Summary Report Supporting the Development of Flow Recommendations for the Stretch of Big Cypress Creek below Lake O' the Pines Dam

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EXECUTIVE SUMMARY

The purpose of this Summary Report is to synthesize available data and literature in order to arm workshop participants with sufficient information to develop ecologically based flow recommendations for the Big Cypress Creek, or Bayou, below Lake O' the Pines Dam (Appendix A). These flow recommendations are intended to enhance the ecological structure and function of Big Cypress Creek, its floodplain, and greater Caddo Lake, with the ultimate goal of providing benefits to local flora, fauna, and stakeholders in the Greater Caddo Lake region. In this document, we report on the historical flow conditions (i.e., pre-dam) in Big Cypress Creek and their role in shaping the lotic, lentic, and floodplain ecosystems of this region. It should be pointed out that hydrologic modifications have not been the only negative impact to this system. Other perturbations, such as nutrient and contaminant loading, altered sediment transport, logging, drainage and conversion to agriculture or residential development, have altered the system to varying degrees. However, the general consensus is that some restoration of the timing, magnitude, and duration flows in Big Cypress Creek is critical to the sustainability of the lotic, lentic, and floodplain habitats as well as beneficial ecosystem functions.

Hydrology

Caddo Lake drains an area of roughly 2,639 square miles and has a storage capacity of around 175,000 acre-feet. Major tributaries into Caddo Lake are Big Cypress, Little Cypress and Black Cypress Creeks (Bayous). Together these account for about 70% of the total drainage area of Caddo Lake. Input from the other 30% of the drainage area is not monitored on a routine basis. There has been no major dredging or channel modifications within the Caddo Lake basin. The major disruption of natural flows into Caddo Lake is caused by the presence of Lake O' the Pines on Big Cypress Creek, upstream from Caddo Lake.

The Lake O' the Pines reservoir was completed in late 1959 and has dramatically altered the flow regime of Big Cypress Creek. The annual hydrograph for post-dam conditions are lower (with reduced high flow pulses and lacking flood flows) relative to pre-dam conditions. Prior to dam construction, annual peak flow was as high as 57,000 cfs. Following dam construction peak flows have remained around 3,000 cfs with very little variation. Additionally, low flows during the historically dry periods have noticeably increased following dam construction. From an annual average inflow perspective, flow has been reduced by about 5% following dam construction, probably because of increases evaporation from the lake surface. The flow regime of the other major tributaries into Caddo Lake, Little Cypress and Black Cypress Creeks have not been altered but are also included in this report for the purpose of comparison.

Geomorphology

The Big Cypress drainage basin reflects geomorphological processes active during the past 2 million years. Three geomorphic surfaces have been identified and differentiated according to their physical characteristics, apparent age, and types of processes active on the surfaces: floodplain, terrace, and valley slopes. Before closure of Ferrell's Bridge Dam in 1960, the floodplain upstream of Caddo Lake was inundated every 1-2 years at a discharges > 6000 cfs. This is the level of discharge needed to sustain floodplain development and riparian ecosystem. The closure of Ferrell's Bridge Dam has changed frequency–magnitude relations so that, at present, little variation in flow magnitude exists, and maximum flows do not exceed ~3000 cfs. Floodplains are therefore not inundated under the present flow regime. Maximum flows of ~3000 cfs are also below the discharge level necessary to maintain an equilibrium channel geometry.

Entrainment calculations indicate that only clays and silts are being mobilized downstream of Ferrell's Bridge Dam under the current water management scheme. Coarser sediments (even sands) require flows greater than 3000 cfs to be entrained. Overall, construction of Ferrell's Bridge Dam has likely affected sediment transport capacities in Big Cypress Creek (downstream of the dam) by as much as 50% and sediment movement and delivery to the floodplain and into Caddo Lake (as much as 492,378 m^3 yr^{-1}). Analysis of sedimentation rates in the upper reaches of Caddo Lake support these conclusions, as two sites located immediately at the outlet of Big Cypress Creek have the lowest sedimentation rates relative to James Bayou.

Water Quality and Macrophytes

The Cypress Creek Basin seems to be at the transition zone between a mesotrophic and eutrophic system. However, the process of eutrophication seems to be accelerated due to anthropogenic activities within the watershed. Many water quality parameters, such as dissolved oxygen and pH, become problematic during periods of low flow. In-water increases in nutrients are detectable in regards to nitrogen, but not phosphorus. This is likely because of phosphorus sequestration in the biota and sediments. Rampant growth of macrophytes in the upper reaches of Caddo Lake are problematic in that decay of this accumulated biomass also leads to conditions of low dissolved oxygen and may fuel summer phytoplankton blooms. Caddo Lake also suffers from pollution of heavy metals and organic chemicals from multiple sources. In the past, this has even led to warnings to lake recreational users to not eat larger fish.

The impact of inflows will vary with time of year. For example, high inflows during the summer months when temperatures are highest and dissolved oxygen and pH are lowest will be the most beneficial. This is also true in regards to flushing of nutrients. It is unclear from available data whether high flushing during winter and spring months will have a strong impact on summer months. Lastly, conditions of high inflow are not likely to alleviate problems associated with rampant growth of macrophytes, even if they are mostly floating species. Control options involving mechanical removal and application of chemicals seem more practical.

Lower inflows will not flush nutrients from Caddo Lake as quickly as higher inflows. For the same reasons mentioned above, intermediate and low flows will be more effective at flushing nutrients from the system during the summer months. Low inflows would likely have very little impact on alleviating potential problems associated with low dissolved oxygen and pH. In other words, during conditions of low inflow Caddo Lake will likely be plagued by periodic conditions of poor water quality. However, we are unsure as to whether these were characteristic traits of the system during historical (i.e. pre-dam) low flow periods.

In other systems, lake draw down has been an effective way to control rampant growth of submerged macrophytes. For Caddo Lake this might not be a viable option. Water hyacinth is a floating macrophytes species, enabling some plants to find refuge in areas of longer hydroperiod. Even more troubling is the presence of hydrilla. Although it is not yet become a problem in Caddo Lake, it's ability for quick growth and wide tolerance for fluctuating water depth, give it an advantage in this system.

Floodplain Vegetation

In the Big Cypress Creek Basin and around the greater Caddo Lake area, bottomland hardwood and bald cypress forests occupy areas of the floodplain ranging from low areas that are permanently inundated to higher areas that are infrequently inundated, yet may still have saturated soils. It is widely accepted that the structure and function of these alluvial river swamps is tightly coupled with hydrologic energy. In fact, hydrologic variability may be the single most important factor affecting the local distribution of bottomland tree species within their natural ranges. In alluvial settings such as the Big Cypress Creek floodplain, these forested wetlands receive periodic disturbances in the form of a flood pulse that is important in delivering nutrients and altering soil physico-chemical properties to the point that upland species are excluded. The high flows typical of these events are also important in scouring and dispersing many of the seeds produced in alluvial river swamps.

The key to the establishment and long-term maintenance of these forests is through seedling recruitment. Without periodic, successful recruitment of new seedlings, these systems may become more even-aged and more susceptible to human perturbations. For most of the species found in these forests, seeds are released in late summer/early fall—usually between September and October. For the Caddo Lake region, this period historically was the dry season and corresponded with low flows in the Big Cypress Creek basin. Rapid growth—from seed germination–seedling stage—up to the next flood pulse (usually in late winter/early spring) is needed for the successful establishment of a new cohort of saplings in the forest. These hydrologic conditions prevailed up to the installation of the dam for Lake O' the Pines in the 1950's. In fact, it has been suggested that seedling recruitment has been depressed in some areas of the Big Cypress and Caddo Lake region as a result of these hydrologic alterations. Still other past impacts such as logging and drainage of adjacent floodplain area and nutrient enrichment need to be considered in addition to biotic processes such as herbivory and exotic species invasion.

Recommendations are for high flows to occur during the historic early spring flood pulse period. These high flows will scour and distribute seeds to a large area of the floodplain and should start to decline into late spring, bottoming out in early summer. Low flows in Big Cypress Creek during the historical dry summer will then be needed to allow for the establishment (i.e. germination) of seeds and growth to a level at which many will be able to survive the following year's spring high water period. Periodic draw down in Caddo Lake will also be important in recruiting a new generation of bald cypress to this perennially lentic environment.

Aquatic Fauna

Fishes obviously depend on in-stream flows to provide aquatic habitats in which to live, but there are many other direct and indirect effects of water availability, flow characteristics, and water quality on fish behavior and ecology. In lowland floodplain rivers, such as the major tributaries that deliver water to Caddo Lake, the annual hydrological regime greatly influences the quantity, quality, and connectivity of aquatic habitats that are required by the various fish species during each stage of their life cycles. The fish fauna of the Big Cypress/Caddo Lake Basin can be divided into four groups: 1) fishes directly dependent on flowing channel habitats, 2) fishes directly dependent on non-flowing backwater habitats, 3) fishes not directly dependent on flowing or backwater habitats but which may use either to varying degrees, and 4) migratory fish.

Rather than develop an exhaustive assessment of each fish species, we have developed a list of "indicator" species under each category that may be useful in establishing targets for restoration. Some of these species are threatened, in a few instances are now locally extinct, as a result of hydrologic modifications and perhaps other impacts.

The paddlefish (*Polyodon spathula*) has been greatly reduced in abundance and distribution throughout its range due to pollution and especially construction of dams that block migration routes, regulate flow, and alter channel geomorphology and substrate composition. Paddlefish spawn in the spring when water levels rise rapidly. After the larvae develop within deep pools of the main channel, the juveniles move into backwater (lentic) habitats. Spring floods have been greatly curtailed in Big Cypress Creek, and this may have eliminated cues and conditions needed for spawning. In addition, the lack of floods has likely resulted in the degradation of shoal habitats that are critical spawning habitat for this species.

The chain pickerel (*Esox niger*) spawns during late February and early March and requires lentic habitats for all stages of its life cycle, even during the egg-laying stage when eggs are typically scattered in littoral vegetation. In terms of its in-stream flow requirements, the chain pickerel would benefit from flow regimes that maintain permanent aquatic habitat in the floodplain. Periodic pulsed flows would be important for dispersal of juvenile and adult pickerels among lentic (backwater) habitats along the margins of the main channel as well as within the floodplain.

The largemouth bass (*Micropterus salmoides*) nests in backwater areas lacking current, either along river or stream margins or in floodplain habitats such as oxbow lakes. It spawns from April until June, with spawning initiated when the water temperature rises above 65°F. Caddo Lake provides an outstanding habitat for this species, which would only be enhanced by maintenance of a flow regime on Big Cypress Creek that maintains oxbows and other permanent lentic habitats in the floodplains and facilitates dispersal.

The freshwater drum, or gaspergou, (*Aplodinotus grunniens*) occurs in pools where it feeds on benthic invertebrates. The drum spawns during April or May near the surface of the water column and buoyant eggs float with the current before hatching into larvae, that also float. At the post-larval stage, they move to the bottom where they begin feeding as juveniles. The freshwater drum has flow requirements for spawning and dispersal of early life stages that are very similar to those described for paddlefish. It might also benefit from extended periods of low flow during summer, as this should enhance benthic foraging opportunities.

The bluehead shiner (*Notropis hubbsi*) is a threatened species that schools in backwaters and marginal areas away from significant current and seems to spawn from early May to July. It appears that late spring and early summer low flow conditions may be most conducive to successful spawning and recruitment by this rare species, but its presence in oxbow lakes reveals a necessity for periodic overbank flows allowing dispersal between channel and oxbow habitats.

The Bigmouth buffalo (*Ictiobus cyprinellus*) and smallmouth buffalo (*Ictiobus bubalus*) do not seem to be strictly dependent on flow regime, but may show enhanced recruitment under appropriate flow regimes. Both species initiate spawning around April in shallow, lentic backwaters after spring floods raise water levels. Therefore, pulsed flows during spring or other periods of the year would allow dispersal of immature and adult individuals between channel and floodplain habitats.

The ironcolor shiner (*Notropis chalybaeus*) spawns from mid April until late September, and eggs are scattered in stream pools over sand substrate. It seems unlikely that reproduction and recruitment by this small stream-dwelling minnow are highly dependent on pulse flows during spring. One could even hypothesize that extended periods of low flow over the summer could enhance recruitment in this spring-summer spawning species.

An Army Corps of Engineers study that surveyed mussels populations in Big Cypress Bayou, Caddo Lake and the upper reach of Twelvemile Bayou revealed 21 native species plus the Asian clam *Corbicula fluminea*. *Plectomerus dombevanus* was the most frequently encountered species, followed by *Corbicula fluminea*, and *Lampsilis teres*. With the exception of a reach within Twelve-mile Bayou, the study area did not support dense and diverse beds of freshwater mussels such as those usually found in gravel shoals in large rivers of the central United States. No evidence of poor water quality that might have led to a decline in mussel populations was observed, although it was suggested that commercial shell fishermen likely impacted mussel populations in some areas. No uncommon or endangered species were found. Even though the mussel fauna was sparse, it was characterized as healthy with good species richness. More recently, 22 mussel species were documented in Caddo Lake. Many of these taxa are widely distributed, however habitat modification has resulted in a decline of populations. Activities in the watershed (e.g., oil drilling and chicken farming) are presumed to have negatively impacted mussel populations. Because many mussel species require a host fish for their parasitic glochidial stage of development, and rely on flow for dispersal of offspring and settlement of juveniles, environmental flows that favor fishes will also favor mussels.

Terrestrial and Semi-Aquatic Wildlife

The streams, wetlands, open water bodies, and bottomland forests of the Big Cypress/Caddo Lake Basin support a rich and abundant herpetofauna, with 45 species document by a study that surveyed a relatively small area. Many, perhaps most species, would respond to restoration of aquatic floodplain habitats with enhanced populations. In some cases, this population enhancement would result from creation of additional breeding and rearing habitats, and in other cases it would be a response to additional food availability and foraging opportunities. In addition, pulse flows provide connectivity of aquatic habitats that permit dispersal by semi-aquatic species. Two of the state's "threatened" reptiles occur within the basin—alligator snapping turtle (*Macrochelys timminckii*) and the timber rattlesnake (*Crotalus horridus*). The bird assemblage of the basin is estimated to contain 313 species. Two of the state's threatened bird species are likely to use habitats present in the basin—whitefaced ibis (*Plegadis chihi*) and woodstork (*Mycteria americana*). The region is an important migratory corridor for many species, with several lakes in the basin used by wintering waterfowl for foraging and resting. Degradation and losses of wetland habitat are considered the major threats to waterfowl. Although many waterfowl now obtain significant food resources from flooded agricultural fields, forested wetlands are required to meet the full biological requirements of most species. Little research has been conducted on mammals of the Caddo Lake region. Historically, the red wolf (*Canis rufus*) and Lousiana black bear (*Ursus americanus luteolus*) would have inhabited the region. A two-year survey of the Longhorn Army Ammunition Plant recorded 10 species, with taxonomic diversity greatest in the pure pine areas, and abundance greatest in the mixed pine-hardwood. Semi-aquatic mammals in the basin include the beaver (*Castor candadensis*) and river otter (*Lutra canadensis*).

Summary of Environmental Flow Relationships

A major alteration of the natural flow regime in the basin occurred Ferrell's Bridge Dam was constructed on the main stem of the upper Big Cypress Bayou in the late 1950s. Flow regulation results in elimination of flood flows during late winter-early spring and greatly reduced pulse flows year-round. This in turn results in reduced bed scouring (yielding loss of structural habitat diversity within the channel and creation of backwater habitats), sediment delivery, sediment deposition on floodplains, and over-bank flooding. All of these changes have detrimental effects on aquatic and riparian population dynamics which ultimately results in reduced species diversity and smaller populations of species of plants and animals that depend on the natural flow regime for creation of essential habitat for foraging and reproduction, maintenance of ecosystem productivity, and/or dispersal. For example, the paddlefish (breeding population was extirpated in the early 1960s) required flood flows to maintain shoals and to provide cues for spawning. This species also required periodic pulse flows to allow movement between channel and backwater habitats used by juveniles and adults for foraging. Similarly, the major bottomland hardwood tree species required high flows for seed dispersal and to limit encroachment of upland tree species into floodplains. Flow regulation also results in higher daily flow fluctuations and higher late spring and early summer flows, which result in lower water temperatures. These changes impact benthic ecosystem productivity in the channel, foraging opportunities for benthivorous organisms, fish growth rates, and spawning by aquatic species that depend on stable, low flows during summer. These impacts result in degraded fisheries, decline of sensitive and rare species, alteration of aquatic and riparian communities and ecosystems. Although it provides about a third of the total inflow to Caddo Lake, flow regulation in Big Cypress Bayou probably has major effects on the lake ecosystem. Sufficiently high inflows would influence nutrient concentrations and phytoplankton dynamics. During periods of low flow, internal nutrient dynamics (involving sediments, bacteria, water column, macrophytes and algae) would be prevalent. Prolonged periods of low-flow, uninterrupted by pulse flows, during late summer result in acute aquatic hypoxia in the shallow (deltaic) upper segment of the Lake.

HYDROLOGY

Site Description

Caddo Lake drains an area of roughly 2639 square miles and has a storage capacity of around 175,000 acre-feet. Major tributaries into Caddo Lake are Big Cypress, Little Cypress and Black Cypress. Together these account for about 70% of the total drainage area of Caddo Lake (Figure 1). Hydrologically it has undergone several very large changes in the last 200 years. It originally was a natural lake formed by the presence of a tremendous and apparently ancient log jam. In the 1800's the original natural dam was removed. This caused the original lake to shrink with typically very shallow water. This condition persisted for more than 100 years, when the USACE constructed a dam and spillway to raise the water level. Outflow cannot be manipulated from the Caddo Lake dam other than when water overtops the spillway. In 1960, with the completion of Lake O' the Pines, inflows into Lake Caddo were substantially altered.

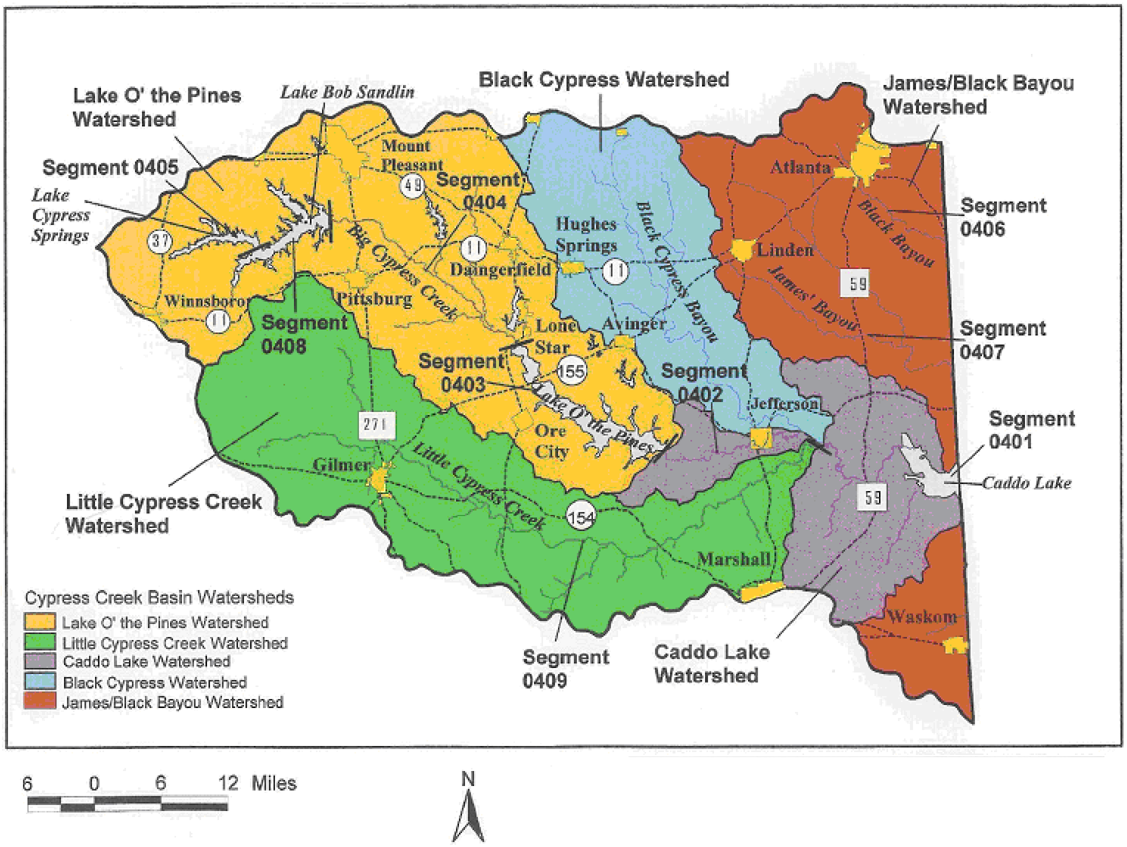


Figure 1. Watersheds in the Cypress Basin. (From the Northeast Texas Municipal Water District- http://netmwd.com/)

Each of the major tributaries is serviced by a USGS gauging station and is part of the larger Cypress River Drainage. Input from the other 30% of the drainage area is not monitored on a routine basis. Summary statistics for the drainage area are presented in Table 1. In addition Table 1 provides estimates of total annual input into Caddo Lake. Estimated input from the ungauged areas was made on the basis of average water input / per unit area from the gauged locations.

Table 1. Summary statistics for Caddo Lake Basin drainage areas

	Big Cypress Ck	Little Cypress Ck	Black Cypress	not gaged	Caddo lake	% gaged
Gauging Station	07346000	07346070	07346045			
Years of Record	1913- present	1946- present	1968-present			
size (ac)	850	675	365	749	2639	71.62%
Avg. annual Flow(cfs)	660	534	373	591	2158	
annual water volume(ac-ft)	477,818	386,598	270,040	428,378	1,562,835	
lake capacity (ac-ft)	175,000					
flushing rate	8.9					

Change in Flow Regime

There has been no major dredging or channel modifications within the Caddo Lake basin. The major disruption of natural flows into Caddo Lake is caused by the presence of Lake O the Pines on Big Cypress Creek (Figure 1), upstream from Caddo Lake. The Lake O the Pines reservoir was completed in 1960, which has dramatically altered the flow regime of Big Cypress Creek.

The annual hydrograph for post conditions is very damped in comparison to pre-dam conditions. Peak flows are reduced significantly. Also low flows increased. Average annual inflow is reduced, and it is about 5% lower following dam construction (see Appendix C for detail tabular results of flow analyses) . This is probably due to increased evaporation from the lake surface.

The flow regime of the other major tributaries into Lake Caddo, Little Cypress and Black Cypress, have not been altered but are included within this report for comparison purposes.

These analyses have largely been accomplished using the Nature Conservancy IHA model. Complete results from this analysis are presented graphically in Appendix B.

Peak Flow

The largest change has been in terms of peak or flood flows as highlighted in Figure 2. Prior to dam construction annual peak flow was as high as 57,000 cfs as occurred in 1945. Following dam construction peak flows remained around 3000 cfs with very little variation. The median annual peak flow prior to the dam was around 15000 cfs. Peak flows for Little Cypress Bayou and Black Cypress Bayou for the period of record are also included for comparison purposes (Figures 3 and 4). Peak flows at Little Cypress are as high as 30,000 cfs and for Black Cypress are as high as 10000 cfs.

