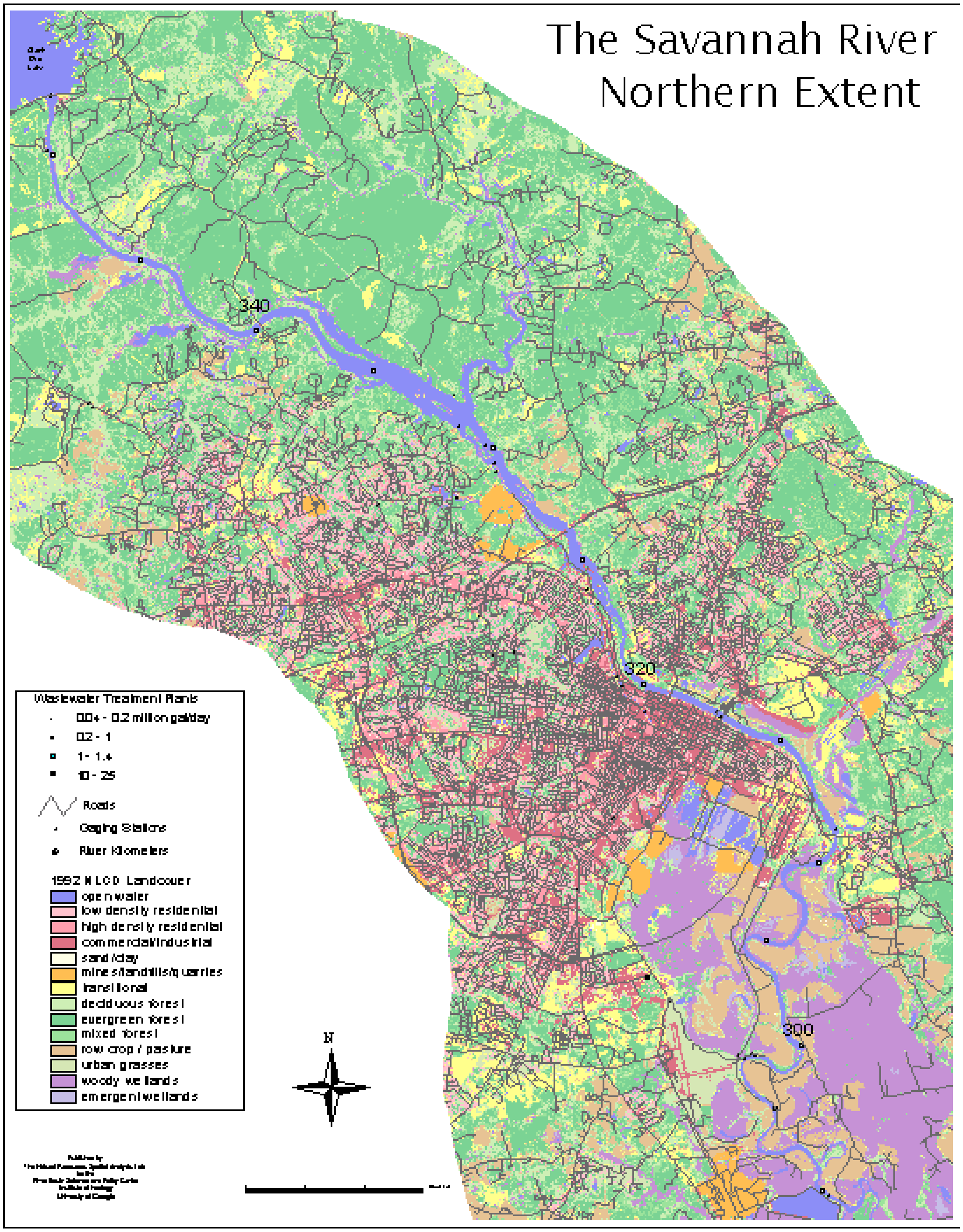
The high pulse level is 10800.00

FACTOR	MEDIANS Pre	MEDIANS Post	COEFF. of DISP. Pre	COEFF. of DISP. Post	DEVIATION Medians	DEVIATION C.V.	SIGNIFICANCE COUNT Medians	SIGNIFICANCE COUNT C.V.
Parameter Group #5								
Rise rate	3443.4	1171.7	.74	.81	.66	.10	.01	.77
Fall rate	-2415.3	-1116.5	-.62	-.84	.54	.36	.01	.33
Number of reversals	142.0	157.0	.38	.10	.11	.73	.05	.02

