CYPRESS FLOWS PROJECT

FLOODPLAIN INUNDATION ANALYSIS INTERIM REPORT

DECEMBER, 2011

FLOODPLAIN INUNDATION ANALYSIS INTERIM REPORT

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1 INTRODUCTION

This report presents the results of an analysis of floodplain inundation in the Cypress River Basin immediately upstream of Caddo Lake. The goal of the study was to develop quantifiable relationships between flow and inundation of riparian and wetland vegetation. The report includes a literature review, which describes ecologically important aspects of environmental flows including flow magnitude, frequency, duration, and rate of change. The remote sensing analysis reported here quantified the actual wetted surface configuration for different daily discharge values including overbank events.

The Cypress Flows Project (CFP) was originally initiated as part of the Sustainable Rivers Project (SRP) partnership developed by the Nature Conservancy (TNC) and the U.S. Army Corps of Engineers (USACE). The purpose of this initiative is to restore and preserve rivers across the country (Richter and others 2006). The CFP was expanded after the initial CFP orientation meeting in December 2004 to reflect the actions and proposals of the Texas Legislature, including the passage of Senate Bill 3 to evaluate environmental flow needs in all river basins in Texas. It was further expanded in 2006 with its integration with a new Watershed Protection Planning process that focused on water quality, aquatic invasive species and related issues in the Cypress basin. The CFP has benefited from the participation of dozens of scientists and stakeholders. With the continued assistance from the USACE, U.S. Geological Survey (USGS), the Northeast Texas Municipal Water District and others, the scientists and stakeholders participating as the "working group" for the CFP are proceeding with implementation using an adaptive management approach.

The documents prepared for and summarizing the results of the major meetings and other work on this project are available on the website of the Caddo Lake Institute (www.caddolakeinstitute.us).

1.1 BOTTOMLAND HARDWOOD FORESTS

1.1.1 RIVER-FLOODPLAIN ECOSYSTEM

A floodplain is a "aquatic-terrestrial transition zone" (Junk et al. 1989). River-floodplain landscapes are continuously changing collections of different environments and habitats, with high spatial and temporal variation. In undisturbed floodplains, habitats are dominated by a diversity of bottomland hardwood (BLH) forests, along with shrub and herbaceous wetlands, and both lentic and lotic aquatic habitats. The different habitat patches naturally connect with each other via water level fluctuations (Thoms et al. 2005).

Floodplains are one of most altered and imperiled ecosystems on Earth (Opperman et al. 2010). More than any other factor, the sustainability of ecosystem processes within floodplains depends upon hydrologic connections. Water intermittently flowing across the surface of bottomland hardwood (BLH) forests improves surface- and groundwater quality, and facilitates the exchange of sediment, nutrients, and biota. A seasonably variable flow regime sustains biological and spatial diversity. If the floodplain is of sufficient size to produce meaningful benefits, overbank flows perform many important ecosystem and societal functions, such as removing nutrients and organic matter, recharging alluvial aquifers, increasing biological and agricultural productivity, sequestering carbon, providing recreation, reducing storm damage, and filtering and redistributing sediment load (Hunter et al. 2008, Opperman et al. 2010). Spanning several counties, the Cypress floodplain is large enough to provide significant amounts of such services.

Hydrologic variability produces spatial and temporal variability of habitats that increases biodiversity. Hydrologic connectivity is multi-dimensional and encompasses longitudinal, lateral, vertical, and temporal variables (Amoros and Bornette 2002). Various species and life cycle stages depend upon the complementary habitats provided by

this connectivity. For example, fish migration between spawning and nursery habitats is evolutionarily adapted to floodplain variability. The current Cypress SRP study focuses on lateral and temporal connections.

Examples of the ecological importance of hydrologic connections within floodplains abound. In lowland forests in southeast Australia, a 55 percent reduction in floodplain area available to overbank flows, and a 22 percent reduction in hydrologic linkages among habitat patches, were shown to decrease potential dissolved organic carbon (DOC) exports from semi-isolated aquatic environments (Thoms et al. 2005). Such reductions may adversely affect the productivity of aquatic biota downstream, since DOC is a primary energy source for microbial processes. Semi-isolated backwaters are focal areas for labile carbon supply to riverine and estuarine food chains. The maintenance of river-floodplain connections also sustains high ecosystem productivity. Where river and floodplains remain connected, freshwater fishery yields are consistently higher (Bayley 1995).