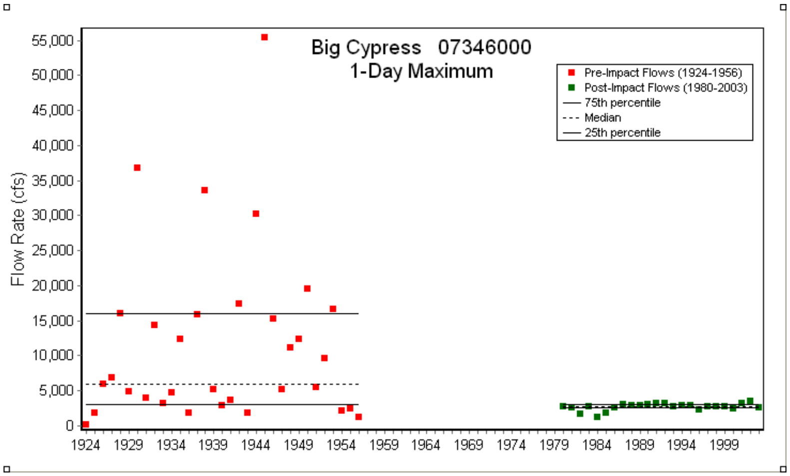


Figure 2. Annual peak flows for Big Cypress Creek at Jefferson.

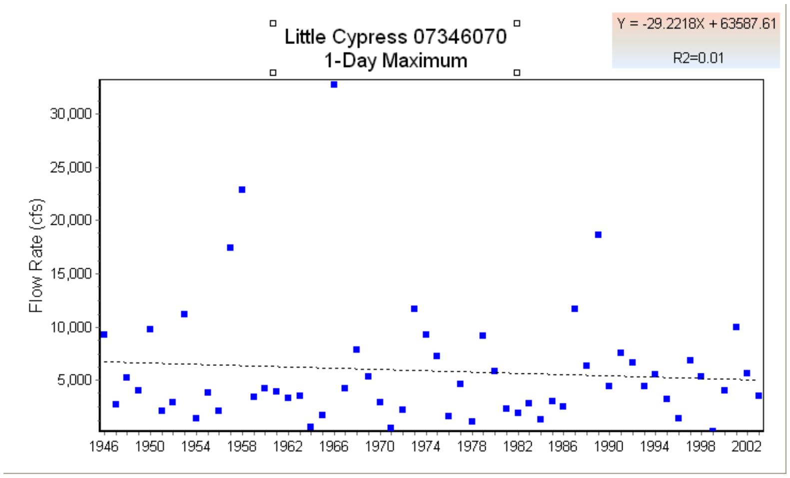


Figure 3. Annual peak flows for Little Cypress Creek at Jefferson.

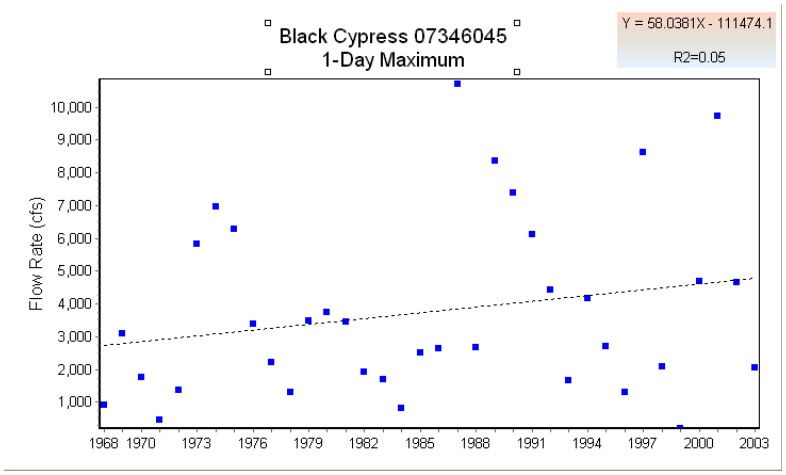


Figure 4. Annual peak flow for Black Cypress Bayou at Jefferson.

Recurrence interval calculations demonstrate the dramatic changes in peak flows that have occurred on Big Cypress (Figure 5). Prior to dam construction, peak flow of at least 6000 cfs occurred on an interval of every 2 years. A 20,000 cfs flow occurred on average about every 10 years. Recurrence intervals have been calculated for Black Cypress Bayou and Little Cypress Creek as well.

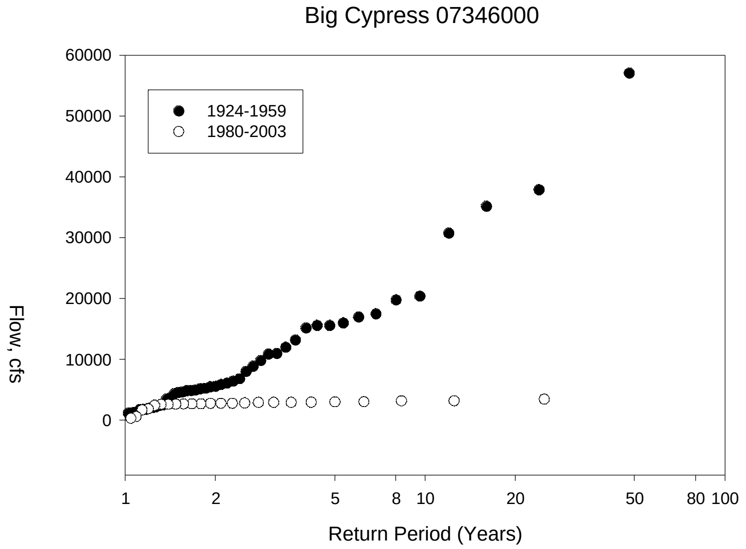


Figure 5. Flow recurrence graph for Big Cypress Creek at Jefferson for pre and post-dam years

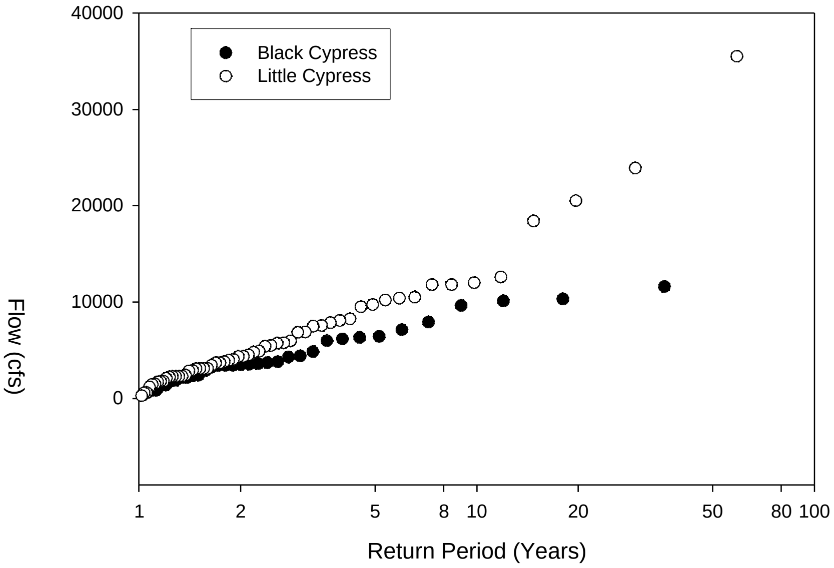


Figure 6. Flow recurrence for Black Cypress Bayou and Little Cypress Creek at Jefferson.

Prior to the dam, most peak flows were concentrated between julian days 50 and 175. After the dam construction, the timing of peak flows was shifted more towards the beginning of the year (Figure 7)

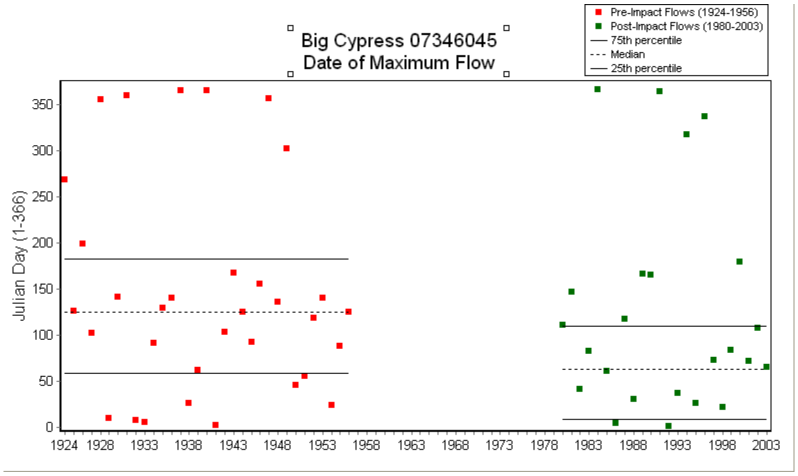


Figure 7. The data of annual peak flows for Big Cypress Creek at Jefferson.

Low Flow

Low flow conditions have changed since installation of the Lake O' the Pines reservoir. Figure 8 highlights how the 7-day low flows have increased in the post-dam years. The median 7-day low flow prior to the dam was around 5 cfs. After the dam, it is around 20 cfs. Of equal if not more importance is that the timing of low flow conditions has changed dramatically as highlighted in Figure 9. Prior to the dam, low flows were consistently around the first part of September (Julian day 250). Following construction of the dam, the date of low flow conditions became much more variable.

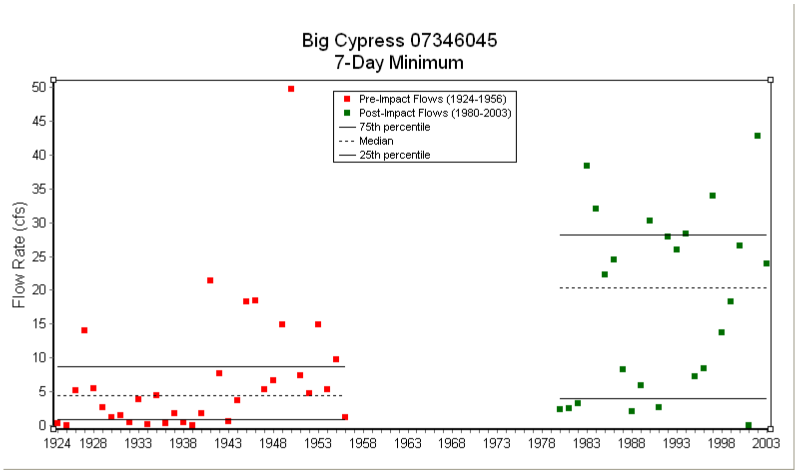


Figure 8. Magnitude of 7-day minimum flows for Big Cypress Creek at Jefferson.

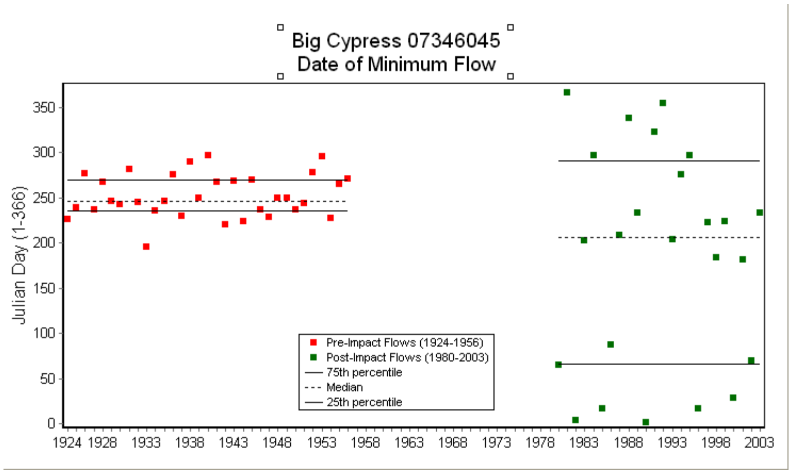


***Figure 9. Timing of low flow conditions for Big Cypress Bayou*.**

Seasonal Runoff Characteristics

The flow changes that have occurred on Big Cypress since Lake O' the Pines are highlighted in Figure 5, which compares annual hydrographs for a 5-6 year periods before and after the construction of the dam. As previously discussed, the dramatic reductions in peak flows are apparent from this comparison. These changes are apparent on the for the multiple year hydrographs of Big Cypress before the dam and after the dam (Figure 10). There are similarities in timing for flow for pre and post-dam construction. Namely that most of the flow occurs during the winter and spring. However, as highlighted in Figure 11, the annual hydrograph has been attenuated so that flows are now higher in April and May than prior to the Lake O' the Pines.

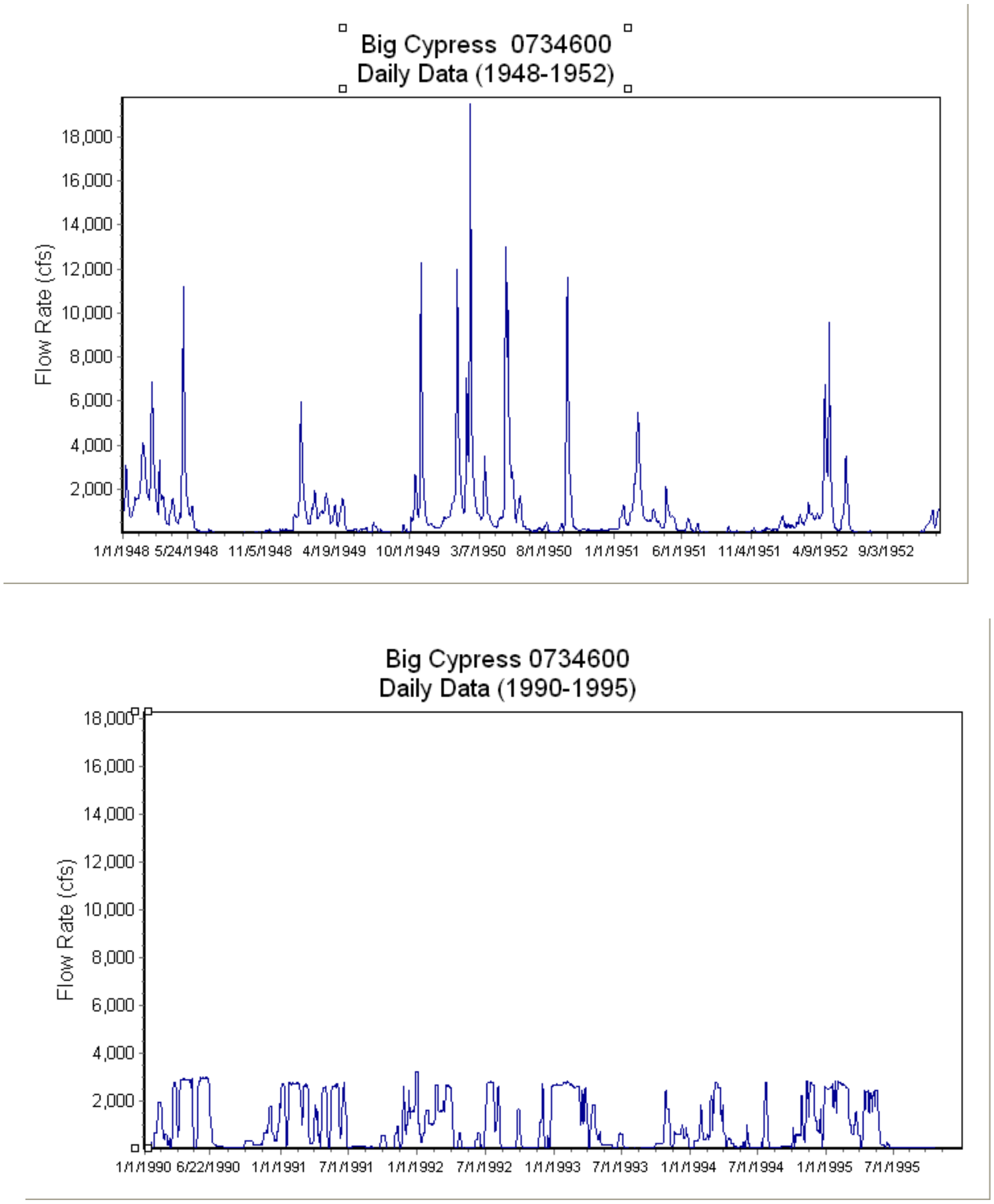


Figure 10. A set of annual hydrographs for Big Cypress Bayou prior ***Lake O' the Pines (top graph) and after Lake O' the Pines.***

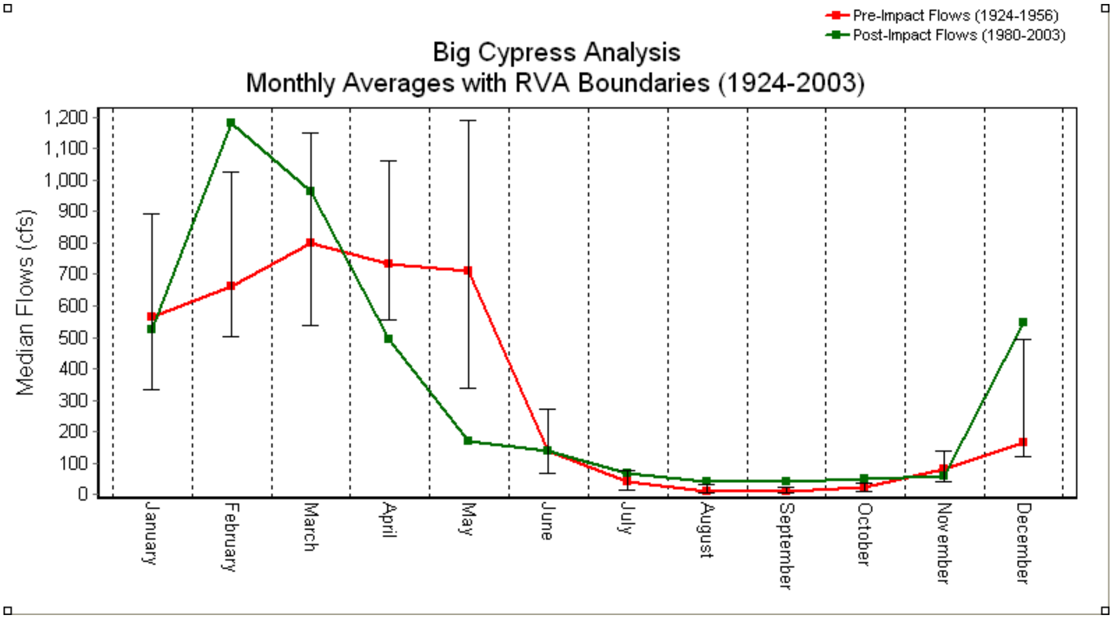


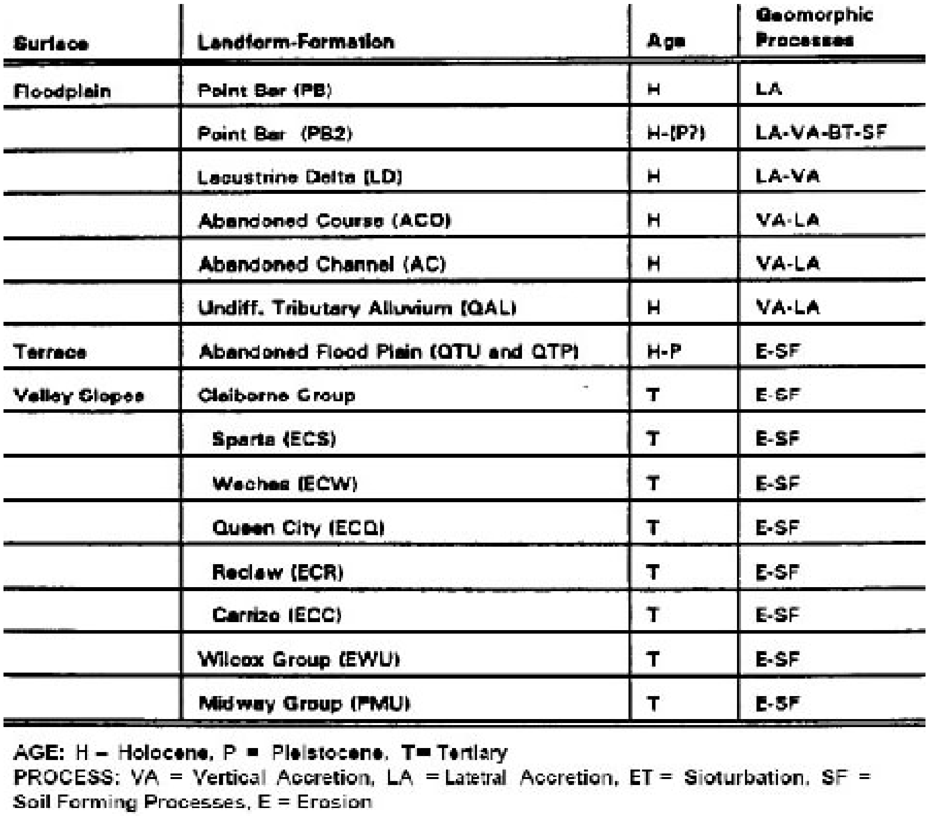
Figure 11. A comparison of average monthly flow at Big Cypress for before and after Lake O' the Pines.

GEOMORPHOLOGY

Changes in Geomorphological Processes

The Big Cypress drainage basin reflects geomorphological processes active during the past 2 million years. The geomorphology of Cypress Creek (reach between Lake of the Pines and Caddo Lake) was mapped by the U.S. Army Corps of Engineers, Vicksburg District as part of the Red River Waterway Project (USACOE, 1994). Three geomorphic surfaces were identified according to their physical characteristics, apparent age, and types of processes active on the surfaces: floodplain, terrace, and valley slopes (Table 2).

Table 2. Geomorphic surfaces in the Big Cypress Drainage Basin (USACOE, 1994)



Surface	Landform-Formation	Age	Geomorphic Processes
Floodplain	Point Bar (PB)	H	LA
	Point Bar (PB2)	H-(P?)	LA-VA-BT-SF
	Lacustrine Delta (LD)	H	LA-VA
	Abandoned Course (ACO)	H	VA-LA
	Abandoned Channel (AC)	H	VA-LA
	Undiff. Tributary Alluvium (QAL)	H	VA-LA
Terrace	Abandoned Flood Plain (QTU and QTP)	H-P	E-SF
Valley Slopes	Claiborne Group	T	E-SF
	Sparta (ECS)	T	E-SF
	Weches (ECW)	T	E-SF
	Queen City (ECQ)	T	E-SF
	Reclaw (ECR)	T	E-SF
	Carrizo (ECC)	T	E-SF
	Wilcox Group (EWU)	T	E-SF
	Midway Group (PMU)	T	E-SF

AGE: H – Holocene, P = Pleistocene, T= Tertiary
PROCESS: VA = Vertical Accretion, LA = Lateral Accretion, ET = Bioturbation, SF = Soil Forming Processes, E = Erosion

Whereas valley slopes are Tertiary in age (65 to 2 million years), the terrace and floodplain were formed primarily in the Quaternary (2 million years to present) and specifically during the Holocene. Terraces are abandoned floodplains elevated above the present river's floodplain; they flood on the order of 100 to 500 years. Floodplains form by deposition of sediments transported by the stream. In the geomorphic analysis conducted by the U.S. Army Corps of Engineers (1994), floodplains were defined as the area subject to inundation by a flood with a recurrence interval of 2 years, following Leopold, Wolman and Miller (1964). The floodplain contains point bars (which range in thickness from 25 to 30 feet and in texture from sand at the base to finer silts and clays toward the surface), levees (formed by vertical accretion when the stream floods and deposits suspended sediments along the banks), and numerous abandoned channels and courses as well as oxbow lakes that form when river channels cut across their point bars (Figure 12). The Big Cypress is therefore characteristic of a lowland meandering river.