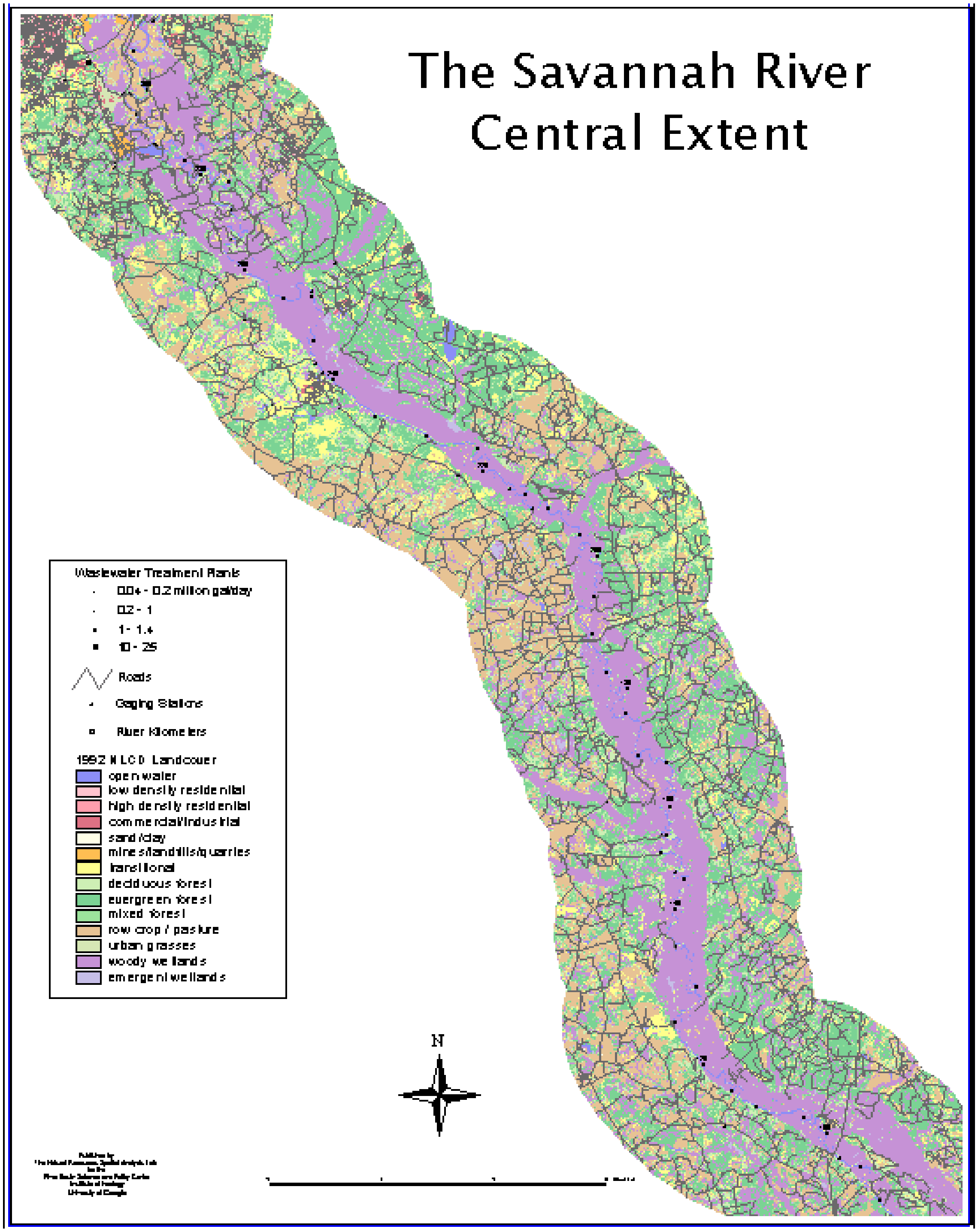
Appendix 2A. Lower Savannah River and floodplain.



Appendix 2B. Augusta Shoals reach.



Appendix 2C. Lower Savannah River and floodplain between Augusta and Clyo.



Appendix 2D. Savannah River and estuary.