In addition to the above DOC subsidy, hydrologically intact floodplains provide important economic benefits, increased biodiversity, and stable environmental services (Bayley 1995). BLH forests also function as the foundation of local and regional food chains; supply critical nesting microhabitats, spawning, rearing, and resting areas for aquatic and upland species; and reduce storm and flood damage within adjacent and downstream areas (Gosselink et al. 1981). Though highly vulnerable to land-use conversion, temporarily flooded BLH forests near the upland edge of the floodplain offer supplemental water storage, which is especially important during extreme flood events. These forests also serve as buffer-traps for nutrients and sediments carried by upland runoff any time of the year (Gosselink et al. 1981).

1.1.2 Bottomland Hardwood Forest: Composition and Hydroperiod

BLH forests typically occur at lower elevations along floodplains of rivers and their tributaries. These forests tolerate saturated soil conditions, but vary widely in their adaptation to the duration and frequency of saturation, depending on associated tree and other plant species. Due to a wide diversity of geomorphology, soils, hydrology, and available plant species, BLH forests vary widely in species composition and structural characteristics within east Texas. BLH habitat diversity within the Cypress study area is high, including 16 such habitat types as mapped by TPWD (Table 1).

Primarily due to environmental variability, these floodplain forest communities exhibit a high diversity of tree species, unlike upland forests that are often dominated by one or two tree species (McKnight et al. 1981). The interaction of a changeable inundation regime with the geomorphologic patchwork of microtopography and soil types also leads to high between-habitat diversity (Junk et al. 1989). As a consequence of this ongoing interplay between hydrology and geomorphology, the biodiversity of BLH forests is usually double that of nearby upland forests (Gosselink et al. 1981).

The “hydroperiod” is the area-specific combination of duration, frequency, timing, and depth of flooding. Due to its effect on habitat availability and connectivity, the hydroperiod is the strongest determinant of BLH species composition for both plant and animal populations (King and Allen 1996). In east Texas BLH forests, Dewey et al. (2006) pinpointed flood duration as the single most important component of the hydroperiod, in terms of influence on wetland vegetation and soil characteristics.

The hydroperiod is accurately predicted by the BLH species composition of an area, due to the evolutionarily tuned correspondence among species distributions and hydrologic cycles (Bedinger 1981). Though tolerance within an individual species to water saturation will vary according to interspecies competition, soil texture and nutrients, and available light, the presence of a particular BLH community consisting of many dominant and co-dominant species identifies the underlying hydroperiod (Huffman and Forsythe 1981b). Incorporating the east Texas BLH

habitat types (TPWD 2009) used in this study, Figure 1 is a schematic presentation of the interdependence of landscape context (relative elevation), tree species, and hydroperiod (adapted from Diamond 2009 and Huffman and Forsythe 1981a).

1.2 Hydrology of Bottomland Hardwood Forests

1.2.1 Natural Overbank Events

Annual or nearly annual flooding is a defining feature of BLH forests. For example, intensive hydrologic studies on the Cache River in Arkansas reveal that more than 90 percent of the annual water budget for BLH forests consists of river inflows and outflows (Walton et al. 1996). These studies show that other water fluxes, including groundwater, precipitation, and evapotranspiration, are insignificant inputs to the BLH-forest water budget.

Floodwaters do not flow across the floodplain as a uniform sheet of water, because of the geomorphological complexity. Instead, floods interact with the variable topography to create temporarily and spatially changing mosaics of lentic and lotic habitats (Benke et al. 2000). In this manner, most overbank flooding results from floodplain constrictions, which funnel intertwined overland flows into backwater and associated overflow channels (Walton et al. 1996). Across the midwestern United States, most rivers and streams with relatively natural hydrology equal or exceed bank-full two out of three years (Leopold et al. 1964, Mitsch and Rust 1984). Generally, as floodplain size increases, floods tend to decrease in frequency, but increase in duration and seasonal predictability (Junk et al. 1989). For unregulated rivers in the southeastern US, the highest flood peaks occur in winter and spring (Benke et al. 2000). In the upper Mississippi floodplain, probably in large part due to dam operations and other riparian construction, floods now occur earlier and more briefly than during the last century (Bayley 1995).