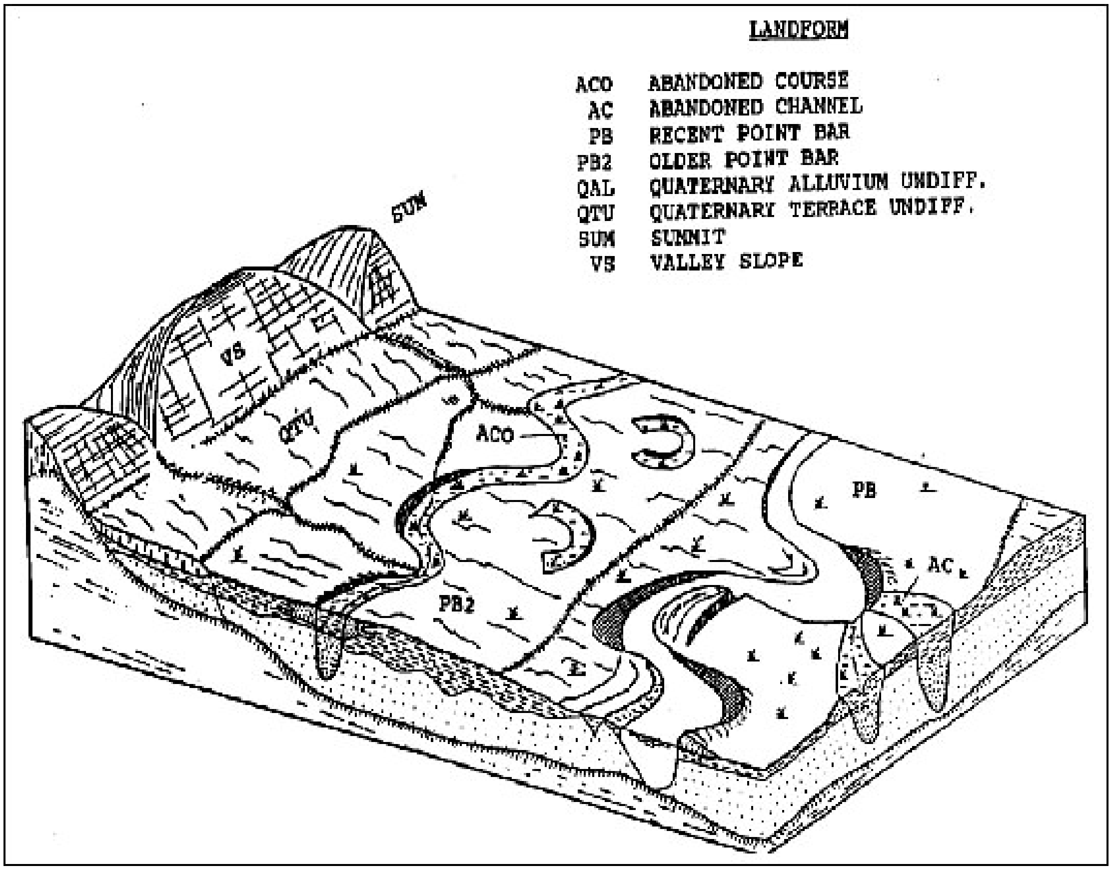


Figure 12. Generalized block diagram of Big Cypress Drainage Basin showing geomorphic features (USACOE, 1994)

Channel-Floodplain De-coupling

The geomorphological features present on the floodplain are evidence of active river migration and a tight channel-floodplain coupling under natural conditions. Before closure of Ferrells Bridge Dam in 1960, the floodplain upstream of Caddo Lake was inundated every 1-2 years at a discharge of 6000 cfs (Figure 5). This flow occupied the bankfull river channel and is the dominant discharge necessary to form and maintain an equilibrium channel geometry (Knighton, 1998). This is also the discharge needed to sustain floodplain development and riparian ecosystem.

The immediate result of flow regulation by Ferrells Bridge Dam has been the de-coupling of the floodplain from river channel processes. The closure of Ferrells Bridge Dam has changed frequency-magnitude relations so that at present, little variation in flow magnitude exists, and maximum flows do not exceed ~3000 cfs (Figures 2 and 5). Floodplains are therefore not inundated under the present flow regime. Maximum flows of ~3000 cfs are also below the dominant discharge necessary to maintain an equilibrium channel geometry.

Sediment Trapping by Lake O' the Pines Reservoir

Construction of Ferrells Bridge Dam has also affected sediment movement and delivery into Caddo Lake. As expected, sediment trapping by Lake O' the Pines Reservoir has reduced sediment input into the downstream channel reach and ultimately into Caddo Lake. The extent of sediment trapping can be estimated by assessing changes in storage capacity in the reservoir (Phillips et al. 2004). In 1958, the original conservation reservoir storage capacity of Lake O' the Pines Reservoir was 254,900 acre-feet. By 1998, the reservoir capacity as reported by the USGS was 238,933 acre-feet (TWDB 2004). This represents a decrease of 6% in reservoir capacity due to sedimentation, equaling 492, 378 cubic meters of trapped sediments per year behind the reservoir. In some cases, such as the nearby Trinity River (Phillips et al., 2004) and Sabine Rivers (Phillips, 2003), this reduction in sediment supply downstream of reservoirs is partly offset by increased bank and bed erosion. However, insufficient information is available for Cypress Creek to determine whether similar erosion processes are producing additional sediments for delivery into Caddo Lake.

Reduced Transport Capacities

The drastic reduction in flood peaks (Figure 2) is also expected to decrease sediment transport capacities downstream of Ferrell's Bridge Dam. Stream power for a cross section represents the total transport capacity of the river at a given cross-section and can be calculated for the pre-dam and post-dam period. These calculations were performed for the cross-section immediately downstream of the dam, where USGS gauging station 07346000 is located.

Stream power is $\Omega = wQS$

where
Ω = stream power (N/s)
w = specific weight of water = 9807 kgm^{-2}s^{-2}
Q = discharge (m^3/s)
S = slope

Using a slope of 2.47 feet/mile or 0.000468 (Slack et al., 2001), the stream power for the pre-dam bankfull discharge of 6000 cfs (that occurred every 2 years, and that inundated the floodplain) is ~779 N/s (Table 3).

Table 3. Stream power of a 2-year recurrence interval flow before and after dam construction.

Ù of 2-yr R.I. Time Period	**Q with a 2-yr R.I. cfs (cms)**	**N/s**
Pre-dam (1924-1959)	6000 (169.8)	779.33
Post-dam (1980-present)	3000 (84.9)	389.66

Now, under the present flow regime, because the maximum discharge has been reduced to 3000 cfs (Figure 5), the maximum transport capacity is ~390 N/s. These results show that sediment transport capacity has been reduced by 50%. Thus, although increased erosion has been demonstrated to occur below some dams due to clear-water or “hungry-water” effects (Kondolf, 1997), these effects tend to be limited to the area immediately below the dam (Phillips, 2003), and the overall effect of reduced flood peaks are decreased transport capacities. A similar decrease in transport capacities in Yegua Creek downstream of Somerville Dam in south-central Texas has resulted in reduced channel capacities over time (Chin and Bowman 2005, Chin et al. 2002).

Sediment Entrainment

To answer the question of whether sediments present in the channel downstream of Lake O’ the Pines are being transported into Caddo Lake, sediment entrainment calculations were performed. Because quantitative particle size data are unavailable for Cypress Creek, these calculations were performed for a series of particle sizes ranging from clay to fine sand, which are known to be typical for this channel reach (Barrett, personal communication). Two sediment samples collected and analyzed in November 2004 by a student at Texas A&M University were also in the fine sand range (median sizes of 0.165 mm and 0.097); they corroborate qualitative estimates of particle size. These samples were collected in the channel close to the banks at locations near Jefferson and at Hwy 43 upstream of Caddo Lake.

Critical shear stresses required to entrain clay, silt, very fine sand, and fine sand were therefore calculated (diameter equal to 0.0015 mm, 0.02 mm, 0.075 mm, and 0.175 mm, respectively). Two equations were used, which produced similar results.

Shield’s equation is:

$$\tau_c = 0.045(s-1)\rho g D$$

where τ_c = critical shear stress (N/m^2 or Pa)
D = median diameter of sediments (mm)
s = relative density of sediments to water = 2.65
ρg = specific weight of water = 9807 kg m^{-2} s^{-2}

Church’s equation is (Church 1978):

$$\tau_c = 0.89D$$

where τ_c = critical shear stress (N/m^2 or Pa)
D = median diameter of sediments (mm)

Table 4 shows that, for sediments ranging from medium sand to clay, flows with shear stresses ranging from 0.274 N/m^2 to 0.001 N/m^2 are required to entrain them.

Table 4. Critical shear stresses required to entrain sediments ranging from medium sand to clay.

Class Name	Diameter (mm)	Shield's $_c$ (N/m^2)	Church's $_c$ (N/m^2)
Medium Sand	0.375	0.274	0.334
Fine Sand	0.175	0.128	0.156
Very Fine Sand	0.075	0.055	0.067
Silt	0.02	0.015	0.018
Clay	0.0015	0.001	0.001

To determine flow depths needed to generate the critical shear stresses required to entrain sediments, the DuBoy’s equation was used:

$\tau_o = \rho g ds$

where τ_o = shear stress
(critical shear stress calculated for various sediment sizes using Shield's and Church's equations, Table 4)
ρg = specific weight of water
d = depth (m)
s = slope

Application of the DuBoys equation indicated that, for sediments ranging from medium sand to clay, flow depths of 60 m to ~0.3 m would have sufficient shear stresses to entrain these sediments (Table 5).

Table 5. Average depths required to have sufficient shear stresses to entrain sediments ranging from medium sand to clay.

Class Name -	Avg. Depth based on Shield's m (ft)	Avg. Depth based on Church's m (ft)
Medium Sand	59.6 (195.7)	72.7 (238.6)
Fine Sand	27.8 (91.3)	33.9 (111.3)
Very Fine Sand	11.9 (39.1)	14.5 (47.7)
Silt	3.2 (10.4)	3.9 (12.7)
Clay	0.24 (0.78)	0.29 (0.95)

The final step to determine whether sediments are capable of being moved under the present flow regime is to relate the average depths to discharges. Using data available at the channel cross-section immediately downstream of Ferrells Bridge dam, where USGS gauging station 07346000 is located (http://nwis.waterdata.usgs.gov/tx/nwis/measurements/?site_no=07346000&agency_cd=USGS), the relationship between average depth and discharge was established (Figure 13). This relationship enables discharges corresponding to the calculated critical depths for sediment entrainment (Table 5) to be determined.

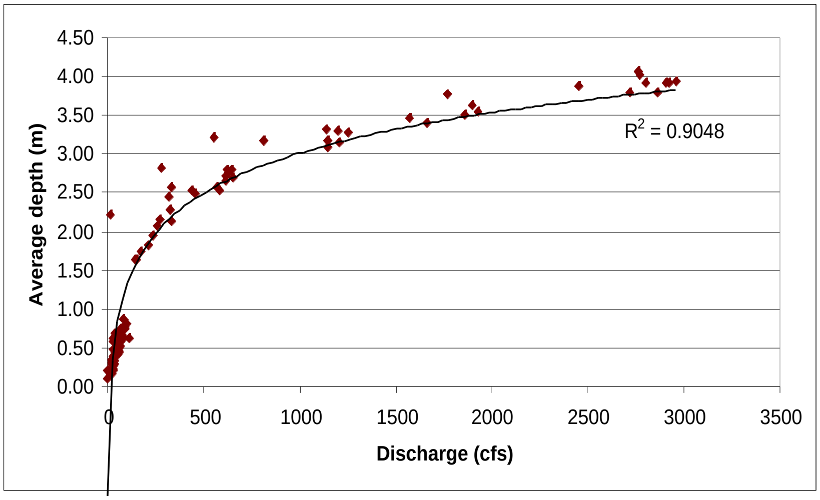


Figure 13. Depth-discharge relationship at cross section downstream of Ferrels Bridge Dam

Combining Table 5 and Figure 13, results indicate that the present flow regime is capable of entraining only silts and clays. Clays are mobilized at a discharge of ~25 cfs, whereas silts require a discharge of 1250 cfs to be entrained (Table 6). Because sands (very fine, fine, and medium) require flow depths corresponding to discharges that exceed 3000 cfs, which is the maximum flow under the present regulated regime (Figures 2 and 5), they are not being mobilized by present flows.

Table 6. Required discharges to entrain sediments ranging from medium sand to clay.

Class Name	Avg. Depth based on Shield's	USGS x-sctn
-	M (ft)	Cfs
Medium Sand	59.6 (195.7)	>3000
Fine Sand	27.8 (91.3)	>3000
Very Fine Sand	11.9 (39.1)	>3000
Silt	3.2 (10.4)	1250
Clay	0.24 (0.78)	25

Sediment Delivery into Caddo Lake

The last piece of available data to give insight to the issue of sediment delivery into Caddo Lake is analysis of sedimentation rates within Caddo Lake (Barrett 1995, Lisanti 2001). Modern sedimentation rates (1963 to present) were measured using gamma ray spectroscopy at seven sites within Caddo Lake (Lisanti 2001), yielding sedimentation rates ranging from 0.22 cm/year to 0.56 cm/year, with two sites not measurable. Although Caddo Lake receives sediment input from sources other than Cypress Creek, and thus sedimentation rates within the lake are not perfect analogs for sediment delivery through Cypress Creek, variations in sedimentation rates nevertheless give additional information to corroborate previous analyses.

It is worthy to note that the two sites located immediately at the outlet of Cypress Creek (Cypress Bayou delta) have the lowest sedimentation rates (both 0.22 cm/year). These sedimentation rates are only half of the rate of 0.56 cm/year at the outlet from James Bayou. Low sedimentation rates at the Cypress Creek outlet support previous conclusions that 1) sediment supplies are reduced downstream of Lake O' the Pines; 2) sediment transport capacities are reduced due to a drastic reduction in flood peaks; 3) only the finest sediments (clays and silts) are being mobilized under the current flow regime.

In summary, both flow regime and sediment regime have been altered by flow regulation at Ferrell's Bridge Dam since 1960. The overall result is a river floodplain disconnected from the river channel at present.

WATER QUALITY

Monitoring Activities

Beginning FY2002, intensive water quality monitoring occurred throughout the Cypress Creek Basin. This monitoring was an integral part of the Clean Rivers Program, and was made possible through a cooperative program directed by the Northeast Texas Municipal Water District. Program participants assisting the Water District in planning, data collection, analysis, and reporting of water quality data included Paul Price Associates, Inc., the Texas Commission on Environmental Quality, the Caddo Lake Institute, and the Franklin County Water District. Sampling locations throughout the basin are shown in Figure 14 (taken from NETMWD 2003). For this more recent effort, sampling stations incorporated three types of monitoring, which included fixed/routine, intensive/systematic, and special study. The methods and materials for all work performed followed published guidelines (TNRCC 1999).

Fixed/routine station monitoring was primarily used to expand and maintain the long-term water quality database. These stations were situated to provide information on each of the classified segments within the Big Cypress Creek basin and Black Cypress Bayou (Figure 15, taken from NETMWD 2003). The frequency of sampling, which varied for each of the parameters listed, ranged between once per year to 12-times per year, with most parameters being sampled quarterly. Intensive/systematic monitoring was designed to investigate known areas of concern and detect areas of potential concern typically on the smaller, unclassified streams. The monitoring schedule was based on a five-year cycle, with one group of stations monitored each of the five years, and complete coverage of the basin accomplished at the end of the rotation. *Special study* sampling was designed to address a specific concern or to provide additional data necessary to complete existing information. For example, the Tankersley Creek Indicator Bacteria Special Study, initiated in FY2003, focused on the expansion of the fecal coliform data into the existing Texas Commission on Environmental Quality water quality database.

For the fixed/routine station monitoring, parameters measured included standard water quality parameters, measurements of dissolved constituents, and characteristics of the physical habitat, biota, and various other parameters. Measured standard water quality parameters were temperature, pH, dissolved oxygen, 24-hr dissolved oxygen, conductivity, Secchi depth, chlorophyll-a, pheophytin-a, *E. coli*, and total suspended solids. Measurements of dissolved constituents were total dissolved solids, sulfate, chloride, ammonia-N, alkalinity, hardness, nitrate-N, nitrite-N, orthophosphate-P, total phosphorus-P, total organic carbon, total Kjeldahl N, methyltertiarybutylether, aluminum, arsenic, chromium, copper, iron, manganese, mercury, nickel, silver, zinc, barium, molybdenum, calcium, and selenium. Characteristics of the physical habitat were streamflow, water depth, sediment grain size, and slope of substrate. Measurements of biota were benthic organisms (those that live near or in the stream bottom), and nekton organisms (fish). Other parameters sampled included oil and grease, acid volatile sulfide, and solids in sediment.

Prior to this period of extensive monitoring in the Cypress Creek Basin, many monitoring efforts of smaller scale and duration, as well as highly focused student research projects occurred. The specifics of location, sampling time, and questions addressed are too fragmented to summarize here. They are, however, documented in the Annotated Bibliography.

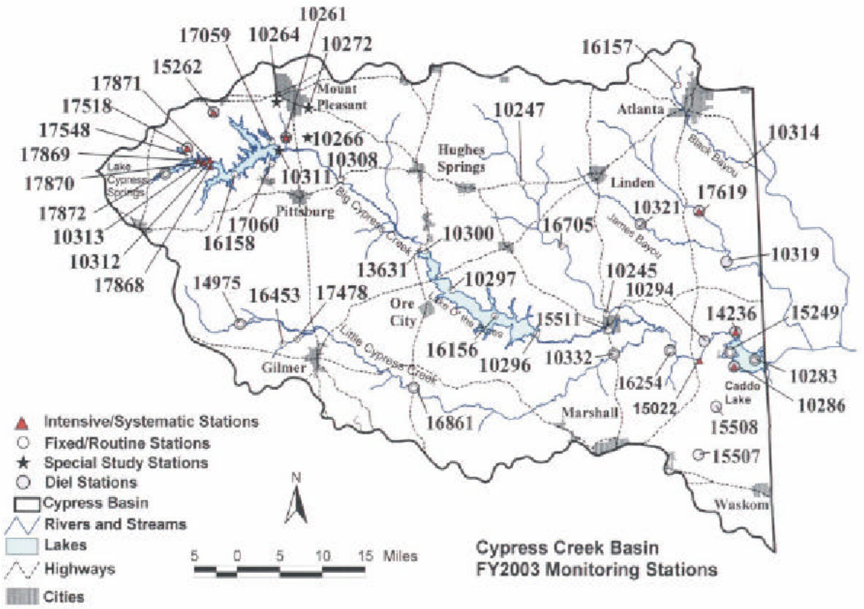


Figure 14. Sample stations in the Cypress Creek Basin beginning FY2002 (taken from NETMWD 2003).

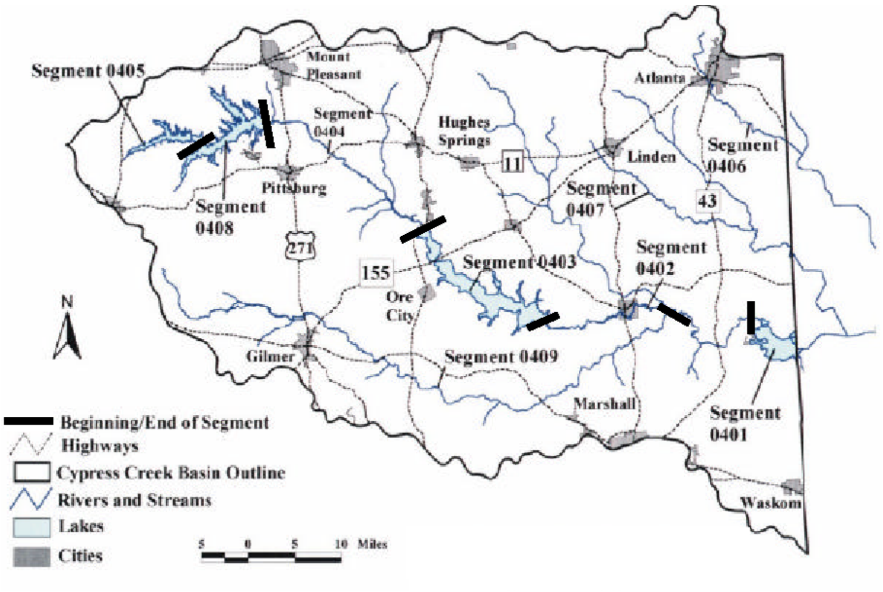


Figure 15. Segment classification within the Big Cypress Creek Basin and Black Cypress Bayou (taken from NETMWD 2003).

Synopsis of Most Relevant (Threatening) Findings

A distillation of the findings from the many studies conducted in the Cypress Creek Basin is as follows: As a whole, the Cypress Creek Basin appears to be positioned at the transition zone between a mesotrophic and eutrophic system. However, the process of eutrophication seems to be accelerated due to anthropogenic activities within the watershed. Many water quality parameters, such as dissolved oxygen and pH, become problematic during periods of low flow. Regarding nutrients, controls of phosphorous-loading have been suggested. In-water increases in nutrients are detectable in regards to nitrogen, but not phosphorus. This is likely because of phosphorus sequestration in the biota and sediments, i.e., most likely nitrogen accumulates in the water column because it is no longer a limiting nutrient as it was 30 years ago. Rampant growth of macrophytes in the upper reaches of Caddo Lake are problematic in that decay of this accumulated biomass also leads to conditions of low dissolved oxygen and may fuel summer phytoplankton blooms. Caddo Lake suffers from pollution of heavy metals and organic chemicals from multiple sources. In the past, this has even led to warnings to lake recreational users to not eat larger fish.

There are also two important issues that are not as well studied, especially in regards to Caddo Lake. The first, loading of organic carbon (dissolved mostly), especially from the poultry farming activities in the watershed. This source of labile (readily usable by microbes) organic carbon likely stimulates heterotrophic bacteria, which may contribute to conditions of low dissolved oxygen. Second, taxonomic composition of the phytoplankton has not been determined for Caddo Lake in recent years. While phytoplankton blooms have been observed, taxa have not been identified in detail since 1977. Thirty years ago nuisance taxa were not prevalent in lake. In fact, they were confined to areas immediately down-flow of sewage treatment plant discharge locations along Big Cypress Creek. But much has changed in Caddo Lake since then, most notably nutrient additions. Eutrophication is known to lead to greater prevalence of less desirable phytoplankton taxa, toxic species in some cases. Until this knowledge-gap is addressed, the current threat of phytotoxins to human health and foodweb stability will remain unknown.

Detailed Account of Most Relevant Findings

Dissolved Oxygen and pH

Low dissolved oxygen concentrations and extreme pH levels, acidic and caustic, are detrimental to the biota of ecosystems (see Kalff 2005; Wetzel 2001). For example, larger organisms that live strictly in-water, i.e., fish and mussels, experience decreased growth and survival when dissolved oxygen and/or pH are poor. In extreme cases, periods of low dissolved oxygen cause large die offs of these organisms. In addition, dissolved oxygen and pH also impact ecosystem functioning. Low bottom water dissolved oxygen frequently results in greater flux of nutrients from the benthos into the water column, which might result in rapid accumulation of phytoplankton biomass (algal blooms). In turn, this might restrict flow of energy through the foodweb, and result in large diel fluctuations in dissolved oxygen to the extent that anoxia may occur during the night. For this reason, spatial and temporal trends in dissolved oxygen and pH within the Cypress Creek Basin are important to understand and manage, if necessary.

Fortunately, two bodies of work occurred nearly 30-years ago that serve as a comparison to the more recent data collected for this system. In regards to dissolved oxygen within Caddo Lake, 30 years ago this parameter never dropped below minimum standards, and it never exceeded saturation levels (Kirkpatrick 1977). From this same study, pH was also measured. While this parameter occasionally dropped below minimum standards, e.g., lowest values were 5.5, it was thought that this might be the natural state of the system. In the sediments of Caddo Lake, chemical oxygen demand (a measure of sediment organic content and the likelihood of bottom water anoxia occurrence) was relatively high, and this was presumably due to decaying plant material (Kirkpatrick 1977). But again, this was likely a natural state of the system. In the flowing waters above Caddo Lake, i.e., Big Cypress Creek, the only problematic areas that were observed, i.e., low dissolved oxygen and pH occurred directly below discharge locations of sewage treatment plants (only four facilities) during periods of low flow (Twidwell 1977).

Reports from the 1980s paint a different picture, however. In the upper portions of Caddo Lake, i.e., the “swamp” region to the west, dense stands of submerged macrophytes impacted the physicochemical environment. The most notable suspected impact was low dissolved oxygen and pH that occurred during times of warmer water temperatures. Also, the detritus produced from the macrophyte die-off in the winter might have been responsible for the high biological oxygen demand found throughout the lake in the winter (Cusak 1984, Hartung 1983, Twidwell 1989). In the oil-producing region of Caddo Lake, chemical oxygen demand was high, presumably due to the large amounts of organic matter in this region that might have originated from oil spills and oil-contaminated sediments found in this region (Hartung 1983). Because thorough monitoring of the Cypress Creek Basin had not yet commenced, and rigorous experimentation had not occurred, it is difficult to surmise if the “poorer” environmental conditions observed during the 1980s were a result of the ecosystem responding to anthropogenic impacts, or if this was still primarily the natural state of the system.

More widespread and frequent monitoring of the Cypress Creek Basin occurred through the 1990s, findings are in stark contrast with the previous works from 1977, and there is little doubt that anthropogenic activities have made a deleterious impact. During the mid-1990s, river sites within the Cypress Creek Basin during low-flow, i.e., high-stress conditions, did not meet even limited criteria for water quality in regards to dissolved oxygen (Crowe and Hambleton 1998, Price 2000). When there was no flow, most sites experienced dissolved oxygen levels less than 2 mg $liter^{-1}$. Crowe and Hambleton (1998) found that the relationship between flow and dissolved oxygen during these low-flow periods, however, was not significant. They did find that drainage area accounted for ~53% of the variation in dissolved oxygen, and that rainfall strongly effected dissolved oxygen during the first two days following a rainfall event. Of the biota, benthic communities were more sensitive to conditions of low dissolved oxygen than fish communities. Aquatic life use scores were typically intermediate to high, despite the conditions of low dissolved oxygen. Another study indicated that the riverine and wetland areas neighboring Caddo Lake experienced conditions of low dissolved oxygen as well (Darville et al., 1998).

Along the shoreline of Caddo Lake, sparse monitoring of dissolved oxygen and pH from 1994 to 1997 indicated that these data were within natural ranges for waters in east Texas, and revealed no specific water quality problems (Darville et al., 1997). To monitor the lake more thoroughly, a comprehensive sampling was initiated in 1997 that included seasonal sampling and open water stations. In addition to this monitoring, studies focusing on other aspects of the lake were conducted. For this latter sampling, a monthly monitoring program, and an intensive summer monitoring program, revealed that dissolved oxygen levels were low and indicated poor water quality (Darville 1997, TRNCC 1997). Low dissolved oxygen was also detected in deeper waters towards the eastern region of the lake (Ensminger 1998). Furthermore, a decreasing trend in dissolved oxygen and pH for the period 1997 to 2001 was observed (Darville 2002). These conditions appeared to be related to inflows. For example, during periods of low flow, low dissolved oxygen events were associated with large diel (day and night) changes (phytoplankton biomass, which often causes these large diel fluctuations, was not excessive during these periods, but it was moderate to high, and occasionally got up to 30 μg $liter^{-1}$). When inflows were high, i.e., during the non-summer months, and dissolved oxygen concentration was not a problem (Price 2003). Despite the trend of declining dissolved oxygen conditions during the 1990s, the lake was still considered to be in “good” condition (Darville 2002).

Submerged Macrophytes

Submerged macrophytes are both important and detrimental to aquatic ecosystems, and this depends on their abundance (see Kalff 2005, Wetzel 2001). For example, macrophyte stands provide refuge habitat for many juvenile fish species, without which these species would experience mortality losses to juveniles to the extent that their populations might become locally extinct. Macrophyte stands also serve to sequester nutrients from phytoplankton, thereby preventing algal blooms and maintaining water clarity (Scheffer 1998). On the other hand, when macrophyte stands become too dense, refuge habitat might increase to the extent that adult piscivorous fishes, such as large mouth bass, cannot find enough food to sustain their body weight. This results in a decline in overall fish body size. Dense stands of macrophytes also result in large diel fluctuations of dissolved oxygen and pH, often to problematic levels, and slow down water flow to the point where sedimentation becomes accelerated.

In the swamp region of Caddo Lake, i.e., the western area of the lake, it appears that macrophyte growth is excessive. Near the sediment-water interface, dense stands of macrophytes caused low dissolved oxygen, low pH, and high ammonia, especially during times of higher water temperature (Hartung 1983, Cusack 1984, Price 2003). Also, the high biological oxygen demand that was found throughout the lake during the winter months was thought to be caused by the decaying detritus that was produced from the macrophyte die-off. Water hyacinth, *Eichhornia crassipes*, was identified as the problematic macrophyte that caused the conditions of low dissolved oxygen. Recommendations by Paul Price Associates, Inc. were to control this macrophyte through use of chemical treatments and mechanical removal (NETMWD 2005, http://www.netmwd.com/reports/bas.html). Additional invasive species that were found in Caddo Lake that will likely become problematic in the future include giant salvinia, *Salvinia molesta*, and hydrilla, *Hydrilla verticillata* (see CaddoDefense.org). The ecology of these exotic and invasive macrophytes, and management options to control their growth, are discussed in a separate section below.

Nutrient Loading

Trends in nutrient loading are often correlated to observed changes in dissolved oxygen and pH (see Kalff 2005, Wetzel 2001), so the same threats to aquatic organisms and ecosystem functioning mentioned in the *Dissolved Oxygen and pH* section apply here. Fortunately, the two bodies of work that occurred ~30 years ago also measured nutrient concentrations, and therefore provide a reference for us to evaluate changes within the Cypress Creek Basin in response to anthropogenic activities.

Prior to 1977, areas of the Cypress Creek Basin appeared healthy. In Caddo Lake, nutrient levels and water transparency indicated that water quality was good. In fact, nutrient concentrations were so low that productivity assays using filtered lake water failed to support additional growth. Because both nitrogen- and phosphorus-enrichment bioassays stimulated productivity, it was concluded that the lake was both nitrogen and phosphorus limited (Kirkpatrick 1977). Along Big Cypress Creek, where four sewage treatment plants were discharging during a period low water flow, nitrogen and phosphorus levels were high, and the biota were impacted. For example, there was low diversity in the benthic community at stations higher in the creek, and the benthic community was dominated by pollution tolerant oligocheate worms (Twidwell 1977). At stations lower in the creek, however, benthic diversity increased. These data mirror findings summarized above, i.e., anthropogenic impacts were confined to areas located near the sewage treatment plant discharges.

Eutrophication occurred from 1981 to 1993 (Brock 1994), and this likely produced deleterious effects within the Cypress Creek Basin. During the 1980s, the zooplankton community in Caddo Lake was diverse, but dominated by zooplankton species representative of eutrophic conditions (Venneman 1984). Based on benthic organism density and productivity, Caddo Lake was classified as eutrophic, and throughout most of the lake the benthos was dominated by species representative of "poor water quality" (Cusak 1984). It was concluded that these observations probably reflected the high benthic primary and water column plant/algae biomass and productivity due to the shallow nature of Caddo Lake and the sub-tropical climate. Studies in the western areas of the lake produced contradictory findings. For example, good water quality was indicated in Black Cypress Bayou, as evidence by ammonia, nitrate and phosphorus (Twidell 1989). On the other hand, the highest sulfate concentrations were found in the swamp region of Caddo Lake, which probably originated from the sediment-water interface, and phosphorus concentrations were higher, which probably reflected a source coming from Black Cypress Bayou. Both observations led the author to conclude that Caddo Lake was eutrophic (Hartung 1983).

The evidence of deteriorating environmental conditions got stronger with monitoring activities throughout the 1990s. While monitoring of nutrients, i.e., nitrate, ammonia, and phosphate, from 1994 to 1997 along the shoreline of Caddo Lake indicated that nutrients were within natural ranges for waters in east Texas, and revealed no specific water quality problems (Darville et al. 1997), more comprehensive sampling of the lake that was initiated in 1997, which included seasonal sampling and open water stations, revealed high nutrient concentrations that were indicative of poor water quality (Darville 1997, Darville et al., 1998). In regards to nitrogen, Caddo Lake showed a dramatic increasing trend for the period 1997 to 2001 (Darville 2002). It is likely that loading of both nitrogen and phosphorus has increased, but only an increase in nitrogen concentrations was observed because phosphorous limited growth more strongly, i.e., it accumulated in biomass instead of dissolved in water. Phosphorus has been identified as the nutrient most limiting growth, and it was recommended that in-lake total phosphorus be reduced by 44%, which would require a 56% reduction in the loading of total phosphorus (Price 2003).

Nutrients are a concern in the Cypress Creek Basin. Monitoring from 1994 through 1999 indicated that in many areas throughout the Cypress Creek Basin excessive nutrient levels occurred, and that in Caddo Lake, specifically, eutrophication was more advanced than other nearby systems (Price 2000). But in some studies, it was concluded that in-lake nutrient concentrations were not excessive (Darville 2002), and that water quality indices indicated that the lake was at the lower end of the “good” category (Price 2003).

Pollutants

Heavy metals and organic chemical pollutants impact the biota of aquatic systems in regards to both growth and survival. Depending on the potency, and whether the exposure is acute or chronic, pollutants can result in diminished population numbers, decreased species diversity, deformities, and in extreme cases death. In regards to humans, pollutants become a threat when they accumulate in the tissues of recreationally important species that are then consumed, such as large mouth bass. For these reasons, loading and persistence of pollutants in the Cypress Creek Basin are important to understand and manage, if necessary.

Prior to 1977, pollutants were found in the sediments of Caddo Lake (Kirkpatrick 1997). These included high levels of polychlorinadted biphenyls, although the source of these pollutants was not identified, and both lead and zinc, which were found to be above normal for what is expected in natural soils, and again the source of these metals was not identified. Monitoring from 1994 through 1999, indicated that metal toxicity in the sediments of Caddo Lake was a concern (Price 2000). Low species diversity was found in the benthos at stations lower in Caddo Lake, and the off-shore oil wells were suggested as a source of pollution that might be responsible for the low diversity (Cusak 1984). It was also suggested that the impact of oil drilling activities needed further investigation because it might have contributed to the decreased mussel populations in Caddo Lake (Howell 1996). Another study, which focused on the sediments within the western portions of the Caddo Lake National Wildlife Refuge, indicated that multiple metals and organic pollutants, such as organochlorine pesticides, polychlorinadted biphenyls, and dioxins, merited further study and might require remedial efforts (Giggleman and Lewis 2002). Areas of the Cypress Creek Basin are on the State's 303(d) list, e.g., Caddo Lake segment 0404 is listed for elevated levels of barium, manganese, mercury, nickel, and zinc in the sediments, and elevated zinc in the water (Darville et al. 1998).

The oil-producing activities are not the only source of pollutants to Caddo Lake. There is also a potential for pollution originating from the Longhorn Army Ammunition Plant. These pollutants, which include ammonia perchlorate and volatile organic chemicals, were found in high concentrations in streams near the plant, but have not been found at stations in Caddo Lake that are in close proximity to the ammunition plant, i.e., southwestern shore (Price 2004).

Along the shoreline of Caddo Lake, monitoring of zinc and copper in the mid-1990s indicated that these data were within natural ranges for waters in east Texas, and revealed no specific water quality problems (Darville et al. 1997). However, metal pollutants are clearly a problem. For example, the Texas Department of Health issued a fish consumption advisory for Caddo Lake during January, 1995. The advisory recommended that people not consume largemouth bass greater than 18 inches in length, or freshwater drum of any size due to elevated mercury concentrations (Darville et al. 1997). In addition, both selenium and mercury contamination were found to be a problem in fish tissues, which in some instances resulted in banning of certain fish species (Price 2003, Twidwell 2000). In addition to mercury, cadmium, lead, and zinc were also a concern in Caddo Lake (TNRCC 1999).

Loading of Dissolved Organic Carbon

Excessive loading of dissolved organic carbon will impact an aquatic system in a fashion very similar to nutrient loading. In fact, loading of organic carbon is inherently linked to nutrient loading because carbon rich molecules often contain nitrogen and phosphorous atoms as well. For organic carbon loading, however, the situation is more complex than for nutrient loading, in that the bioavailability of the organic carbon is an issue. For example, loading of refractory organic carbon (low bioavailability), which often originates from non-point sources, e.g., runoff over forests and rangelands, does not have as a pronounced effect on biota as loading of labile organic carbon (high bioavailability). Labile organic carbon sources are often at specific locations, e.g., chicken farms and processing plants. Loading of labile organic carbon stimulates bacterial production, which in turn might deplete dissolved oxygen. In such a scenario, it is possible to have large changes in dissolved oxygen even though phytoplankton biomass is not excessive. Another concern is the types of bacteria that are stimulated. Fecal bacterial populations, i.e., coliform and streptococci, are often elevated when the labile organic carbon originates from a source involving animal excrement. When populations of fecal bacteria are high, human health issues become a concern.

In Caddo Lake prior to 1977, levels of organic material indicated water quality was good, e.g., fecal coliform bacteria counts were low (Kirkpatrick 1977). However, fecal bacteria (both coliform and streptococci) contamination appeared to accompany eutrophication that occurred from 1981 to 1993. Maximum counts exceeded 1000 colonies per 100 ml at stations throughout the lake, with maximum values in excess of 10,000 (Brock 1994). Along the shoreline of Caddo Lake, fecal coliform monitoring indicated that significant problems existed in certain areas (Darville et al. 1997). To monitor the lake more thoroughly, a comprehensive sampling was initiated in 1997 that included seasonal sampling and open water stations. For both the monthly monitoring program and the intensive summer monitoring program, high fecal coliform bacteria counts indicated poor water quality (Darville 1997).

What might be the sources of organic carbon loading? Without detailed chemical analyses of the organic carbon, e.g., isotopic analyses, there can be only speculation regarding this issue. It was suggested that chicken farming needed to be investigated because of the fecal bacteria increase, and also because it might be a factor contributing to diminished mussel populations in Caddo Lake (Howells 1996). Loading of materials from poultry farms was indicated to be a concern in Caddo Lake (TNRCC 1999). The oil producing activities might also have had an impact. For example, CO_2 concentrations (evidence of stimulated bacterial production relative to primary production) and chemical oxygen demand were highest in the oil-producing region of the lake due to the large amounts of organic matter in this area, which might have originated from oil spills and oil-contaminated sediments in this region (Hartung 1983).

Phytoplankton

In-water productivity, i.e., photosynthesis originating in the phytoplankton, is essential to foodweb functioning. Carbon fixed (CO_2 converted to organic carbon, which all animals need to sustain life) by phytoplankton often enters the foodweb more quickly and is transferred up the foodweb more efficiently than carbon fixed by submerged macrophytes, or organic carbon entering the lake system from terrestrial sources. But not all phytoplankton species are beneficial to aquatic ecosystems. For example, some species of phytoplankton are inedible, due to their cell size or toxicity characteristics, and their growth leads to unsightly blooms that deteriorate water quality. Other species produce toxins that accumulate in the tissues of larger organisms that upon ingestion pose major threats to consumers. These threats range from fish kills, to avian vacuolar myelinopathy (AVM or “madbird” disease), to nausea/diarrhea, and even cancer, in humans (Whitton and Potts 2000, NWHC 2004, TPWD 2005). Which species proliferate in an aquatic system has been the study of limnologists for nearly 100 years. Of the many physicochemical factors that influence phytoplankton species composition, available nutrients and flows are paramount, i.e., high nutrient and low flow conditions almost always result in proliferation of nuisance taxa. Because the physicochemical environment in Caddo Lake has changed, it is essential that phytoplankton species composition be monitored. Unfortunately, this has not been monitored in recent studies.

In Caddo Lake prior to 1977, dissolved oxygen levels never dropped below minimum standards, and they never exceeded saturation levels. Furthermore, diel changes were small

(Kirkpatrick 1977). This indicated that excessive primary production by accumulation of phytoplankton biomass was not a problem. Chlorophyll *a* levels indicated the lake was mesotrophic, and phytoplankton assemblages were comprised of a diverse mixture of species that included green algae and diatoms, which are not known to comprise many nuisance taxa. Several of the genera present were indicative of “clean” waters.

Along Big Cypress Creek prior to 1977, where four sewage treatment plants were discharging into the creek and water flow was low, the phytoplankton were dominated by cyanobacteria, primarily *Anacystis* sp. (Note that the older classification term, “*Anacystis”*, comprised non-toxic and toxic forms of cyanobacteria, which included *Microcystis*. So it is impossible to discern from this report if toxic species where present at the time of this study). At stations lower along Big Cypress Creek the phytoplankton became more diverse and chlorophyll *a* levels dropped, i.e., <20 µg liter^{-1} (Twidwell 1977). Again, this is consistent with other information that indicated areas of diminished habitat quality were confined to areas located immediately down-flow of sewage treatment plant discharge locations.

Taxonomic details are lacking in recent work. However, there is some information that can be discerned, mostly speculation, using the available chlorophyll *a* data. Within Caddo Lake, chlorophyll *a* levels were not excessive, but they were moderate to high, and occasionally reached 30 µg liter^{-1} (Price 2003). Chlorophyll *a* values were lowest in the swamp region. A spring phytoplankton bloom was absent, and maximum chlorophyll *a* values were found in the summer and fall (Hartung 1983). This latter observation is consistent with a phytoplankton community comprised of less edible taxa, which might include nuisance species. Typically, healthy phytoplankton communities are grazed heavily soon after spring bloom, which leads to a clear water phase in the late spring. Another peak in phytoplankton biomass typically occurs in the late summer. Consequently, in healthy lake systems usually two biomass peaks occur per year. At lower latitudes, this seasonal trend diminishes. In an impaired lake, e.g., a lake plagued by nuisance species, sometimes only one late-year peak will occur. For Caddo Lake, it is unclear whether the observation of only one seasonal peak in phytoplankton biomass that occurred in the late summer/fall was a result of the lake’s lower-latitude, or the proliferation of nuisance taxa.

Nutrient Sources within the Watershed, and Limitations to Nutrient Loading Control

Prior to 1977, there were no wastewater discharges permitted directly into Caddo Lake (segment 0401), but several facilities located in Cypress Creek above Caddo Lake, mostly sewage treatment plants (City of Jefferson probably the most significant), where permitted to discharge, which likely impacted Caddo Lake in terms of high loading of BOD and nutrients (Kirkpatrick 1977). Indirect effects likely originated from agricultural runoff and septic tank effluent.

A Total Daily Maximum Load study was performed for the Lake O' The Pines. This report can be found via the internet (see Paul Price, Associates 2003). The primary findings from this study were that selenium contamination was a problem that had resulted in banning of certain fish species, although the source of the selenium was not mentioned. In addition, it was found that dissolved oxygen was low during the summer months and during times of water stagnation in the upper segments of the reservoir. These low dissolved oxygen events were associated with large diel changes. No conditions of anoxia were reported. Nutrients were listed as a concern, but reported in-lake values, while sometimes high, were not excessive. Nutrient loading focused on total phosphorus, and nearby chicken farms were suggested as likely sources. The recommendation was that in-lake total phosphorus be reduced by 44%, which would require a 56% reduction in the total phosphorus load. Chlorophyll *a* levels were not excessive, but they were moderate to high, and occasionally got up 30 µg liter^{-1}. Inflows were high during the non-summer months, and dissolved oxygen was not a problem during that time.

There are two natural processes that must be understood before implementing the restrictions on total phosphorus loading as recommended in the TDML. Both processes are a form of internal loading (within the lake) that might mask the effectiveness of external total phosphorus loading reductions (see Kalff 2005, Wetzel 2001). The first involves sediment release of phosphorus under conditions of anoxia. This process perpetuates a state of eutrophic conditions in that the released phosphorus becomes available for excessive growth of phytoplankton. The excessive accumulated biomass of phytoplankton eventually dies and sinks. In the bottom waters it then decays, which again results in depletion of bottom water dissolved oxygen. In turn, this prevents the sediments from sequestering the phosphorus, and this nutrient then becomes available for the next phytoplankton bloom. This process can only be circumvented through periods of sustained high-flushing, i.e., the phosphorus must be “washed” from the system. The second process involves rooted macrophytes. Rooted plants often “tap” into the sediments to acquire nutrients that are limiting in the water column, e.g., phosphorus. Invariably, some of the nutrients acquired from the sediments “leak” from the plant into the water-column. This process has been coined the “macrophyte pump”. Control of excessive growth of rooted macrophytes is an effective way to limit this process.

Ecology of Invasive Macrophytes, and Potential Control

There are many sources via the internet that provide basic information regarding the biology and ecology of invasive macrophytes. The information summarized below was drawn from two sources, the Caddo Lake Institute (caddodefense.org/plants.htm) and Texas A&M University Extension Service (http://aquaplant.tamu.edu).

Water Hyacinth

Water hyacinth, *Eichhornia crassipes*, is a free-floating plant that grows up to three feet in height. It has thick, waxy, rounded, glossy leaves, which rise well above the water surface on stalks. The leaves are broadly ovate to circular, 4 to 8 inches in diameter, with gently incurved sides, often undulate. Leaf veins are dense, numerous, fine and longitudinal. Water hyacinth leaf stalks are bulbous and spongy. Water hyacinth grows an erect thick stalk (to 20 inches long) at the top of which is a single spike of several (8 to 15) showy flowers. The flowers have 6 petals, purplish blue or lavender to pinkish, the upper petals with yellow, blue-bordered central splotches. Water hyacinth reproduces vegetatively by short runner stems, called stolons, which radiate from the base of the plant to form daughter plants, and also reproduces by seed. Its roots are purplish black and feathery.sides, often undulate. Leaf veins are dense, numerous, fine and longitudinal. Water hyacinth leaf stalks are bulbous and spongy. Water hyacinth grows an erect thick stalk (to

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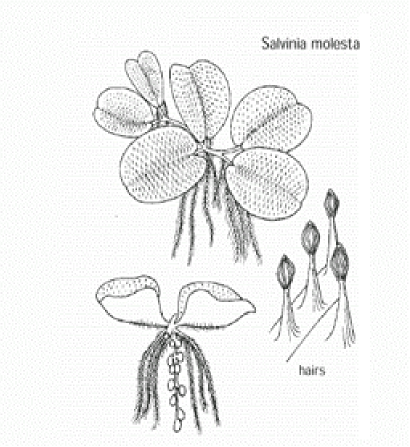
Water hyacinth is native to South American and was introduced into Florida in the 1880s. Unfortunately, it is one of the most invasive macrophytes in the world. Its growth rate is among the highest of any plant known: hyacinth populations can double in as little as 12 days. Besides blocking boat traffic and preventing swimming and fishing, water hyacinth infestations also prevent sunlight and oxygen from getting into the water. Decaying plant matter also reduces oxygen in the water. Thus, water hyacinth infestations reduce fisheries, shade out submersed plants, crowd out submerged plants, and reduce biological diversity. Until only a few years ago, this floating plant was a major problem in Florida (as it still is in many places throughout the world) covering as many as 125,000 acres of water: boat traffic on several rivers was halted; hundreds of lakes and ponds were covered from shore to shore with up to 200 tons of hyacinths per acre.

Now, however, water hyacinth in Florida is under "maintenance control", due to years of concerted effort by local, state and federal water managers. Maintenance control means that plant managers have the plants at a low level, and keep them at a low level using herbicides, machines and biocontrol insects. Without constant vigilance by the many aquatic management agencies in the state, within a year water hyacinths likely would return to infestation levels that would require millions of dollars worth of effort to return to maintenance levels.