Across the Mississippi/Red River region, most BLH forests along relatively unregulated rivers flood about once per year for about 40 days on the average (Gosselink et al. 1981). In one of the most intensive studies of a natural flood regime in the southeastern US, the Ogeechee River in Georgia flooded greater than 50 percent of the natural floodplain for a minimum of least 30 days annually (Benke et al. 2000). In this long-term study, less than 50 percent of the floodplain was inundated in only four out of 58 years. The duration of overbank events averaged 30 or more days, when inundation covered at least 50 percent of the floodplain. For 17 river gages located in the Mississippi River alluvial valley of southeast Missouri, each year 39.4 percent and 30.0 percent of the gages recorded winter floods longer than 5 and 10 days, respectively (Heitmeyer 2006).

1.2.2 Influence of Overbank Events on BLH Tree Recruitment and Species Diversity

Rood et al. (2005) describe the "flood pulse" as a natural disturbance, amenable to management much like prescribed fire, which can revitalize floodplain habitats. For many BLH tree species, seed germination and seedling establishment must follow floods severe enough to remove existing vegetation and create new seedbeds from bare soil. In order to provide new substrates in different configurations, some vegetation must be razed. Vegetation destruction during overbank events initiates new lateral or point bars (Hughes and Rood 2003). At the same time, floods distribute seeds and vegetative propagules to reestablish plants across the floodplain (Bendix and Hupp 2000). The timing of forest-regeneration floods is important, since not only do the flood-induced erosion and deposition of bare seedbeds need to occur before seed dispersal (Hughes and Rood 2003), but the timing of subsequent seed germination varies by tree species. The spatial configuration and timing of vegetation destruction and renewal during floods causes BLH forests to consist of mosaics of vegetation of different ages and species compositions.

When characterizing or re-establishing "regeneration flows," Hughes and Rood (2003) list the most important considerations as: (1) timing inundation to coincide with the phenology (seed dispersal and germination) of target tree species, (2) varying the interannual timing of floods to increase plant diversity, (3) adjusting the rate of flood-water recession, and (4) promoting channel movement and new sedimentation sites to create regeneration sites. The current study primarily addresses the first three items for characterizing and re-establishing regeneration flows. The fourth item should be a future research question for geomorphologists. A distinctive characteristic of regeneration flows is their requirement for between-year variability of overbank events on a decadal scale, which are superimposed on annual "maintenance flows" that depend on within-year variability for seedling survival.

Post-recruitment maintenance flows should provide sufficient moisture in the seedling rooting zone during the growing season, while at the same time maintaining the main stream channel by transporting suspended sediment. The importance of following high spring flows that promote seedling establishment with a slow drawdown of floodwaters to improve seedling survival has resulted in the term "Recruitment Box Model" (Rood et al. 2005). A gradually receding slope of the flood hydrograph is critical to seedling subsistence. Hughes and Rood (2003) make the case that the water table should not drop faster than the rate of seedling root growth, i.e., less than one inch or 2.5 cm per day. Therefore, the recession rate for overbank and high flows should not allow the stream stage elevation to drop faster than one inch per day.

In addition to their importance in maintaining BLH species diversity, the frequency and duration of overbank flows need to be sufficient to exclude upland species. Extended flooding during extremely wet years has the strongest control on BLH species composition (Townsend 2001), largely due to its adverse impact on upland species. Figure 1 lists flood duration and frequency targets to maintain each BLH habitat type in the study area. In order to achieve the same effect on species composition, the total duration of intermittent flooding needs to exceed the duration of continuous flooding (Gosselink et al. 1981).

Quantifying annual and seasonal flow targets depends upon the specific requirements of dominant species within desired BLH habitats. As a component of the annual hydroperiod, the seasonal timing of flooding largely determines which species regenerate within BLH forests. The competitive sorting and species composition of annual tree recruitment is mostly determined by the spring hydroperiod, which exerts a disproportionate influence on seedling establishment and the early stages of succession. However, the annual hydroperiod is the more consequential determinant of the long-term survival of BLH species and, thus, species dominance within mature BLH forests (Townsend 2001). The species-specific effects of extreme flood events, in particular, maintain high species diversity. Without such variability, BLH forests are degraded by artificially homogenous species composition with lower productivity.

Within the Cypress basins as elsewhere, different seasonal distributions of flows have significant species-specific effects on BLH regeneration. In contrast to species which appear early such as green ash, later germinating tree species such as red maple gain a competitive advantage when overbank flows occur in late spring (Townsend 2001). On the other hand, early flooding promotes earlier germination, which in turn increases seedling survival (Streng et al. 1989, Jones et al. 1994). Streng et al. (1989) provide examples of early April floods leading to heightened emergence of earlier germinating species, such as ironwood, deciduous holly, American holly, sweetgum, and blackgum.

1.3 Ecosystem Processes in Floodplain Forests with Variable Flows

1.3.1 Ecosystem Benefits of Floodplain Forests

All five of the hydrologic services of floodplains listed by Brauman et al. (2007), are important in the Cypress study area: (1) extractive water supply; (2) in-stream water resources (recreation, freshwater fisheries); (3) flood-damage reduction; (4) aesthetics, education, and tourism; and (5) maintenance of aquatic habitats and future options for adaptive management .

One of the most important ecosystem functions of BLH forests to society is improving water quality through the removal of high N concentrations. The wet-dry fluctuations of floodplain soils create successive aerobic and anaerobic environments. Nitrification is an aerobic or dry-cycle process, which through microbial oxidation basically converts ammonia compounds to nitrate compounds. During the succeeding wet period, anaerobic soil conditions are created, which promote denitrifying bacteria that, in turn, convert the nitrate compounds to N gases such as nitrous oxide. In this fashion, high N concentrations in river flows are reduced.

The health of BLH forests affects local and downstream nutrient loading. The healthy BLH forests with natural hydroperiods have high and long-term capacities to remove N and retain P from floodwaters (Ardon et al. 2010). Due to longer residence times to absorb large nutrient pulses during storms, restoration of large floodplains, such as the Cypress watershed, is important to reverse pollutant loading

Diminished high-flood events limit floodplain connectivity, which in turn lowers nutrient assimilation and increases nutrient loading downstream (King et al. 2009). Connectivity is important since different floodplain habitats have different nutrient processing rates. For example, though an anaerobic process, denitrification rates are higher in BLH forest soils than in lake sediments (Scaroni et al. 2011).

Many important BLH ecosystem processes peak with annual flooding, including primary production, plant diversity, animal habitat use, and organic matter export; (Gosselink et al. 1981). The hydrologic measures in BLH forests, which most directly impact functionality and, thus, which warrant consideration in regard to potential flow alterations include: flood water storage; frequency, duration, depth, and timing of overbank events; flow velocity; soil saturation; and soil infiltration rate (Gosselink et al. 1990). Not part of the current study, the last three hydrologic measures are recommended for future research.

The high genetic and species diversity of BLH forests augment primary and secondary production (Bayley 1995). An extensive literature review by Conner et al. (1990) shows that primary production of BLH forests with natural hydrology is greater than 1000 g/m2/y, which ranks these forests among the most productive wetland ecosystems. BLH productivity appears to peak with annual floods in winter and early spring, with primary production highest in seasonally and temporarily flooded forests (Conner et al. 1990). The proposed permanent vegetation plots (Appendix C) would include monitoring of primary productivity as a prime indicator of forest health. Tree productivity (above and below ground) is calculated from stem diameters, using live tree biomass equations, such as those available from Jenkins et al. (2003).

Anderson and Mitsch (2008) found significant polynomial relationships between annual tree basal growth and flood duration, but only when examined over a combined two-year period. When only concurrent or previous year flood regimes were examined, no significant relationships occurred. Prior growing conditions are important, since stem growth occurs early in the growing season and, therefore, depends upon stored energy from the prior growing season. Current-year flooding additionally affects growing conditions.