Regarding forms of biological control, the first biocontrol insect released against water hyacinth in the U.S. was the mottled water hyacinth weevil (*Neochetina eichhorniae*). Its life cycle is 90 to 120 days, depending on temperature and other factors; both the adults and the larvae feed on various parts of the plant. This weevil was first released in Florida in 1972, and subsequently in several other states. It also has been established in Australia, Fiji, Honduras, India, Malaysia, Papua New Guinea, South Africa, and Thailand and has been released in several other countries. The second biocontrol insect released against water hyacinth in the U.S. was another Neochetina species: the chevroned water hyacinth weevil (*Neochetina bruchi*), first released in Florida in 1974. Its life cycle is shorter than that of *N. eichhorniae*, i.e., its impact is similar. Another biological control insect introduced against water hyacinth is the Argentine water hyacinth moth (*Sameodes albiguttalis*). Its life cycle is only 30 days; the larvae are the only life state that feeds on the plant. It was released and is established in Florida, Louisiana and Mississippi, as well as in Australia, South Africa and Sudan. It may retard growth in the early stages of water hyacinth mat development. Not all biocontrol insects are exotic to the U.S. The larval stage of *Bellura densa* (formerly *Arzama densa*), a native southern U.S. moth commonly known as pickerelweed borer, also attacks water hyacinth. Efforts were made in the early 1980s to augment natural populations of the moth's larvae in an effort to cause an impact on water hyacinth plants in Louisiana. Unfortunately, there was little impact.

Giant Salvinia



Giant salvinia, *Salvinia molesta*, is native to South America. It is a small free-floating plant that grows in clusters and develops into dense, floating mats or colonies in quiet water, undisturbed by wave action. The floating leaves of giant salvinia are oblong (1/2 to 1 1⁄2 inches long) with a distinct midrib along which the leaf may fold forming a compressed chain-like appearance. Salvinias have stiff leaf hairs on the upper surface of the leaves. In giant salvinia the leaf hairs have a single stalk that divides into four branches that reconnect at the tip, giving the hair a cage-like or egg-beater appearance. Underwater the leaves are modified into small root-like structures. The entire plant is only about 1 to 2 inch in depth. Salvinias are ferns and have no flower. Giant salvinia has sporangia but are thought to reproduce only by fragmentation. It can double in size in 4 to 10 days under good conditions, and it is an aggressive invader species. Dense salvinia colonies provide habitat for micro invertebrates, but if colonies cover the surface of the water, then oxygen depletions and fish kills can occur. In addition, these colonies will eliminate submerged plants by blocking sunlight penetration. Salvinias have no known direct food value to wildlife and is considered an exotic and highly undesirable species. Salvinias are not native to North America and it is illegal to possess

Hydrilla

Hydrilla, *Hydrilla verticillata*, is a perennial plant that forms dense colonies and can grow to the surface in water over 20 feet deep. Hydrilla branches profusely and after reaching the surface it extends across it forming thick mats. Hydrilla can reproduce by fragmentation, from seeds, from turions (axilary buds), and from tubers. Leaves are blade-like about 1/8 inch and 3/8 inch long with small tooth margins and spines on the underside of the midrib, which make them feel rough. Leaves are usually 4 to 8 in a whorl.

Hydrilla is native to Europe and Asia and was probably brought to the U.S. for the aquarium industry. It is considered a noxious pest because it grows so rapidly, out competing and eliminating native species, and forming surface mats that hinder recreation, navigation, and water intakes.

Hydrilla is often confused with the native Elodea or the non-native Egeria. Hydrilla has one or more teeth on the underside of the midrib, neither Elodea nor Egeria have these midrib teeth. The teeth make Hydrilla feel rough when drawn through your hand from base to tip. Flowers of Hydrilla are much smaller (1/4 inch in diameter) than Egeria.

Submerged portions of all aquatic plants provide habitats for many micro and macro invertebrates. These invertebrates in turn are used as food by fish and other wildlife species (e.g. amphibians, reptiles, ducks, etc.). After aquatic plants die, their decomposition by bacteria and fungi provides food (called “detritus”) for many aquatic invertebrates. Hydrilla turions and tubers are consumed by some ducks but generally it is not considered a good wildlife food. Hydrilla is not native to North America and it is illegal to possess or transport it within Texas.

Managing Nuisance Aquatic Plants

Again, there are many sources via the internet that provide basic information regarding the control of invasive macrophytes. The information presented below was drawn from web pages maintained by the Texas Parks and Wildlife Department, and can be found at www.tpwd.state.tx.us/fish/infish/vegetation/plant_control.phtml.

Management of nuisance aquatic vegetation in public water is regulated under the State Aquatic Vegetation Plan. Under the plan, a treatment proposal must be filed with the Texas Parks and Wildlife Department and the controlling authority for the lake or stream in question. Treatment proposals are not required for private water, but treatment with a restricted or limited-use herbicide requires certification from the Texas Department of Agriculture. Control options fall into four basic categories: mechanical, environmental, biological, and chemical (herbicides). Each method has advantages and disadvantages. Factors to consider include effectiveness, cost, availability, ease of application, potential environmental consequences, and whether special permits are required.

Mechanical Control

Draglines, cutters, rakes, booms, mechanical harvesters and bottom barriers are common tools for vegetation management and control. Mechanical controls don’t require the introduction of chemicals to the environment, and some people prefer them for that reason. On the other hand, mechanical methods tend to be labor-intensive and costly.

Large floating species such as water hyacinth can be removed by harvesting or shredding. Marginal plants can often be controlled by cutting, especially if cutting starts early in the growing season. Cutting machines may also be used on submergent and emergent vegetation, but regrowth may occur, making it necessary to cut several times in a single growing season. With species like hydrilla, which can grow from fragments, it’s important to remove cuttings from the water; otherwise, fragments may grow in areas that were previously uninfested. In small areas, control may be achieved by pulling up young plants in the early spring.

Bottom barriers can inhibit the growth of submerged and emergent plant species. Semi-permeable material should be used in order to avoid a buildup of gases underneath the barrier that can lift it off the bottom.

Environmental Control

Reshaping the shoreline to eliminate long gradual slopes and reduce the amount of shallow water is one way to reduce shoreline vegetation. Shallow water is especially conducive to plant growth. It warms up first in spring, and sunlight reaches all the way to the bottom, inviting young plants to grow. Lowering the water to allow excess vegetation to dry out or freeze in winter can also be effective. This technique is used in some large, public reservoirs.

Biological Control

Stocking sterile triploid grass carp or white amur (*Ctenopharyngodon idella*) is a popular method of biological control. Young grass carp are voracious vegetarians. Under certain conditions, they have been known to eat 50% to 300% of their body weight per day. Feeding rates drop in older fish, but remain substantial at 25% per day or more. The grass carp's preferred food, hydrilla (*Hydrilla verticillata*) is one of Texas' most problematic submerged plant species. However, these fish will eat nearly anything green, and should be used with the understanding that they could potentially consume all the vegetation in a pond or lake. Because grass carp are included on the state list of harmful or potentially harmful exotic species, a permit from TPWD is required for stocking.

Insects have been used to manage some plant species. For example, alligator weed (*Alternanthera philoxeroides*), can often be controlled by the alligator weed flea beetle (*Agasicles hygrophila*), which affects only this species. Insects are also available for control of hydrilla, water hyacinth, and giant salvinia. (also see text in previous section).

Chemical Control

Farmers have long used herbicides to control weeds in their fields, and there are herbicides that work on aquatic weeds as well. Copper sulfate has been in use since 1904. Chelated copper compounds are often preferred today, as they are slightly less toxic to fish and approved for use in drinking water. Organic herbicides became available for aquatic weed control in the 1940s with 2,4-D (2,4-dichlorophenoxyacetic acid), followed by diquat, endothall, glyphosate, and fluridone. Each chemical is sold under several brand names. Only those brands registered and approved by the United States Environmental Protection Agency for aquatic use may be legally used to control aquatic vegetation.

Herbicide is seldom a permanent solution. Many plants have seeds or tubers that are not killed by the chemical and live to sprout another day. With that caveat, most herbicides work best when plants are actively growing. They should be applied in the spring after water temperatures reach 60 to 70ºF. However, precautions must be taken in warmer months to prevent oxygen depletion. As treated plants decay, the level of dissolved oxygen in the water decreases. If it drops too low, a fish kill can result. To minimize this effect, severe infestations covering more than half the water body should be treated in stages.

Adjuvants and surfactants are commercially available compounds that help chemicals disperse more evenly and/or provide better leaf penetration. These additives should be used when recommended on the herbicide label. Finally, product specimen labels should be read carefully for water use restrictions, application rates, health and safety precautions, and applicability to the plant species being treated. Improper use of pesticides may endanger people, livestock, and fish and wildlife resources.

Caddo Lake Water Quality and Ecology Under Varied Hydrologic Conditions

High-Inflow

The impact of inflows will vary with time of year. For example, high inflows during the summer months when temperatures are highest and dissolved oxygen and pH are lowest will be the most beneficial. This is also true in regards to flushing of nutrients (see Figure 16). As mentioned in a previous section, internal nutrient loading from sediments might mask the impact of restrictions of external nutrient loading, and the only way to circumvent this process would be to increase flushing of the lake during periods when nutrients are fluxing from the sediments. It should be noted that even if nutrient concentrations are excessive, high inflows can maintain good water quality.

In regards to nuisance and potentially harmful phytoplankton species (keeping in mind that it still needs to be investigated whether nuisance taxa are a current problem in Caddo Lake), their prevalence will likely be greatest in the summer months. Because these species are characteristic of low growth rates, high flushing losses will greatly reduce their abundance. How much flow, and for how long, is enough? Without in-lake experiments, and without knowing what species are present, it is difficult to answer. But if we assume that lake flushing between 0.1 and 0.2 d^{-1}, sustained for a period of one to two weeks, would be enough to impact the nuisance taxa, then for Caddo Lake this would be equivalent to inflows ranging between 4,000 to 8,000 cfs. This back-of-the-envelope calculation assumes that the total volume of the lake, i.e., 80,000 acre-ft, is well-mixed.

Of course, higher flushing rates would be better. Growth rates of nuisance taxa typically range between 0.3 and 1.0 d^{-1}, while growth rates of more beneficial forms are often >1.0 d^{-1}. Therefore, inflows in the range of 40,000 cfs, e.g., what used to occur in this system before dam construction, would very efficiently remove nuisance taxa and leave the more quickly growing, more beneficial, phytoplankton forms.

It is unclear from available data whether high flushing during winter and spring months will have a strong impact on summer months, i.e., when water quality conditions are likely to be the lowest. Initial conditions, e.g., community composition during the winter and early spring, are known to sometimes greatly effect water quality and ecology during the summer. Sometimes minute changes early in the season have profound impacts on the late season characteristics of the system. So, it would be well worth investigating this relationship because it may reveal additional management strategies not necessarily linked to inflows.

Conditions of high inflow are not likely to alleviate problems associated with rampant growth of macrophytes, even if they are mostly floating species. As recommended before, control options involving mechanical removal and application of chemicals seem more practical.

Intermediate and Low-Inflows

Lower inflows will obviously not flush nutrients from Caddo Lake as quickly as higher inflows. For the same reasons mentioned above, intermediate and low flows will be more effective at flushing nutrients from the system during the summer months (see Figure 16). Low inflows would likely have very little impact on alleviating potential problems associated with low dissolved oxygen and pH. In other words, during conditions of low inflow Caddo Lake will likely be plagued by periodic conditions of poor water quality until the system has underwent oligotrophication (removal of nutrients associated with a decrease in system trophic state). Flushing losses to the phytoplankton that would result from intermediate and low inflows, e.g., $<0.025\ d^{-1}$ that would occur at inflows of ~1,000 cfs, would not have a strong impact on the prevalence of nuisance taxa.

Lake Draw-Down

In other systems, lake draw-down was an effective way to control rampant growth of submerged macrophytes. This management technique works because it exposes the sediments containing the underground biomass of the macrophytes to the atmosphere. When the sediments dry, the underground portion of the macrophytes die (see Figure 16). After the lake is refilled the macrophytes will eventually re-establish themselves. But that process might take years depending on the prevalent species.

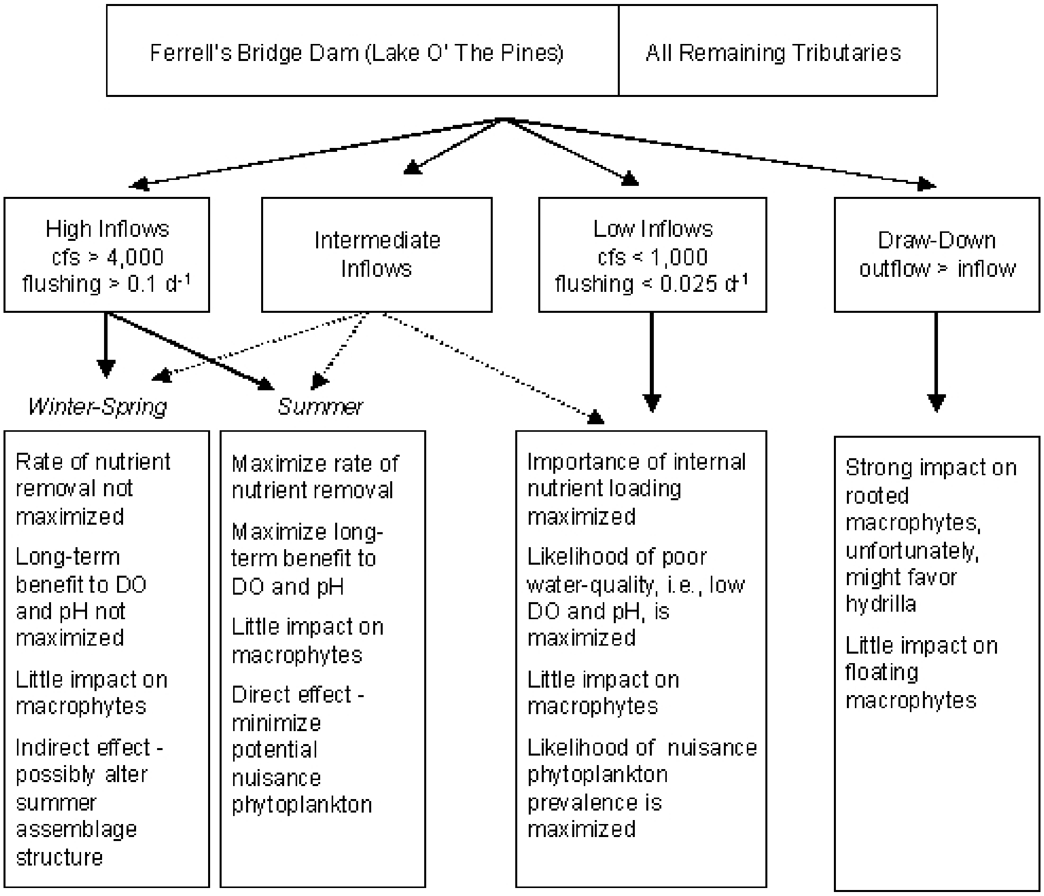


Figure 16. Response from water quality parameters and aquatic plants to different levels of inflow

For Caddo Lake this might not be an option. For example, water hyacinth is a floating macrophytes species. It is very likely that the plant will move with the changing shoreline as the wind blows it along. Even more troubling is the presence of hydrilla. This rooted macrophyte does not yet seem to be problem in Caddo Lake, but it might be one day. Hydrilla is quick growing and has a wide tolerance for changing water depths. While exposing hydrilla's underground biomass to the atmosphere will kill the plant, along with other submerged and rooted macrophytes, after the lake is refilled hydrilla will likely be the first macrophyte species to return. Because it is such an efficient competitor, it is likely that the other indigenous macrophytes will not return.

FLOODPLAIN VEGETATION

Bottomland Hardwood/ Bald Cypress Swamps

Bottomland hardwood/bald cypress swamps can be found along floodplains of rivers in nutrient-rich, mineral-dominated soils. In many cases, these are jurisdictional wetlands under Section 404 of the Clean Water Act (U.S. Army Corps of Engineers, 1987). These forests are also typically characterized by their unique morphological and physiological adaptations to the wetland environment such as trunk buttressing, pneumatophores (i.e. knees), a well-oxidized rhizosphere, and a dependency on water for seed dispersal. In the U.S. these forests range from as far north as Illinois down to the Mississippi Delta and from the south Atlantic coastal plain to central Texas. This broad range of coverage facilitates comparison of community structure and function across areas of dramatically different climatic patterns. However, in nearly all cases, riparian hydrology is among the most critical environmental drivers for these wetlands (Allen et al. 2004).

Big Cypress Basin & Greater Caddo Lake Area

In the Big Cypress Basin and around the greater Caddo Lake area, bottomland hardwood and bald cypress forests occupy an elevation gradient from low areas that are permanently inundated to higher areas that are infrequently inundated, yet may still have saturated soils. Campo (1986) described two forest types under the bottomland hardwood forest group. These include the mixed hardwood bottomland forest at the higher elevation end and a bald cypress swamp/ flooded hardwood forest category at the lower end (Campo 1986). Similarly, Walker et al. (1998) described the two main forest types in this region: bottomland hardwood forest (BLH)—which occupies the "higher" elevation areas that grade away from the stream edge—and bald cypress forest—a pioneer forest that develops in saturated soils, but can withstand extended periods of deep flooding at the adult phase.

Using more site-specific criteria and multivariate statistical tools, Van Kley and Hine (1998) combined field and remote-sampling techniques to identify four distinct community types in the same general area. These community types ranged from bottomland oak flats to open cypress swamps, at the deeper end. More recently, Changxiang et al. (2005) divided the latter category into bottomland hardwoods—that often contain bald cypress—and swamp/bald cypress—that are dominated by bald cypress and are found in the lowest elevations occupied by these forest types. They also included a willow/birch category that includes the narrow fringe (about 100 m wide) of woody species found along the channels and at the interface of the river and lake (Changxiang et al. 2005). See Table 7 for a list of the most common tree species found in each of these zones in the Big Cypress Creek watershed and around Caddo Lake (species list compiled from Campo 1986, Walker et al. 1998, Van Kley and Hine 1998, and Changxiang et al. 2005). Additionally, the Savannah River report by Meyer et al. (2004) and the USGS report by Allen et al. (2004) provide excellent species lists for these forest types and descriptions of the habitat, flood/shade tolerance, and seed dynamics for each of these species (see Table 14 in Meyer et al. 2004; Chapter 4 in Allen et al. 2004). Lastly, Townsend (2001) presents an excellent multivariate statistical analysis of the relationship between hydroperiod (spring and annual) and vegetation patterns for many of these same tree species in the Roanoke River system, North Carolina.

These floodplain and shallow water forests dominate the eastern third of the Big

Cypress Basin near Caddo Lake, but only comprise about 3.3% of the entire system (Changxiang et al. 2005). After comparing their findings to a set of images shot in the early 1970s, Changxiang et al. (2005) showed that there has been a 33.9% reduction in the acreage of these bottomland hardwood and bald cypress forests. This trend coincided with an increase in deep water bodies (e.g. Lake Bob Sandlin) and agricultural land and might also be due in part to the heavy logging activity in this area's recent past (Changxiang et al. 2005). Walker et al. (1998) noted that some bottomland hardwood areas containing isolated (i.e. older trees that pre-date the original formation of Caddo Lake) bald cypress individuals have likely experienced changes in hydrologic regimes. In other words, where conditions were once suitable for bald cypress establishment and growth, they are now relatively drier (i.e. shallower depth, more frequent soil exposure) and more suitable for bottomland hardwood forest development (Walker et al. 1998).

Table 7: List of common tree species and their corresponding zone of distribution in the Big Cypress/Caddo Lake Floodplain. Adapted from Campo 1986, Van Kley & Hine 1998, and Changxiang et al. 2005.

Common Name	**Scientific Name**	**Vegetation Zone**
American elm	*Ulmus americana* L.	Bottomland hardwood – Bald cypress/hardwood – Willow/birch
American hornbeam	*Carpinus caroliniana* Walt.	Bottomland hardwood – Bald cypress/hardwood
Bald cypress	*Taxodium distichum* (L.) Rich.	Bald cypress/hardwood – Bald cypress swamp
Black willow	*Salix nigra* Marsh.	Willow/birch
Chinese tallow*	*Sapium sebiferum* Roxb.	Bald cypress/hardwood
Deciduous holly	*Ilex deciduas* Walt.	Bottomland hardwood – Bald cypress/hardwood
Green ash	*Fraxinus pennsylvanica* Marsh.	Bottomland hardwood
Loblolly pine	*Pinus taeda* L.	Bottomland hardwood
Overcup oak	*Quercus lyrata* Walt.	Bottomland hardwood

Table 7 cont.

Common Name	**Scientific Name**	**Vegetation Zone**
Pecan	*Carya illinoensis* (Wangehn.) K. Koch	Willow/birch
Red maple	*Acer rurbum* L.	Bald cypress/hardwood – Willow/birch
River birch	*Betula nigra* L.	Willow/birch
Sugarberry	*Celtis laevigata* Wild.	Willow/birch
Swamp Tupelo	*Nyssa sylvatica* var. *biflora* Marsh.	Bottomland hardwood – Bald cypress/hardwood – Willow/birch
Sweetgum	*Liquidambar styraciflua* L.	Willow/birch
Water elm	*Planera aquatica* L.	Baldcypress/hardwood
Water hickory	*Carya aquatica* (Michx. F.) Nutt.	Bottomland hardwood – Bald cypress/hardwood
Water oak	*Quercus nigra* Marsh.	Bottomland hardwood – Bald cypress/hardwood – Willow/birch
Water tupelo	*Nyssa aquatic* L.	Bald cypress/hardwood
Willow oak	*Quercus phellos* L.	Bottomland hardwood

* Invasive exotic species.

Forest Ecology

It is widely accepted that the structure and function of alluvial river swamps is tightly coupled with hydrologic energy and fertility (Conner & Day 1976; Mitsch et al. 1979; Mitsch & Ewel 1979; Lugo et al. 1988; Townsend 2001). In fact, hydrology is the single most important factors affecting the local distribution of bottomland tree species within their natural ranges (Allen et al. 2004). In alluvial settings, these forested wetlands receive periodic disturbances in the form of a flood pulse that is important in delivering nutrients and altering soil physico-chemical properties to the point that upland species are excluded (Mitsch et al. 1979). The high flows typical of these events are also important in scouring and dispersing many of the seeds produced in alluvial river swamps. By connecting the river to the floodplain, flood events also provide habitat and a significant source of energy for aquatic consumers (Junk et al. 1989; Mitsch & Gosselink 2000). Given this reliance on riparian hydrology, it should come as no surprise that these forests are sensitive to human perturbations that dramatically alter spatial and temporal patterns of floodplain inundation.

Seedling Recruitment

The key to the establishment and long-term maintenance of these forests is through seedling recruitment. Without periodic, successful recruitment of new seedlings, these systems may be more susceptible to large-scale human perturbations. In a sense, species like bald cypress are like classic pioneer species in that they establish following a hydrologic disturbance (i.e. when water levels change dramatically)—in this case a drawdown. Although it can survive and persist under relatively stable conditions of flooding, bald cypress is a poor competitor at the drier, shallow water end of the hydrologic spectrum in spite of its requirements for seed germination. Many of the species in Table 7, including bald cypress (*Taxodium distichum*), swamp tupelo (*Nyssa sylvatica* var. *biflora*), and water tupelo (*Nyssa aquatica*) are considered hydrochoric in that they are dependent upon flooding water for seed dispersal (refer to Table Meyer et al. 2004 and Chapter 4 in Allen et al. 2004). Although floodwater is required for seed dispersal, a sufficient drawdown—creating oxic conditions at the soil surface—is necessary for the germination and establishment of these species (Keeland 1996, Keeland and Conner 1999).