The predictable seasonal timing of long-duration floods allows biotic adaptations and more efficient resource utilization, as water flux across the floodplain fosters rapid recycling of organic matter and nutrients (Junk et al. 1989). As with seedling establishment, drawdown following a flood is likely more important to production than rising water levels in many temperate systems (Bayley 1995). In addition to the rate of rise and fall, the timing of overbank flows relative to rising temperatures also influences productivity on an annual basis. Since most floods in the southeastern United States occur in winter or spring, water temperatures are more conducive to high biotic productivity during drawdown, as opposed to the rising phase of the hydrograph.

In the temperate US, Gosselink et al. (1981) and Junk et al. (1989) both find that more organic matter and detritus is exported by retreating winter and spring floods, than by summer floods. Relative to summer floods, within floodplains greater productivity and diversity of aquatic macrophytes follow spring floods (Robertson et al. 2001). As discussed above, when the post-flood infusion of carbon and nutrients from productive habitats coincides with warming spring temperatures, the fertility of in-stream and estuarine waters is enhanced.

1.3.2 Floodplain Hydrology and Primary Productivity

Variable river levels trigger switches between biological production and transfer phases within floodplain habitats, which initiate the exchange of organic matter and nutrients among different terrestrial, aquatic, and estuarine habitats (Amoros and Bornette 2002). Flood pulsing causes successive oxic and anoxic soil conditions within floodplain BLH forests, which drive nutrient processing important for sustainability. The temporal distribution of repeated overbank flows is the primary determinant of not only habitat types, but also drives biogeochemical processes in bottomland soils, such as decomposition, sedimentation, and N cycling (Hunter et al. 2008).

Overbank flows subsidize the high productivity of BLH forests in many ways. These include elevating rates of annual litterfall and nutrient turnover, increasing decomposition rates, flushing of accumulated detritus and metabolic waste products, and providing optimal environmental fluctuations, which promote microbial nutrient conversions (Conner et al. 1990). Hunter et al. (2008) document positive linear correlations of soil moisture in BLH forests with heterotrophic microbial activity, readily mineralizable carbon, and soluble organic C. These researchers also find positive relationships linking flood-generated sedimentation, with decomposition rates, N mineralization, and microbial biomass. The most important BLH biogeochemical services identified by Hunter et al. (2008) are decomposition, downstream export of organic carbon, phosphorous uptake and sequestration, nitrification, and denitrification.

Research indicates that a variable hydrologic regime increases BLH forest productivity. After reviewing related research, Kozlowski (2002) determined that BLH tree species are more productive during intermittent floods, not prolonged floods. During an extensive study of unregulated floodplains in Mississippi, Alabama, and Arkansas, Rypel et al. (2009) likewise found baldcypress productivity to be positively correlated to the annual number of floods, and negatively correlated to reduced frequency of annual floods.

Concerning flood duration, BLH tree species are adapted to both annual and decadal variability. For example, baldcypress depends on long-term hydrologic variability, since annual high flows replace nutrients and reduce competition, and less frequent, drought-induced low flows are essential for regeneration (Rypel et al. 2009). Mitsch and Rust (1984) measured a 50 percent increase in the radial growth of BLH tree species due to winter flooding, while long summer floods decreased tree growth and increased mortality. For baldcypress, early spring (May and June) discharge amounts are positively correlated with productivity (Rypel et al. 2009. To be most

effective, both in terms of maintaining BLH tree species and discouraging invasive upland and facultative-wetland species, early spring floods following leaf emergence probably should last a total of two to four weeks.

The enhancement of primary productivity due to overbank flows allows river floodplains to achieve the highest biomass per area of any temperate ecosystem (Gosselink et al. 1981). In addition to exceptional erosion protection, this forest structure represents significant carbon storage. A literature review by Bridgham et al. (2006) documents that freshwater wetlands, on the average, sequester 162 Mg C/ha. Recent research in northeast Louisiana found the range of carbon storage in BLH forests to be 90-124 Mg C/ha (Hunter et al. 2008). The potential role of BLH forests in mitigating climate change is substantial.