For most of the species found in these forests, seeds are released in late summer (usually between September and October; Allen et al. 2004, Meyer et al. 2004). For the Caddo Lake region, this period historically was the dry season and corresponded with low flows in the Big Cypress Creek basin. Rapid growth—from seed germination–seedling stage—up to the next flood pulse (usually in late winter/early spring) was needed for the successful establishment of a new cohort of saplings in the forest. These conditions prevailed up to the installation of the dam for Lake O' the Pines in late 1959, when the late winter/early spring pulse signal was captured by the dam, significantly diminished in magnitude, and spread across the entire spring. It has been suggested that seedling recruitment has been depressed in some areas of the Big Cypress and Caddo Lake region as a result of hydrologic alterations such as these (see ***Past Impacts*** below). In a study of the importance of hydroperiod on seed germination and establishment, Keeland (1996) found that overall survival in the permanently inundated areas after 1 year was 61% compared to the periodically flooded area that showed survival > 90%.

Growth and Productivity

Growth of bottomland hardwoods and bald cypress are often studied in relation to their hydrologic regime. This is because the overwhelming body of evidence linking increased productivity of some of these species to timing and frequency of flooding, duration of inundation, or depth of flooding (Conner and Day 1976, Mitsch et al. 1979, Keeland and Sharitz 1995, Keeland et al. 1997, Keeland and Conner 1999 among others). Flushing and aeration of soils, delivery of sediment and nutrients, and elimination of upland competitors are some of the more important hydrologically influenced factors that promote increased productivity in these types of forests. Impacts of diminished pulse magnitude and increased duration of inundation are described below (see *Past Impacts*).

Competition and Herbivory

Competition with upland species is an ongoing process and intensity of competition is expected to increase during dry years or when hydrologic modifications have reduced pulse magnitude, resulting in the subsequent reduction in floodplain area (Walker et al. 1998, see *Past Impacts* below). These swamp forest species are typically poor competitors when growing in upland conditions, therefore competition is likely to result in the exclusion of these species in the marginal areas of the floodplain, leading to reduced seed availability and recruitment.

Herbivores such as tent caterpillar, beaver, nutria, and swamp rabbits also warrant consideration and continued monitoring as to their impact on bottomland hardwood/bald cypress ecosystems. However, current evidence indicates their influence on forest structure and function is minimal in comparison to the effect of hydrologic processes (Walker et al. 1998, King et al. 1998). Still, the long-term implications of herbivory are not well understood nor are the historical changes in herbivore densities of over time. Further, there is hardly any understanding of the interaction between hydrology (including hydrological modifications) and herbivory. Keeland (1996) found no herbivory on seedlings in flooded treatments, indicating that flooded or periodically flooded seedlings may be better protected from herbivores than those in upland areas. However, seedling growth rates were higher significantly higher in upland and periodically flooded treatments, suggesting a potentially important interaction between hydroperiod and herbivory (Keeland 1996).

Past Impacts

Historical impacts on bottomland hardwood and bald cypress forests need to be considered when assessing the potential effects of hydrologic restoration for a few reasons. First, of all wetland types, freshwater swamps have been most affected by human activity, with less than 25% remaining in the United States since settlement (King and Keeland 1999, Mitsch and Gosselink 2000). Allen et al. (2004) even mention that East Texas and the Lower Mississippi Alluvial Valley have experienced the greatest losses in these wetlands. As such, it needs to be understood that current conditions in these forests have already been shaped to a great extent by human activity in both the past and present. Further, any future hydrologic modifications may have compounding and unexpected effects, as a result of these past modifications to the system.

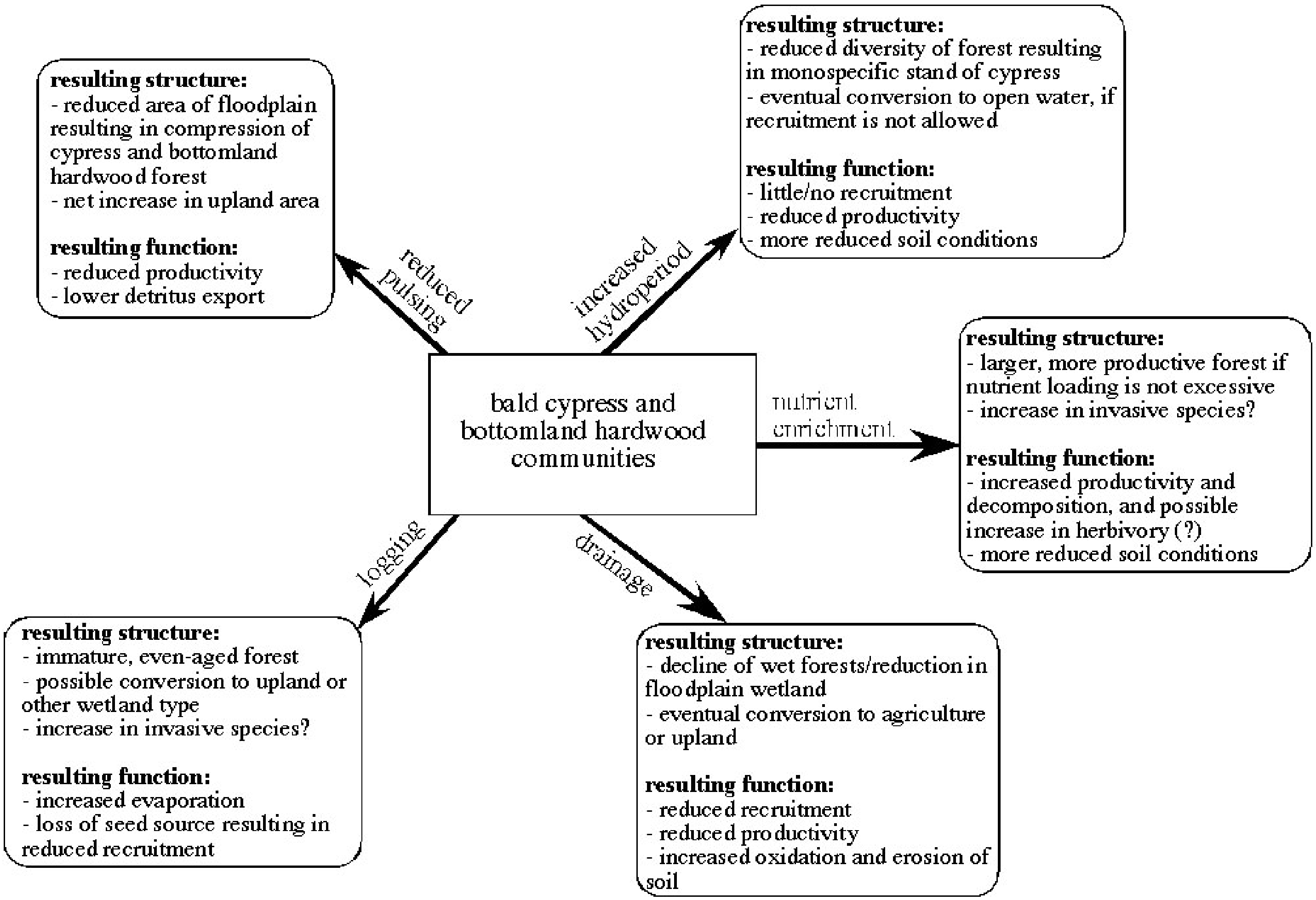
Second, from a restoration standpoint, past impacts to the system will set spatial or temporal constraints on restoration goals. Changes in floodplain shape/area, species composition, water and soil quality, and atmospheric conditions brought about over the recent past may be impossible to restore to pre-settlement conditions. In the development of restoration targets or goals, successful restoration projects will consider limitations imposed by past impacts, recognizing that the ecosystem's "original" or pre-settlement state will never be achieved. Additionally, restoration goals should be adaptively assessed as conditions change—either through the attenuation of past impacts to the system or through future modifications. For example, human activities such as logging and drainage of these wet forests have declined in the recent past, but their long-term impact may still prevail across this region. Through time, these impacts may attenuate if some aspects of the hydrology were restored and the forest community reaches some equilibrium state.

Figure 17 provides a conceptual model of the hypothesized effects of past impacts (such as logging, drainage, nutrient enrichment, increased hydroperiod, and reduced pulsing) on bottomland hardwood/bald cypress ecosystem structure and function. Many of these concepts are supported by data collected from original research. These studies are referenced where appropriate.

Logging

Logging of these forests was most intense from the late 1800's up to the early-1900's (Mitsch and Gosselink 2000). Obviously logging activity has immediate, direct effects on forest structure in that it converts a more mature forest ecosystem into a more immature system by removing the older, taller trees. Logging also artificially selects for the least desirable timber species to succeed in the short-term by removing the more desirable timber species (especially bald cypress). However, over the long-term, logging can produce an even-aged forest of low diversity that is more susceptible to perturbation or species invasion.

Figure 17: Past and current threats to cypress and bottomland hardwood forests and hypothesized impacts on forest structure and function.



The effects of logging on wetland function are many-fold, but the direct impacts to the forest could result in changes in species-specific seedling recruitment as a result of a change in seed availability.

Selective harvesting of the older, taller trees also creates light gaps in the canopy that can facilitate establishment of new seedlings and enhance the atmospheric component of the system's water budget. During the dry season, the latter may be extremely important in controlling evapotranspiration rates and levels of soil saturation. This could have significant implications for the ecosystem when considering that changes in a site's water balance (rainfall minus ET) can be more important than changes in water level across a hydrologic gradient in terms of its affect on bottomland hardwood and bald cypress tree growth (Keeland and Sharitz 1997).

Drainage

Drainage, no doubt, has also had a significant impact on bottomland hardwood/bald cypress forests in the Big Cypress Basin. Drainage can come about directly as the result of ditching and channeling of water out of natural depressions (sloughs, oxbows, etc.) across the floodplain and was often associated with logging activity or conversion to upland for agricultural use—the latter being the primary cause for bottomland hardwood loss in the United States (Allen et al. 2004). [Drainage can also be the indirect result of an upstream impoundment. The impact of this hydrologic modification on alluvial river swamp structure and function will be described below.]

The short-term effects of drainage on wetland function can be reduced seed dispersal and recruitment, reduced productivity, and increased soil oxidation, paving the way for upland species to move in. Drainage also has the effect of converting an ecosystem that was once a net sink for nutrients and sediment to a net source of both as drainage and subsequent erosion increases (Brinson 1988). The long-term consequence of logging and drainage in the Big Cypress Creek watershed has been shown by the reduction in bottomland hardwood and bald cypress forest area and the subsequent rise in pasture and farmland (Changxiang et al. 2005).

Reduced Pulsing

As indicated earlier for Big Cypress Creek and Lake O' the Pines outfall and has been shown in other systems, impoundments change the peak flow and discharge rates of water, oftentimes resulting in higher flows during the historical low water periods and lower flows during the historical high water periods (Petts 1977, Hadley et al. 1987). For bottomland forests, the most critical effect of impoundments is the reduction in pulse magnitude. The immediate effects of this can be found in the change in productivity of species like bald cypress, that tend to have highest rates of primary productivity in pulsed environments. Next, reduced pulsing effectively compresses the area of a given river's floodplain. Given sufficient time, the result of this will be a conversion of the periphery of the historical floodplain to upland. Wetland hydrology and subsequent changes in the physico-chemical properties of wetland soils are the primary environmental filters that allow for the establishment of wetland vegetation. Since many wetland plants (including some of the tree species in Table 17 are poor competitors in upland environments, these species will eventually be eliminated as flood pulses are diminished. Refer to Middleton (1999, pp 13-22) for an excellent review of the of impoundment effects on hydrological, geochemical, and biological processes at upstream and downstream areas.

Increased Hydroperiod

In areas upstream of an impoundment, increased hydroperiod (i.e., depth and duration of flooding) results from water backing up against the dam. This situation also applies, although to a much lesser extent, in some areas downstream of an impoundment, where hydroperiod has been artificially extended as a result of the higher outflows during the dry season (described above). Inundation over short intervals is important in structuring these different communities, but mean depth may be most important in determining rates of primary productivity for species such as bald cypress, that occupy the entire range of inundation (Keeland & Sharitz 1995). In looking at seasonal growth trends and the relationship with hydroperiod for three bottomland species, Keeland & Sharitz (1995) found that *Nyssa sylvatica* var. *biflora* seemed least sensitive to changes in water levels. *Nyssa aquatica* grew best under conditions of deep periodic flooding, and *Taxodium distichum* grew best in shallowly flooded sites, regardless of duration (Keeland and Sharitz 1995).

Extended periods of inundation (i.e., decades to centuries) can effectively reduce diversity in bottomland hardwood and bald cypress forests, as species less tolerant to extended durations of flooding and saturation are eliminated from the community. In extreme cases, monospecific stands of bald cypress are the resulting product as this species is most tolerant to extended flooding. This can also be facilitated by functional changes in primary productivity and soil conditions (Keeland et al. 1997). Moreover, with the lack of a drawdown, recruitment of bald cypress is inhibited and the forest may eventually (over several generations) revert to an open water ecosystem (Schneider and Sharitz 1986, Keeland and Young 1997). Although Keeland & Young (1997) point out that water management in the Caddo Lake region has not resulted in an overall decline in bald cypress growth, they do point out that stable water levels have yielded little or no forest regeneration over the period of water management. They also note that there was no observed recruitment during the period of their study (Keeland and Young 1997).

Nutrient Enrichment

Nutrient enrichment is another impact to these forests that continues even to the present day. It can be the result of agricultural runoff (in many cases from converted floodplain ecosystems), urban storm water runoff, or even as direct loading for the purpose of municipal wastewater treatment. Regardless of the source, nutrient enrichment tends to have cumulative effects in nature. However, the long-term change in bottomland hardwood/bald cypress forest ecosystem structure and function brought about by nutrient enrichment is not well understood. Long-term data from a municipal wastewater treatment wetland in coastal Louisiana suggest that bottomland hardwood forests can effectively process nutrients loaded over a relative extended period of time (50-yr) and that these loadings have consistent, positive impacts on forest productivity and wetland sustainability (Day et al. 2004). However, studies from other wetland ecosystems would suggest that nutrient enrichment can lead to an ecosystem-wide reduction in nutrient-use efficiency and that nutrient processing by swamp forests cannot be sustained at these levels without some degree of management (Lugo et al. 1988; Mitsch & Gossleink 2000). Further, evidence from other wetland ecosystems suggests that shifts in ecosystem structure and function would result from excessive nutrient loading (Nichols 1983; Davis 1994).

Recommendations for Future Water Management

Allen et al. (2004) stress that hydrology must be restored to approximate some historical pattern of flooding before a bottomland restoration project can be considered complete. As such, current and future water managers in the Big Cypress/Caddo Lake watershed need to consider the role of hydrology in driving these ecosystems and should strive to simulate historical water level, flood pulse timing, and flood pulse magnitude as much as possible. This will be crucial to the sustainability and perhaps re-establishment of bottomland hardwood/bald cypress forests across this watershed.

Our recommendations call for pulsed high flows to occur during the historic early spring flood pulse period. These high flows will scour and distribute seeds to a large area of the floodplain and should start to decline into late spring, bottoming out in early summer. Low flows in Big Cypress Creek during the historical dry summer will then be needed to allow for the establishment (i.e. germination) of seeds and growth to a level at which many will be able to survive the following year’s spring high water period. Periodic draw down in Caddo Lake will also be important in recruiting a new generation of bald cypress to this perennially lentic environment.

If current conditions persist, we will likely witness a reduction in numbers of bottomland trees, as historical areas of the Big Cypress Creek floodplain are converted to upland forest due to competitive exclusion. Meyers et al. 2004 point out that the lack of a winter flood may be critical in allowing the successful invasion of upland species and exotic species such as the Chinese tallow tree in the Savannah River floodplain. This invasive bottomland species has also been documented in the floodplain of Big Cypress Creek and may continue to proliferate under current management schemes. However, if water management at the outfall of Lake O’ the Pines mimics a more natural hydrologic pattern, we should expect to see a re-expansion of the floodplain and a subsequent retreat of the upland forest community and perhaps this invasive species. In this system, as is the case for all other systems of this type, low flows (resulting in the drawdown of water in the floodplain) during the dry season are needed to allow for seedling establishment and recruitment of younger trees to the forest. Pulsed, high flows, on the other hand serve to scour and distribute seeds, deliver nutrients and sediment to the floodplain, and flush wetland soils—removing soil toxins and increasing soil redox—allowing for typical, high rates of primary productivity in these forests. This reconnection to the floodplain also has significant implications for numerous faunal species that inhabit these areas.

Evidence suggests that successful results of hydrologic restoration efforts can be immediate or, at most, can take up to a few growing seasons to observe. For example, Keeland and Conner (1999) found significant bald cypress seedling establishment following 44 years of flooding and no recruitment in Lake Chicot, Louisiana. This recruitment coincided with a good seed crop from the previous growing season. They also indicated that there was little competition from other species and that this was also a key to successful bald cypress regeneration in these types of areas. In situations where water levels are routinely managed, drawdowns should be of sufficient duration (a few weeks to a few months) to allow for seedling establishment and maximum water levels should not exceed average seedling height in order to maximize regeneration success (Keeland and Conner 1999). Meyer et al. (2004) echo this notion in their report for the Savannah River. Regardless of the amount of time it takes to restore forest species in bottomland hardwood/bald cypress areas, a monitoring program should be implemented in order to ensure the long-term success of the project and to track the restoration trajectory of bottomland ecosystem structure and function.

AQUATIC FAUNA

Effects of Flow Regime on Big Cypress Creek/Caddo Lake Basin Fishes

General Fish Ecological Responses to Flow Variation in Southern Lowland Rivers

Fishes obviously depend on instream flows to provide aquatic habitats in which to live, but there are many other direct and indirect effects of water availability, flow characteristics, and water quality on fish behavior and ecology (Figure 18). In lowland floodplain rivers, such as the major tributaries that deliver water to Caddo Lake, the annual hydrological regime greatly influences the quantity, quality, and connectivity of aquatic habitats that are required by the various fish species during each stage of their life cycles. This complex subject has been reviewed extensively (e.g., Junk et al. 1989, Agostinho and Zalewski 1994, Bayley 1995, Ward et al. 1999, Dettmers et al. 2001, Galat and Zweimüller 2001, Scheimer et al. 2001a, Amoros and Bornette 2002), yet many crucial aspects of most of the world's river ecosystems remain very poorly understood. For example, rivers of the Gulf coastal plain of the southern U.S. support high taxonomic diversity represented by diverse life history strategies, yet the means by which this diversity is maintained in face of high environmental variation is largely unknown. This paucity of knowledge about ecological mechanisms and species responses to environmental variation is what led Poff et al. (1997) to propose the "natural flow regime" paradigm as a means to conserve biological diversity and essential ecosystem functions in the face of incomplete knowledge and uncertainty (see also Sparks 1995, Arthington et al. 2005). Lowland rivers and their floodplains are among the most perturbed natural ecosystems on Earth, and impacts in developed countries of Europe and North America have been particularly severe.

Although fishes of southern coastal-plain rivers display diverse life-history strategies, most populations of virtually all species are dependent or enhanced by floods that connect aquatic habitats of the main channel with those lying in depressions on the floodplains. Floods of short duration allow fishes to move back and forth between channel and floodplain habitats. Floods of short duration can also carry significant

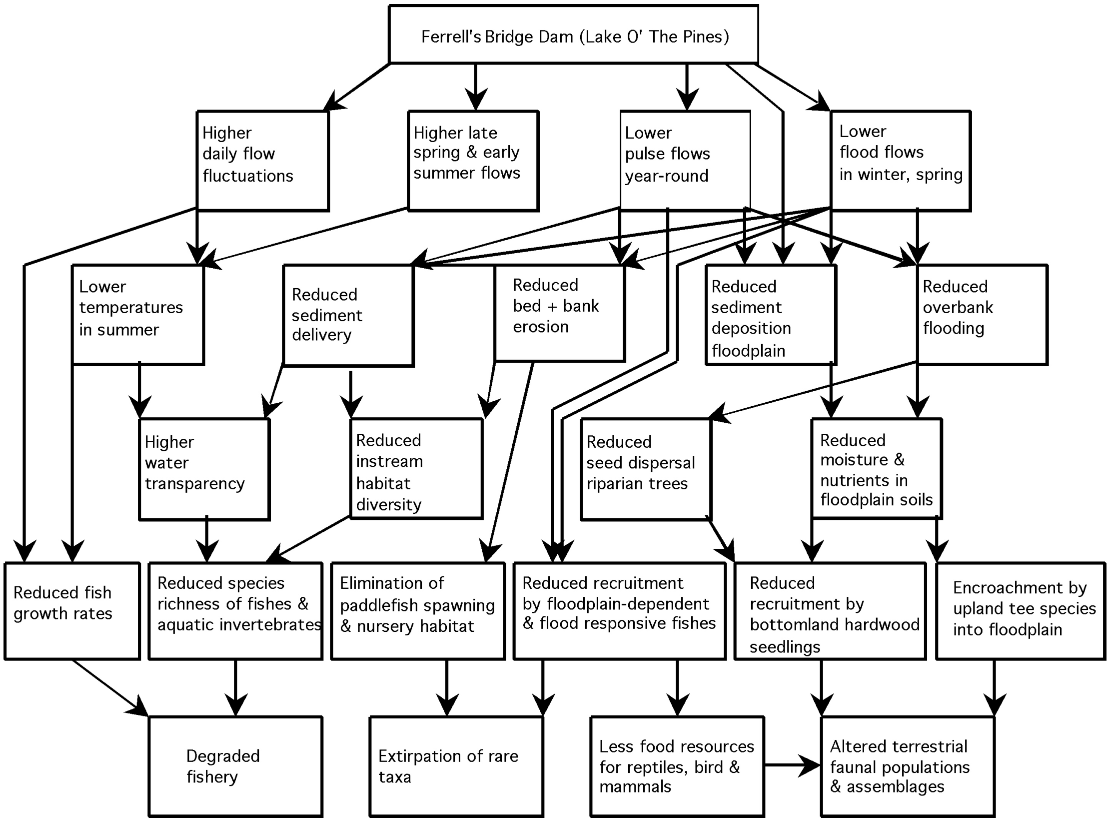


Figure 18. Conceptual scheme of flow sensitive components of the Big Cypress Bayou system

amounts of sediments and nutrients into floodplain habitats like oxbow lakes and sloughs (Tockner et al. 1999). Floods of longer duration may create greatly expanded lentic habitats that provide excellent foraging opportunities for adult and juvenile life stages (Agostinho and Zalewski 1994, Bayley 1995, Winemiller 1996, 2005, Ward et al. 1999, Winemiller et al. 2000). Abundance of larval (Turner et al. 1994, Killgore and Baker 1996) and juvenile (Turner et al. 1994) fishes is greater in floodplain habitats than connected backwater habitats of the main-stem river channel. Larval fish abundance in marginal, bottomland hardwood forests of the Cache River, Arkansas, was greater during a year with a higher spring flood compared with a year with a lower flood (Killgore and Baker 1996). In general, floods of longer duration tend to yield greater levels of fish recruitment in lowland rivers (Agostinho and Zalewski 1994).

Almost all of the literature sources that specifically deal with the aquatic fauna of Caddo Lake are agency reports based on surveys of aquatic habitats of the Big Cypress Bayou/Caddo Lake Basin, fishes (several reports), herpetofauna and waterfowl (few reports), and mussels (few reports). Hubbs (2002) lists 86 fish species for Caddo Lake region, with an additional 17 that could occur in the basin given information reported in range maps. Four fish species are listed as exotics to the basin, although it is unclear if the white bass is exotic or native, and two (walleye and striped bass) appear to have never established populations. The basin contains four fish species that are considered threatened by the Texas Parks and Wildlife Department, but none are listed as threatened by the US Fish and Wildlife Service (Hubbs et al. 1991), and thus do not fall under the protections of the Federal Endangered Species Act. One of these threatened fishes, the paddlefish, was extirpated from the basin in the late 1950s-early 1960s following construction of Ferrell’s Bridge Dam on the Big Cypress Bayou. The principal fishery concern is stocks of game fishes, a few of which were evaluated for instream flow requirements (white bass, channel catfish, spotted bass). The methods and estimates of instream flows needed for fish stock maintenance (status quo) were relatively crude and based on limited data (mostly obtained from other regions of the country), and these initial estimates were viewed with a high degree of skepticism in a review by the Espey, Huston and Associates (1987). Perhaps the most notable current fishery problem in the basin is the occurrence of periodic fish kills in the upper reaches of Caddo Lake during the late summer and early fall period when warm water temperatures and decomposition of aquatic macrophytes causes aquatic hypoxia. The Texas Parks and Wildlife Department stocks Caddo Lake with fingerling sport fish most years.

The fish fauna of the Big Cypress/Caddo Lake Basin can be divided into three groups: 1) fishes directly dependent on flowing channel habitats, 2) fishes directly dependent on non-flowing backwater habitats, and 3) fishes not directly dependent on either flowing or backwater habitats but which may use either to varying degrees. Of course virtually all of the fish species in the basin are indirectly dependent on instream flows that create habitat structure and maintain essential ecosystem processes. Appendix D designates membership in each group within the “habitat dependent” column. Species assignments among the three categories follow Schramm (2005). In addition, a fourth group—migratory species—deserves special comment. Only six species are considered longitudinal migrants, and four of these species have not been collected from the Caddo Lake catchment since the mid 1950s (3 spp.) or early 1960s (1 sp.).

Fishes directly dependent on flowing channel habitats (6 spp.)

This group contains few species, but some of them are important either because they are now rare (paddlefish), or because they are common in the regional fish fauna (river carpsucker, freshwater drum, scaly sand darter). The paddlefish is also considered a migratory species and is listed as threatened in Texas (see below).

Two species of hiodontid fishes (goldeye, mooneye) have not been captured in any of the regional surveys conducted since 1950, and it appears likely that these species were never present in the Big Cypress Basin. They appear to have been listed on some species lists for the basin because range maps place them at the edge of their geographic range within the region. Hiodontids inhabit the largest rivers within the Mississippi River Basin, and it seems unlikely that they ever have occurred in the upper Big Cypress Basin.

Most of the species in this group also use non-flowing backwater habitats either for foraging or as nursery areas for larvae and/or juveniles. Nonetheless, these species are dependent on flowing channel habitats for spawning habitat and environmental cues that trigger spawning behavior. Adult scaly sand darters (*Ammocrypta vivax*) occur over clean sandy substrates in slow-moderate current velocities (Robison and Buchanan 1988).

Fishes directly dependent on non-flowing backwater habitats (50 spp.)

Fishes in this group may inhabit non-flowing habitats, such as backwaters connected to the river channel or oxbow lakes disconnected from the channel, throughout their life cycle (e.g., most sunfishes, pickerels, and mosquitofish) or during a particular stage of the life cycle (e.g., larval and early juveniles of longnose gar, red shiner, and smallmouth buffalo). Many of the species in the first subgroup are abundant in Caddo Lake.

Fishes not directly dependent on either flowing or backwater habitats (37 spp.)

Species in this group can complete their life cycle either in lentic backwater habitats or in flowing-water habitats without major access by larvae, juveniles or adults to backwater habitats. Some of these species occur in larger rivers (e.g., blue, channel and flathead catfishes), but most of them (e.g., blacktail shiner, creek and lake chubsuckers) typically inhabit smaller tributary streams where flow conditions are highly variable and access to flooded marginal habitats may be limited relative to larger lowland rivers (Ross and Baker 1983). The smaller streams of the Big Cypress Basin have not been surveyed extensively, and information about the distribution and abundance of stream fishes is consequently poor. Moreover, detailed life history accounts and other ecological information is generally lacking for most of the small species that inhabit low-order streams of the basin. Many of the species in this group (30 spp. listed in Appendix D) use backwater habitats regularly, and thus would be expected to respond positively to flow regimes that enhance or improve access to these habitats.

Migratory fishes (6 species)

All six of the migratory fishes of the Big Cypress/Caddo Lake Basin undergo longitudinal movements during their life cycles. The chestnut lamprey undergoes annual migrations into small tributary streams for spawning. After spawning, the adults die and juveniles drift and migrate downstream to larger channel areas where they burrow into sandbanks and filter feed. The chestnut lamprey has not been reported as collected since 1964, however the species is very cryptic and targeted sampling is required to collect the immatures from sandbanks. It seems likely that sufficient longitudinal connectivity remains within the watershed to support the chestnut lamprey.

Relatively little ecological information has been collected for the paddlefish. The best available field information on reproduction is based on research conducted in the Osage River in Missouri (Purkett 1960). Given the seemingly rapid disappearance of paddlefish from Caddo Lake following construction of Ferrell's Bridge Dam (creating Lake O' The Pines) in the late 1950s, it is apparent that the longitudinal gradient of lotic channel habitat now present in the system is insufficient for paddle fish spawning and/or larval transport to nursery habitats in backwaters. The skipjack herring has spawning requirements similar to the paddlefish and also seems to have been eliminated from the catchment in the late 1950s, probably for the same reasons.

The American eel is catadromous, with a complex life cycle that has been well documented on the eastern seaboard of North America. Adults spawn in the region of the Sargasso Sea, and larvae develop in pelagic waters of the Atlantic Ocean. Young elvers migrate to estuaries and make their way upstream variable distances (in some cases hundreds of kilometers) as they metamorphose into young eels. Juveniles remain in rivers and tributary streams for several years before undergoing their spawning migrations. Dam construction has reduced the distribution and abundance of American eels in many regions (Robison and Buchanan 1988). American eels have not been collected in surveys of the Big Cypress/Caddo Lake Basin since the mid 1950s.

The other two migratory species in the catchment are the white and yellow basses. These species migrate upstream during early spring to spawn in mid-lower reaches of tributary streams. The yellow bass is reported to be less migratory than the white bass. Both species support sport fisheries in the lake. White bass are not as abundant as yellow bass, and the former are caught mostly during fall and winter. Though abundant, yellow bass attract little angler interest due to their relatively small size. Striped bass were reported on one regional species checklist (US Fish and Wildlife Service 1993), but no records were found that could confirm stocking or collection during surveys. The striped bass is an anadromous species native to the eastern seaboard of North America, but it has been widely stocked in reservoirs throughout the United States to support pelagic sport fisheries. Hybrid striped bas (*M. chrysops* x *M. saxatilis*) have been stocked into Caddo Lake and Lake O' The Pines for over a decade. Because these hybrids are sterile, their population is entirely supported by stocking. The freshwater drum could be considered a possible seventh "migratory" species that, in some systems (e.g., reservoirs) may undergo small-scale movements (e.g. relative to *Morone* spp.) into tributary rivers for spawning. Similarly, the skipjack herring may migrate longitudinally in large rivers, possibly for spawning. Some reports consider the species a diadromous species that moves between rivers and estuaries (e.g., Hubbs 2000), but this does not appear to be the case in many systems (Robison and Buchanan 1988).

Fish Species Not Collected in Regional Surveys Since the Early 1960s

Review of the available literature (see Caddo Lake Annotated Bibliography) reveals that several fish species reported as present in the Big Cypress Bayou/Caddo Lake Basin have not been collected during recent surveys. Of greatest interest are species that were collected prior to the construction of Ferrell's Bridge Dam (1955-1959) but not collected since the early 1960s or even earlier (i.e., paddlefish). Given that low-order streams of the region have been surveyed only sporadically, some of the stream species not collected in recent years may persist within the catchment, but perhaps were not captured due to insufficient sampling effort given their low abundance or restricted spatial distribution.

Migratory species not collected since the early-mid 1950s**:** paddlefish, American eel, skipjack herring. The pre-1950 abundance of the American eel and skipjack herring in the region is unknown and may have been low. Paddlefish supported a commercial fishery in Caddo Lake as late as 1950 (Texas Game and Fish Commission 1954).

Migratory species not collected since the early 1960s: chestnut lamprey.

Species at the western edge of their geographic ranges, probably were present in low abundance, and not collected since the mid-late 1950s: alligator gar, shortnose gar, river darter.

Species inhabiting low-order creeks, rare or patchily distributed, and not collected since the late 1950s-early 1960s: creek chubsucker, blacktail redhorse, slough darter, goldstripe darter, redfin darter.

Species reported for the basin (probably based on range maps) but never confirmed in surveys: goldeye, mooneye, blackspot shiner, black buffalo, striped bass (the latter is an exotic species often stocked in reservoirs).

Flow Effects on Selected Fish Species

A literature search on flow effects on Big Cypress Creek/Caddo Lake fishes yielded site-specific information relevant to the issue of environmental flows for only a few of the 85 species native to the system. The primary sources of this information were reports by Cloud (1984), Espey, Huston & Associates (1987), and US Fish and Wildlife Service (1993). Brief summaries/assessments of the information in these reports appear below. The present summary of fish responses to instream flow variation will focus primarily on a few indicator species that are either riverine or backwater dependent and that attract attention due to status as a threatened species or sport fish.

Flow-Dependent Indicator Species – Listed as Threatened in State Waters

1. Paddlefish (*Polyodon spathula*)

Paddlefish are one of two living species (the other relict taxon is found in the Yangtze River in China) belonging to the primitive family Polyodontidae. This strange-looking and primitive group of fishes is related to the sturgeons (the two families constituting the order Acipenseriformes). Paddlefish are filter feeders that use their huge mouth and comb-like gillrakers to strain zooplankton and aquatic insects from the water column. Because they lack scales, paddlefish are often referred to as “spoonbill catfish” in some regions, however they are very distantly related to catfishes as well as all of the other more recently derived bony fishes. In eastern Texas (Red, Sulphur, Big Cypress, Sabine, Neches, Trinity Rivers), the paddlefish occupies the southwestern extent of its full geographic range (major rivers of the Mississippi Basin). The species has been greatly reduced in abundance and distribution due to pollution and especially construction of dams that block migration routes, regulate flow, and alter channel geomorphology and substrate composition (Figure 19). The ecology and conservation status of paddlefish were reviewed by Dillard et al. (1986) and Pitman (1991). The species was considered extirpated in Texas (Hubbs et al. 1991).

A reproducing population of paddlefish in Big Cypress Creek and Caddo Lake that supported a small commercial fishery apparently was extirpated following construction of Ferrell’s Bridge Dam (1955-1959). The Texas Game and Fish Commission (1954) reported findings from a survey of commercial fishermen and the principal buyer on Caddo Lake during the period Nov. 1, 1953- Oct. 31, 1954. Although buffalo were the most abundant species in the fishery (41.7 % of catch by weight), paddlefish were collected during half of the months of the survey. The average retail market price of paddlefish ($0.15 per pound undressed) was the lowest among the 7 commercial species reported (others ranged from $0.25 to $0.40). Subsequent gillnet, hoopnet, and seine-net surveys in Caddo Lake and surrounding region over the following four decades yielded no paddlefish. In 1994 and 1998, TPWD stocked 14,745 fingerling paddlefish into Caddo Lake, but no evidence of reproduction has been observed in the system. A few of these stocked paddlefish have been captured in recent agency surveys. Robison & Buchanan (1988) cited Purkett (1961) for the following information on paddlefish reproduction in the Osage River, Missouri:

> “Spawning occurs in early spring when the river is high and muddy. The adults move upstream into swift currents over gravel bars when the water temperature reaches about 60°F (15.7°C). Spawning takes place in midstream over the gravel substrate and the adhesive eggs stick to the first object they touch, normally stones on the stream bottom. After hatching, the fry are swept downstream out of the shallows into deep pools.”

When a new dam blocked access by pre-spawn paddlefish to a limited number of gravel bars in the Osage River, all natural reproduction in the system stopped (Lyons 1992). A large stocking program now maintains the Osage River paddlefish fishery.

Paddlefish spawn irregularly, even when adequate spawning habitat is available (Lyons 1992). Paddlefish spawn in the spring when water levels rise rapidly and the temperature is between 50 and 65° F. After the larvae develop for an unknown period within deep pools of the main channel, the juveniles either passively transported by currents or actively move into backwater (lentic) habitats that serve as nursery areas. In most large rivers, these backwater habitats seem to be oxbow lakes and other permanent off-channel water bodies. In this sense, Caddo Lake probably functions much like a giant oxbow lake that is permanently connected to the river. Paddlefish populations persist in some southern reservoirs, even exhibiting somatic growth rates higher than individuals from river populations, but they require access to lotic river habitats (affluent channels located upstream) in order to reproduce (e.g., Paukert and Fisher 2001).

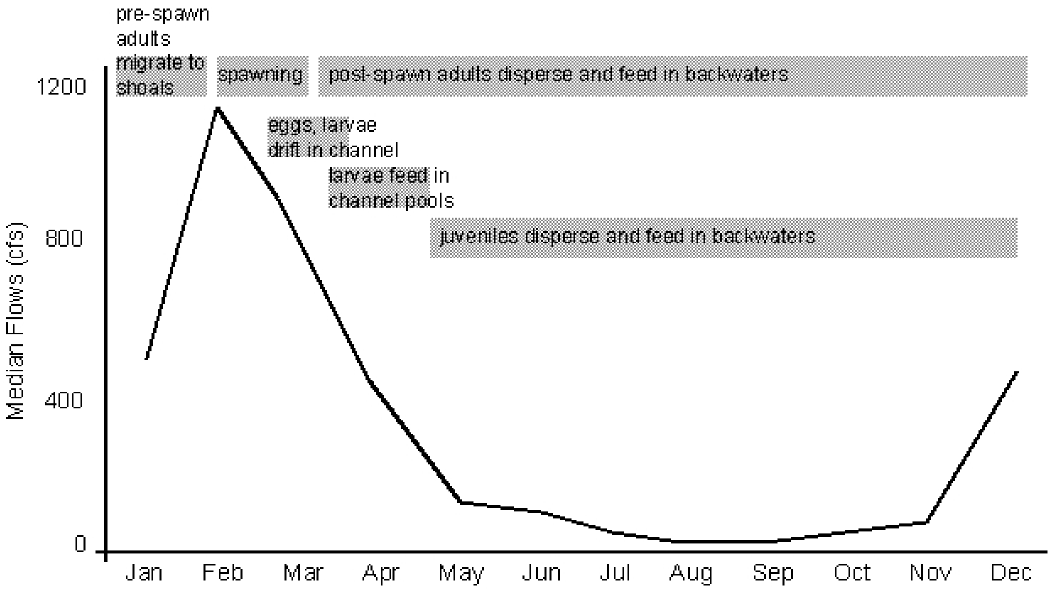


Figure 19. Paddlefish (flow dependent riverine species) life cycle in relation to seasonal flow (relative to pre-1957 median flows in Big Cypress Bayou).

In the Upper Mississippi River, paddlefish in pre-spawning condition were captured between March 1 and April 10, 1981 when the river was rising (discharge 800-2,600 m^3/s) and temperature as less than 13°C (Southall and Hubert 1984). Spawning occurred between April 11 and May 25 at peak discharge (peaks of 2,800 and 3,000 m^3/s) and temperatures between 13 and 19 °C. From May 26 to June 22, when water was decreasing (fluctuations around a mean of 1,200 m^3/s) and temperature was 20-24 °C, post-spawn paddlefish were captured. Summer discharge in this river reach fluctuated around a mean of 1,000 m^3/s in 1980 and 1,800 m^3/s in 1981. Paddlefish mostly used tailwater and river channel areas plus one backwater slough. Paddlefish often congregated below man-made structures where there were eddies and reduced current velocities.

Paddlefish grow about 50 inches (1.27 m) during the fist ten years of life, after which their growth rate slows to about 2 inches (0.05 m) a year. According to Becker (1983), an average of 7 years are required for males to attain sexual maturity (4-9 years according to Lyons [1992]) whereas females require nine to ten years (as many as 12 years according to Lyons [1992]). Paddlefish would be characterized as having a periodic life history strategy in which large, long-lived females produce huge clutches of eggs each year (a large female may contain more than 500,000 eggs), only a very small fraction of which would survive to maturity even under ideal environmental conditions. For periodic strategists, successful recruitment that sustains the population would normally occur only periodically—perhaps only one or two years—during the lifetime of an organism that may live 20 or more years (Winemiller and Rose 1992).

It appears likely that paddlefish were extirpated from the Caddo Lake catchment when construction and/or operation of Ferrell's Bridge Dam (Lake O' The Pines) on Big Cypress Bayou either caused the loss of shoals essential for spawning, or interrupted the hydrological regime required for triggering spawning, transport of eggs and larvae, or maintenance of connectivity between the river channel and backwater habitats used as paddlefish feeding and nursery areas. The fact that no evidence of paddlefish reproduction exists following reintroduction of the species in 1994 and 1998 supports this hypothesis. Spring flood flows have been greatly curtailed in Big Cypress Bayou, and this may have eliminated cues and conditions needed for spawning. In addition, the lack of scouring floods probably has destroyed shoal habitats that almost certainly were limited in extent within this relatively short river reach lying above Caddo Lake. It is unknown if the historical spawning shoals were located above or below the current location of Lake O' The Pines. Because little detailed information is available regarding spawning and the ecology of paddlefish, it may prove difficult to make a recommendation regarding instream flows to restore a self-sustaining population under existing constraints.

Flow-Dependent Indicator Species – Sport fish

2. Chain pickerel (*Esox niger*)

The chain pickerel is widely distributed throughout the eastern and southeastern United States. In eastern Texas, the species occupies the far western extent of its geographic range. The chain pickerel occurs in clear, non-flowing waters of lakes, rivers and streams of the Gulf coastal plain. In Arkansas, the species spawns during late

February and early March when the water temperature reaches 45-50°F. Eggs are scattered in vegetation in shallow water, and no parental care is provided afterward. This species requires lentic habitats for all stages of its life cycle (Figure 20). The species lives a maximum of 8-9 years (Robison and Buchanan 1988).

The chain pickerel remains a minor but significant species in the Caddo Lake sportfishery. Because it prefers shallow vegetated waters where it can ambush prey, it is susceptible to adverse impacts (including mortality) during periods of acute aquatic hypoxia in the upper reaches of Caddo Lake. In recent years, aquatic hypoxia has occurred in this region of the lake during late summer and early fall when high temperatures and decomposition of aquatic macrophytes result in high microbial respiration that depletes dissolved oxygen from the water column. Chain pickerels and other fishes that are unable to emigrate from these regions become trapped with resulting fish die offs.

In terms of instream flow requirements in Big Cypress Creek, the chain pickerel would benefit from flow regimes that maintain permanent aquatic habitats in the floodplain. Periodic pulse flows would be important for dispersal of juvenile and adult pickerels among lentic (backwater) habitats along the margins of the main channel as well as within the floodplain. Given that the chain pickerel thrives in lakes throughout its range, pulse flows do not appear to be a requirement for triggering spawning behavior by this species.

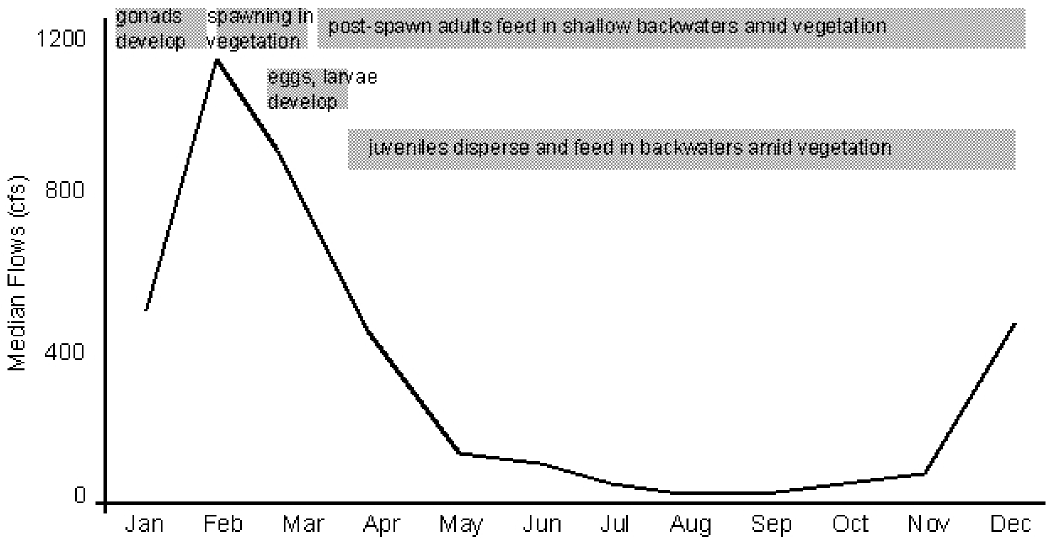


Figure 20. Chain pickerel (backwater-dependent species) life cycle in relation to seasonal flow (portrayed relative to pre-1957 median flows in Big Cypress Bayou).

3. Largemouth bass (*Micropterus salmoides*)

The largemouth bass has ecological requirements similar to those of the chain pickerel, however it is much more widely distributed (both within its natural, and introduced range) and occupies a greater range of habitats. By most accounts, the largemouth bass is the most popular freshwater sport fish in North America. As a result, it is one of the best-studied fish species in the world (e.g., Stroud and Clepper 1975, Stuber et al. 1982). The largemouth bass nests in backwater areas lacking current, either along river or stream margins or in floodplain habitats such as oxbow lakes (Figure 21). In Arkansas, the species spawns from April until June, with spawning initiated when the water temperature rises above 65°F. Following deposition of eggs into the nest constructed by the male, the male fertilizes and guards the eggs. The male continues to guard the larvae and postlarvae for one to several weeks. The normal growth rate for adult largemouth bass is about 450 g per year, but growth is highly variable depending on region and habitat (Stuber et al. 1982). The maximum life span is 15 years.

In the Big Cypress/Caddo Lake system, the largemouth bass is influenced by essentially the same water quality and flow issues that affect the chain pickerel (e.g. aquatic hypoxia in the lake, maintenance of aquatic habitats in the floodplain, dispersal opportunities). Caddo Lake provides an outstanding habitat for this species, which would only be enhanced by maintenance of a flow regime on Big Cypress Creek that maintains oxbows and other permanent lentic habitats in the floodplains and facilitates dispersal.

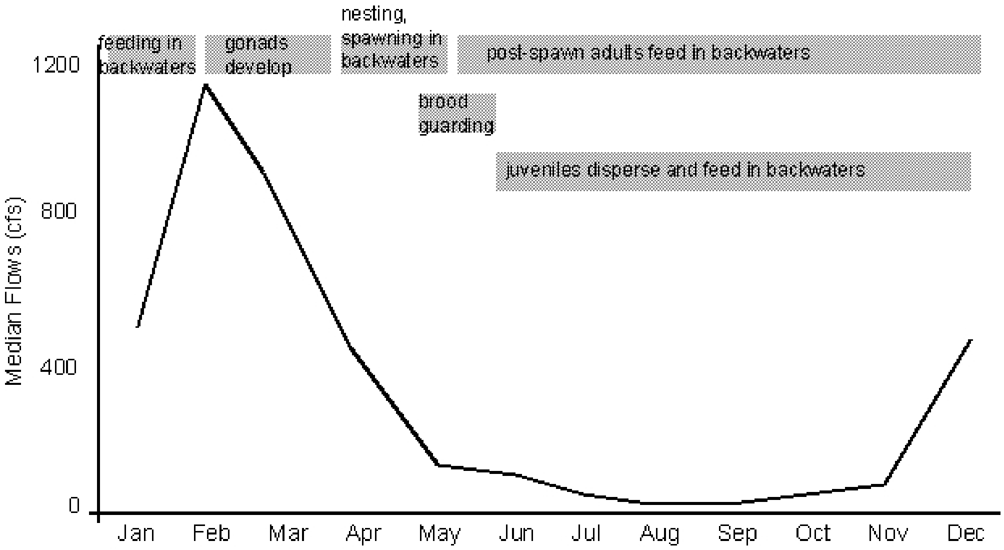


Figure 21. Largemouth bass (backwater-dependent species) life cycle in relation to seasonal flow (portrayed relative to pre-1957 median flows in Big Cypress Bayou).