1.3.3 Floodplain Hydrology and Fish and Wildlife Productivity

Many studies show that human activities, which decrease flood frequency, also reduce bird, mammal, and fish densities in riparian ecosystems (Gosselink et al. 1981). Access to floodplain resources during overbank flows is critical, since almost all animal biomass within riverine systems is produced within floodplains rather than river inputs of organic matter (Junk et al. 1989). For instance, even for smaller streams, 67-95 percent of invertebrate production takes place in the floodplain, not the stream channel (Smock et al. 1992). Consequently, for animals the primary function of the main river channel is not production, but to act as an access route for fish and other biota to adjacent floodplain resources.

A strongly positive relationship exists between fish production and the amount of accessible floodplain (Junk et al. 1989). For instance, fish spawning is often coordinated with rising floodwater, with spring spawners targeting the seasonal coincidence of rising floodwaters and warmer temperature. Similar to the effect on tree recruitment, following spring floods good fish recruitment depends on the gradual retreat of flood waters during the warm growing season (Junk et al. 1989). A slow drop in water levels also allows invertebrate prey populations, which increase due to coincidental nutrient runoff, to reach even higher densities. Bayley (1995) documented that earlier and briefer overbank events in recent decades, largely due to anthropogenic floodplain disturbance as noted above, disrupts the evolutionarily synchronized timing of fish spawning and invertebrate prey availability.

In a similar manner, the rapid rise and fall of floods decrease resource utilization by mallards, due to decreases in habitat accessibility, food availability, and nutritional quality (Heitmeyer 2006). As is the case for many plant and animal species, late winter and early spring floods are preferable for mallards, since females are molting and prepping for spring migration.

The annual production of most freshwater mussel species in the southeastern United States depends upon the maintenance of base flows (Rypel et al. 2009). However, mussels grow best when the number of hydrographic reversals, due to intermittent high-flow events, increases. Long-term mussel productivity also depends upon occasionally higher flows, which remove accumulated sediments, increase carbon and nutrient inputs from the floodplain, and create new substrate for recruitment.

1.4 Water Development Impacts

1.4.1 Water Development Impacts to River Hydrology

During the twentieth century, global human population and water withdrawal increased four and eight times, respectively (Gleick 1998). This disproportional impact on water supplies promotes to unsustainable water management, as reflected in a large number of related environmental problems, including decreased water quality, invasive species, and reduced biodiversity and biological productivity (Richter et al. 2003). As ecosystem

services of river basins decrease, remedying water quality degradation and associated public health problems becomes especially expensive and technologically difficult.

Dams typically reduce high flows and supplement low flows downstream. A literature review by King and Allen (1996) presents strong evidence that dam operations lead to reduced peak flows and decreased variability in the timing and duration of overbank flows below dams. Kozlowski (2002) also cites several research studies showing that flood-control dams decrease flood peaks and frequency. Long-term research within the large Murray River basin in Australia examines the consequences of construction of both dams and flood-control structures to the overbank flow regime (Robertson et al. 2001). These researchers reveal long-term decreases in the frequency and duration of spring floods, along with an increased frequency of summer floods.

More recently, Stallins et al. (2009) report the results of an intensive long-term study of the hydrologic consequences of reduced flows within the Apalachicola–Chattahoochee–Flint (ACF) river basin. One of the largest BLH ecosystems in the United States, the ACF river basin is an ecologically and economically important region encompassing portions of three states: Florida, Alabama and Georgia. Following dam construction in the basin, both the stage duration and the annual average discharge dropped off significantly, with the largest declines in spring and summer (Stallins et al. 2009). This study makes the case that artificially lower flows in spring and summer within this three-state region are primarily caused by water consumption, reservoir storage and resulting evaporation, channel incision below dams, and constructed navigational infrastructure.