4. Freshwater drum (*Aplodinotus grunniens*)

The freshwater drum, or gaspergou, is broadly distributed throughout the Mississippi River and Great Lakes basins. In Texas the species occurs in all major river drainages. This is the only freshwater representative of the Sciaenidae in North America (the redfish and speckled seatrout are marine representatives on the Gulf coast). Adults usually range from 12-20 inches (30-51 cm) and up to 5 lbs. (2.3 kg). Individuals of 60 lbs. have been recorded historically (Robison and Buchanan 1988), but like so many fish species, such large sizes are unheard of today. This species occurs in pools of medium to large rivers and large reservoirs where it feeds on benthic invertebrates ranging from microcrustacea to mollusks.

In Arkansas, the drum spawns during April or May, and in the upper Mississippi River spawning occurs when the water temperature is 66-72°F (18.9-22.2°C)(Robison and Buchanan 1988). At this time, adults move from rivers or reservoirs into tributary streams where males produce a drumming sound that presumably attracts and courts receptive females. The species spawns in the water column near the surface (sometimes observed at the surface) and releases from 43,000 to over 500,000 eggs per clutch. Eggs are buoyant and float with the current for 1-2 days before hatching. Larvae float at the surface for an additional 1-2 days, and at 25 mm the postlarvae move to the bottom where they begin feeding as juveniles. Thus, the freshwater drum has flow requirements for spawning and dispersal of early life stages that are very similar to those described for paddlefish. Because of the benthic feeding mode of juveniles, the freshwater drum may be less dependent on access to (connectivity with) aquatic habitats in the floodplain. There seem to be few reports of juvenile freshwater drum from permanent floodplain habitats, although adults are sometimes captured there. At least in the short-term, freshwater drums probably benefit from extended periods of low flow conditions during summer, because these promote benthic secondary production and hence foraging opportunities.

Non-Flow-Dependent but Flow-Responsive Species - Threatened

5. Bluehead shiner (*Notropis hubbsi*)

The bluehead shiner has a limited geographic distribution in northeast Texas, southwest Arkansas, and northern Louisiana. According to Robison and Buchanan (1988), this small minnow inhabits “quiet backwater areas of small to medium sized sluggish streams and oxbow lakes (Bailey and Robison 1978)”. This species is typically found in tannin-stained water containing dense stands of submerged aquatic plants. The substrate of its habitat is mud or a mud-sand mixture. This minnow schools in backwaters and marginal areas away from significant current. The species is reported to migrate upstream to spawn in Ouachita drainage streams, and individuals have been taken from the main stem of that river during various periods of the year (Robison and Buchanan 1988). Based on the presence of tuberculate males (indicating prespawning or spawning), the species appears to spawn from early May to July. Juveniles have been collected in early June. Females mature at one year and 47 mm standard length. A single female examined by Burr and Warren (1986) contained 781 mature eggs. The species appears to live a maximum of 2 yrs.

The blueheaded shiner was collected at multiple locations during the USFWS (1993) survey that have targeted smaller tributary streams of the Big Cypress/Caddo Lake Basin. Given the narrow habitat preference of this species (non-flowing stream margins), it appears that late spring and early summer low flow conditions may be most conducive to successful spawning and recruitment by this rare species. Nonetheless, its presence in oxbow lakes reveals a necessity for periodic over-bank flows allowing dispersal between channel and oxbow habitats.

Non-Flow Dependent but Flow-Responsive Species - Nonthreatened

6. Bigmouth buffalo (*Ictiobus cyprinellus*) and smallmouth buffalo (*Ictiobus bubalus*)

The two common buffalo species of the Big Cypress/Caddo Lake Basin are representative of those fish species that do not seem to be strictly dependent on flow regime (either for spawning cues or for access/maintenance of critical habitats), but nonetheless may reveal enhanced recruitment under appropriate flow regimes. These large catostomids are considered roughfish that are exploited by commercial net fishermen in some regions of North America. Both species have broad diets, but the bigmouth buffalo tends to be more planktivorous (a filter feeder) than the benthivorous smallmouth buffalo. Both species occur in a wide variety of flowing and non-flowing habitats, with the smallmouth buffalo occurring in a greater range of habitats. Both species are distributed throughout the Mississippi River Basin. The smallmouth buffalo is distributed throughout Texas (excluding the panhandle), whereas the bigmouth buffalo is restricted to the northeast corner of the state. The bigmouth buffalo is believed to be more tolerant of turbid water than the smallmouth buffalo. The bigmouth buffalo can tolerate aquatic hypoxia (dissolved oxygen concentration of about 1 mg/l). The smallmouth buffalo lives up to 15 years, and sexual maturity is attained at 2-3 years. The smallmouth buffalo from 2 to 15 lbs are common, and the record size is 68 lbs (Lake Hamilton, Arkansas, 1984; Robison and Buchanan 1988). Bigmouth buffalo are reported to attain up to 80 lbs, but are generally less than 20 lbs.

In Arkansas, both species initiate spawning in April. The bigmouth buffalo spawns through May, and the smallmouth buffalo may spawn through June. Both species spawn in shallow, lentic backwaters over vegetation. The smallmouth buffalo also may spawn over non-vegetated substrates. According to Robison and Buchanan (1988), spawning by the bigmouth buffalo is initiated after spring floods raise water levels. Eggs of the smallmouth buffalo are broadcast and hatch after 10 days. No parental care is provided by either species. Juveniles of both species are common in aquatic floodplain habitats. Smallmouth buffalo adults, postlarvae and juveniles were common in oxbow lakes of the Brazos River, Texas (Winemiller et al. 2000). Thus, it appears that floodplain habitats provide important nursery habitats for these species, and spring floods that transport (or permit migration) of early life stages into floodplain habitats would be expected to enhance recruitment and populations of these species (Figure 22). Pulse flows during spring or other periods of the year would allow dispersal of immature and adult individuals between channel and floodplain habitats.

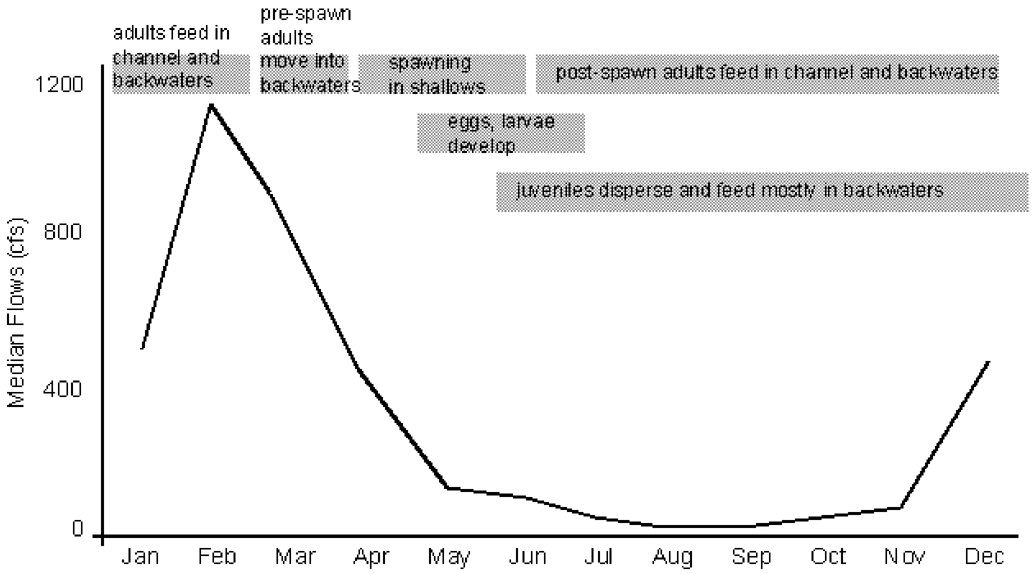


Figure 22. Smallmouth buffalo (flow-responsive species) life cycle in relation to seasonal flow (relative to pre-1957 median flows in Big Cypress Bayou).

7. Ironcolor shiner (*Notropis chalybaeus*)

The ironcolor shiner inhabits clear, but often stained, streams and rivers of the Gulf coastal plain. The shiner is widely distributed across the southeastern U.S., but is considered a “threatened species”. This small species probably has an average life span of no more than 2 years. According to a study in Florida (Marshall 1947), the ironcolor shiner spawns from mid April until late September. Eggs are scattered in stream pools over sand substrate, and no parental care is provided for the developing eggs or larvae. It seems unlikely that reproduction and recruitment by this small stream-dwelling minnow are highly dependent on pulse flows during spring. One could even hypothesize that extended periods of low flow over the summer could enhance recruitment in this spring-summer spawning species. Low flows would yield minimal disturbance to eggs and larvae associated with sandy substrates, and also allow benthic food resources (periphyton, fine particulate organic matter, microcrustaceans, rotifers, aquatic insects, etc.) to build up (thus providing foraging opportunities for larvae and juveniles)(Benke et al. 1984, Power 1990). It also should be noted that most of the regional population of ironcolor shiners is probably distributed within small tributary streams and not the mainstem of the major rivers. These tributary streams are unregulated and should have relatively natural flow regimes.

USFWS Stream Impact Analysis (USFWS 1993)

This USFWS report was submitted to the US Army Corps of Engineers (USACE)-Vicksburg. Appendix 6 of that report estimates losses of fish habitat associated with barge alternative navigation channels in the Cypress Basin of east Texas and western Louisiana. A project authorized in 1989 provided for 76 miles of navigation channel, ca. 9 ft. deep and 200 ft. wide, with locks located at Caddo Lake and Lake O' the Pines and in the vicinity of Jefferson, TX. At least 18 stream bendways, containing 14 miles of natural stream channel, would have been cut off by the navigation channel. In 1992, the USACE concluded that the project was neither economically nor environmentally feasible.

Appendix 6 of the USFWS study summarizes potential impacts on aquatic resources. Ecological guilds were constructed for the known fish fauna based on spawning and velocity preferences of individual fish species. This provided the basis for selecting evaluation species, but commercial and recreation importance, sensitivity to environmental disturbances, and availability of existing habitat models also were factors. The fish guilds were derived from categories along two dimensions: preferred velocity (swift water, slack water, generalist) and spawning substrate (open water, sand and gravel, vegetation, crevice). The study area for this assessment was from the mouth of Twelvemile Bayou to the upper reaches of Lake O' the Pines.

Eight evaluation species were chosen for the stream impact analysis: pickerels, blacktail shiner, ironcolor shiner, spotted sucker, flathead catfish, spotted bass, bluntnose darter, and blackside darter. These species represent 5 ecological guilds containing 56 species. Data for fish-habitat models were taken from a variety of literature sources. New field data were collected from 21 stations during April-August 1992. Fishes were collected with a seine (10 hauls through each habitat). In habitats > 6 ft. deep, gillnets were set overnight to sample fishes. The instream flow incremental methodology (IFIM) was used to project changes in habitat with changes in hydrology (Bovee 1982). The flow for 1985 was considered a typical water year in the region (near median discharge). Physical habitat for these fish species was simulated under a wide range of discharges in upper Big Cypress Bayou (5-5,000 cfs), lower Big Cypress Bayou (5-8,000 cfs), and Twelve mile Bayou (900-36,000 cfs). Suitability indices (S) for floodplains were created for 7 species as SI=(mean relative abundance in reach)/(mean relative abundance in system + one standard deviation). Several assumptions are stated (e.g., all species use floodplain habitat). In general, high SI values were obtained for most species in slow, shallow water with cover. Tables present estimates of fish habitat losses under post-project conditions, and mitigation requirements were discussed. The report contains a multiple regression analysis of stream fish habitat (independent variables include turbidity, velocity, temperature, conductivity, dissolved oxygen, width, and depth). The report concluded that habitat losses in the reservoir are not anticipated (0 acres), habitat losses in the streams will be minimal (0 acres), but habitat losses in floodplains will be substantial (3,646 acres) from the navigation project. This study was criticized by Espey, Huston & Associates (1987) who felt that use of white bass and river darter was not warranted in the IFIM study, because these species are very rare in surveys Little Cypress Creek, and thus unlikely to respond demographically to flow variation. Routine summer flows are much lower than the estimates for maintenance flows based on IFIM, and they concluded that estimated maintenance flows would render the reservoir economically infeasible.

Nonetheless, the USFWS study provides the best available information on species responses to flow variation and estimated habitat availability in the BigCypress/Caddo Lake system (i.e., habitat suitability curves for velocity, depth, and cover). Field sample sizes were relatively small (<100 individuals collected) for 5 of the 8 species that were modeled (the two pickerel species were combined for their analysis). Among the taxa examined, the following species are likely to be present in the Big Cypress Bayou main channel or upper Caddo Lake: pickerels (*Esox americanus, E. niger*), spotted sucker (*Minytrema melanops*), flathead catfish (*Pylodictus olivaris*), spotted bass (*Micropterus punctulatus*), and blackside darter (*Percina maculata*) ("threatened" TPWD). Very few individual flathead catfish were collected, which renders their flow-dependent habitat availability estimates for this species invalid. Species modeled in the USFWS study that are likely present primarily in small tributary streams are blacktail shiner (*Cyprinella venusta*), ironcolor shiner (*Notropis chalybaeus*) (“threatened” TPWD), and bluntnose darter (*Etheostoma chlorosomum*).

USFWS Reservoir Impact Analysis (USFWS 1993)

In addition to the issue of how instream flows influence fish habitat availability in rivers, there is also concern for maintenance of a productive fishery in Caddo Lake. The lake has continued to support popular and productive fisheries for largemouth bass, white and black crappie, bluegill and other sunfishes, channel and flathead catfishes, and white and hybrid striped bass. Less abundant or less popular sport fishes in the lake include spotted gar, chain pickerel, yellow bass, bullhead catfishes, and freshwater drum.

As part of a reservoir impact analysis, Appendix 6 of USFWS (1993) estimated the production potential for five evaluation species: spotted gar, threadfin shad, channel catfish, bluegill sunfish, and largemouth bass (these 5 species represent 4 ecological guilds that contain 34 species from the system). Statistical models (multiple regression models) to estimate fish standing crops (pounds per acre) in the reservoir were developed based on field data reported in Ploskey et al. (1986). Independent variables were Secchi depth, nitrogen, phosphorus, growing season, alkalinity, chlorophyll a, and storage ratio.

The following relationships were derived:

$\text{Gar} = -13.63 - \text{Log(Secchi depth)} - 2.57\text{Log(Nitrogen)} + 5.88\text{Log(Growing season)}$; $r^2 = 0.31$

$\text{Threadfin shad} = 2.02 + 1.11\text{Log(Secchi depth)} + 1.64\text{Log(Phosphorus)}$; $r^2 = 0.11$

$\text{Channel catfish} = 0.99 + 0.35\text{Log(Phosphorus)} + 0.275\text{Log(Alkalinity)}$; $r^2 = 0.12$

Bluegill= 1.52 + 0.94Log(Secchi depth) + 0.67Log(Phosphorus) - 0.16Log(Storage ratio); r^2= 0.19

Largemouth bass= -4.11 + 0.33Log(Secchi depth) + 0.55Log(Chlorophyll a) + 1.87Log(Growing Season); r^2= 0.29

These models predicted the following stock densities (lbs/acre) in Caddo Lake at that time: spotted gar= 0.24, threadfin shad= 0.51, channel catfish= 1.11, bluegill= 1.15, and largemouth bass= 1.21. The analysis concluded that because no long-term project-related changes in water quality were anticipated in association with the proposed construction of barge channels in the lake, changes in fish habitat within the lake were undetectable. This analysis is obviously quite crude, with very low coefficients of determination for the regression models. In addition, this modeling approach fails to take into consideration the many other species present in the lake, and the ecological interactions that occur among species of this diverse fish assemblage. Issues associated with physical and biological responses to instream flow variation also are not considered. These models provide an unsound basis for determining the fish production characteristics of Caddo Lake, but unfortunately no other means of estimating fish production in the lake have been attempted.

Effects of Flow Regime on Big Cypress Creek/Caddo Lake Basin Mussels

General Biology and Ecology

Although most freshwater mussel species prefer sand and gravel as substrate, other substrates are also utilized and include gravel, cobble, bedrock, and even mud and silt. Because mussels are relatively sedentary, it is critical that preferred habitat types remain inundated during periods of low flow.

Filtration and ingestion are strongly influenced by water velocity and temperature in mussels. In regards to flow, preference is species specific and widely varied. For example, of the 32 species that occur in the Savannah River system, six show preferences for strong or swift current, while the remaining species prefer more moderate flows. Mussel species are also differentially affected by temperature, but in general, when temperatures are too high, i.e., above 25°C, mortality of juveniles is increased. When temperatures are too low, mussel growth is slowed and reproduction inhibited.

Gravid individuals are mostly found in the late spring and early summer. Because many mussel species require a host fish for their parasitic glochidial stage of development, and rely on flow for dispersal of offspring and settlement of juveniles, environmental conditions that favor fish and that are linked to flowing environments will also favor mussels.

Populations in the Big Cypress Creek/Caddo Lake Basin

The Shreveport, LA, to Daingerfield, TX, reach of the Red River Waterway begins upstream of Shreveport, LA, with an overland channel to Twelvemile Bayou and continues through Caddo Lake and Cypress Bayou, ending in Lake O' The Pines near Daingerfield, TX. The reach includes three locks and one additional dam connected by a 9 by 200-foot navigation channel. An Army Corps of Engineers study (1992) investigated mussels populations in this area so that any negative impact from a proposed waterway project could be evaluated.

To summarize, 21 native mussel species plus the Asian clam *Corbicula fluminea* were collected and identified. *Plectomerus dombevanus* was the most frequently encountered species, followed by *Corbicula fluminea*, and *Lampsilis teres*. With the exception of a reach within Twelve-mile Bayou, the study area did not support dense and diverse beds of freshwater mussels such as those usually found in gravel shoals in large rivers of the central United States. No evidence of poor water quality that might have led to a decline in mussel populations was observed, although it was suggested that commercial shell fishermen likely affected mussel populations in some areas. No uncommon or endangered species were found. Even though the mussel fauna was sparse, it was characterized as healthy with good species richness.

In Caddo Lake, 22 mussel species were found (Howells 1996). In 1992, several mussel taxa supported harvesting by local people. Although many taxa are still found and widely distributed, habitat modification has resulted in a decline of populations. It was suggested that activities in the watershed, which included oil drilling and chicken farming, might have had a deleterious impact on mussel populations

TERRESTRIAL AND SEMI-AQUATIC WILDLIFE

Herpetofauna

The streams, wetlands, open water bodies, and bottomland forests of the Big Cypress/Caddo Lake Basin support a rich and abundant herpetofauna. Virtually all species of amphibians and reptiles known to range into the region would be expected in the catchment, with many species locally abundant. For example, a two-year survey of 3,440 ha bordering Big Cypress Creek at the Longhorn Army Ammunition Plant yielded 2,0028 amphibians (17 species) and 1,397 reptiles (28 species) (Autrey 1997). The list from this survey appears in Appendix E. In terms of spawning cues, few if any of the reptile and amphibian species are directly dependent on the Big Cypress flow regime. However many, perhaps most species, would respond to restoration of aquatic floodplain habitats (e.g., sloughs, oxbows, shallow temporary ponds) with enhanced populations. In some cases, this population enhancement would result from creation of additional breeding and rearing habitats (e.g., amphibians), and in other cases it would be a response to additional food availability and foraging opportunities (e.g., aquatic turtles, snakes, alligators). In addition, pulse flows provide connectivity of aquatic habitats that permit dispersal by semi-aquatic species. Two of the state's "threatened" reptiles occur within the basin—alligator snapping turtle (*Macrochelys timminckii*) and the timber rattlesnake (*Crotalus horridus*).

Avifauna

Oberholster (1974) listed 235 bird species in the Caddo Lake watershed. Additional records compiled by Ingold (1995) raised this total to 313 species (Appendix F). Historical changes in the local avifauna include species extinctions (passenger pigeon, ivory-billed woodpecker, Carolina parakeet) and local extirpations (greater prairie chicken, red-cockaded woodpecker). Two of the state's threatened bird species are likely to use habitats present in the Big Cypress/Caddo Lake Basin—whitefaced ibis (*Plegadis chihi*) and woodstork (*Mycteria americana*).

The region is an important migratory corridor for many species of waterfowl, with several lakes in the basin used by wintering waterfowl for foraging and resting (Cloud 1993). In the pineywoods of East Texas, the following waterfowl are the principal species harvested by hunters (listed in order of average hunting area estimated in TPWD's annual harvest surveys): wood duck, mallard, green-wing teal, gadwall, scaup, blue-wing teal, American wigeon, pintail, shoveler, mottled duck, canvasbask, redhead, and whistling duck. Degradation and losses of wetland habitat are considered the major challenges for waterfowl management in North America. Citing Bellrose (1980), Cloud (1993) asserted that "wood ducks (*Aix sponsa*) use overcup oak, cypress/tupelo forest types and scrub/shrub habitats during fall courtship and pairing. After pairing, wintering habitat includes the deeper areas of lowland hardwoods, cypress/tupelo, overcup oak, and scrub/shrub habitats."

In the early fall, mallards occur most often in recently flooded openings of bottomland forests with shallow depths. During winter pairing, mallards forage on seeds and acorns in flooded forests and agricultural fields. After pairing, mallards continue to feed in flooded forests on acorns and also aquatic insects (Cloud 1993). Whereas pastures and other agriculture lands have become important foraging habitats for dabbling ducks in the Big Cypress Basin, they continue to use forested wetlands and associated shrub swamps, beaver ponds, and riparian habitats for roosting, isolation from human disturbance, protection from predators, and courtship (Cloud 1993). Thus, forested wetlands are required to meet the full biological requirements of most waterfowl species.

Mammals

The pineywoods region of East Texas has a diverse mammal fauna, and the bottomland hardwood forests and wetlands of the Big Cypress/Caddo Lake Basin should provide excellent habitat for a variety of local species. Historically, the red wolf (*Canis rufus*) and Lousiana black bear (*Ursus americanus luteolus*) would have inhabited the region. The red wolf is now considered extirpated from Texas, and the Louisiana black bear (listed as "threatened" in Texas) is making a gradual comeback in East Texas via immigration from the Lousisiana population. Little research has been conducted on mammals of the Caddo Lake region. A two-year survey of the Longhorn Army Ammunition Plant recorded 10 species of small mammals among several forest types (Daniel 1995). Mammal diversity was greatest in the pure pine areas, and mammal abundance was greatest in the mixed pine-hardwood. Small mammals were tied to ground cover and litter. Notable semi-aquatic mammals in the ecosystems of the basin include the beaver (*Castor candadensis*) and river otter (*Lutra canadensis*). Beavers are important ecosystem engineers that create additional aquatic habitat and destroy and damage trees in riparian forests. Otters feed primarily on fish, and would be expected to respond positively to flow regimes that enhance fish stocks.

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