In addition to the impacts upon flow dynamics, another adverse result of dam construction is river and floodplain fragmentation. Dams prevent the movement of aquatic biota and sediments. In Texas, 97 percent of the 7,053 dams registered in the National Inventory of Dams are small and medium dams with storage capacities under 10,000 acre-feet (Chin et al. 2008). The average density of such dams across the state is 100 per square kilometer, though the density is much higher in east Texas. The major environmental impact of these mostly private, smaller dams is fragmentation of the riparian ecosystem.

1.4.2 Water Development Impacts to Bottomland Hardwood Forests

A recent literature review by Rypel et al. (2009) found that the hydrologic impacts of dams led to widespread degradation of BLH ecosystems. Dams capture sediment leading to incised and stationary channels, which accelerate downstream declines in overbank flows and alluvial aquifer recharge. Direct effects of dams as biological barriers include depletion of woody debris, impeded dispersal of plant seeds and vegetative reproduction, and genetic fragmentation within riparian animal and plant populations (Rood et al. 2005).

An examination of studies published on the effects of river channelization and dams allowed King and Allen (1996) to link declines in BLH ecosystem health to specific biological factors. They found that such river infrastructure diminishes natural flow regimes and thus harm BLH forests by: (1) reducing the growth and primary production of plant communities, (2) shifting plant species composition to that of drier communities, (3) preventing river-floodplain connections leading to reduced sedimentation and water quality, and (4) causing failures in fish and herptologic reproduction.

Kozlowski (2002) found that reductions in the variability of river flows reduced groundwater levels, which in turn lowered BLH ecosystem productivity and species diversity. More explicitly, less soil moisture prevents seed germination and slows tree growth. These adverse impacts to plant establishment alter the course of plant succession and reduce productivity, including through the introduction of maladapted species.

Long-term field monitoring by Stallins et al. (2009) along the Apalachicola River floodplain, which drains the ACF regional river basin, reveals that BLH forests are now dominated by tree species adapted to drier habitats,

compared to previous sampling in the 1970s. This widespread successional change is most pronounced among understory species, including tree seedlings and saplings. In many areas of the southeastern USA, including east Texas, the understory is now dominated by species adapted to much drier environments, relative to overstory species in the same forests.

Stallins et al. (2009) found the greatest declines in species density and dominance of overstory species in backswamps, since these habitats are no longer sufficiently connected by overbank flows. Declines in BLH tree species composition were more consistent at higher elevations, where hydroperiod and soil moisture are more dependent upon overbank flows. Change in species composition was more variable in backswamps, since in these habitats local ponding, caused by topographic constrictions impeding the retreat of overbank flows, exerted more hydrologic control than river levels.

2 METHODS

2.1 SCOPE

The scope of this study is defined spatially by the geographic area included, functionally by the habitat types evaluated and hydrologically by the range of flows that are analyzed.

2.1.1 GEOGRAPHIC SCOPE

The geographic scope of this study was defined based on three river segments and wetland areas associated with Caddo Lake that have been the focus of the Caddo Flows Project. Located in northeast Texas and centered on the city of Jefferson, Texas, the overall study area includes portions of Cass, Harrison, and Marion Counties. The area contains the upper portion of Caddo Lake and the lower reaches of the Big Cypress, Little Cypress, and Black Cypress Creeks. The sub-basin study areas are shown in Figure 1. These were largely determined by the location of USGS stream gages providing historical and current discharge data for analysis. Other selection criteria included floodplain areas with extant BLH forest of high quality (Figure 2 - Figure 5)

The sub-basin areas focused on stream segments associated with USGS gages and with Caddo Lake. Based on a review of inundation mapping (described below), study area boundaries encompass the full width of the adjacent floodplain potentially affected by main-channel overbank events. Study areas associated with specific river segments were bounded laterally either the adjacent sub-basin or a distance of 1,500 meters from the main channel. The boundaries were enforced to exclude from analysis areas that may have been wet but were not connected to the river segments by overbank flows. The downstream boundaries were defined by confluence with major tributaries and the upstream boundaries were selected so that each sub area was approximately the same length with Big Cypress, which is bounded on its upper end by Lake O' The Pines Reservoir. The Caddo Lake study area is delineated by the DEM land surface elevation of 185 ft-msl downstream of the major tributary confluences. The elevation of 185 ft-msl corresponds to the elevation of wetlands of international importance.

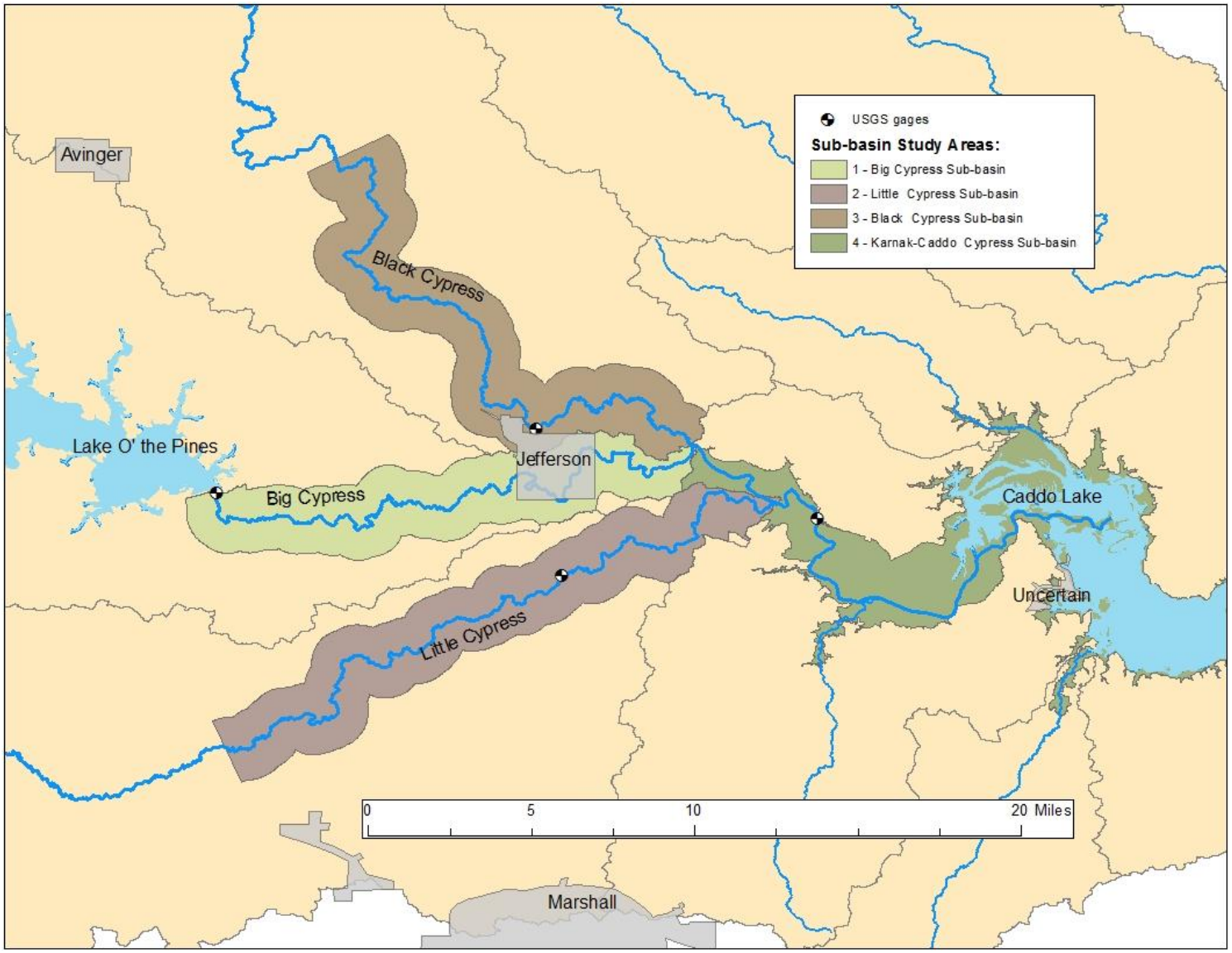


Figure 1 Overall Cypress-Caddo Flows SRP Project Area: Four Sub-basin Study Areas, USGS Gage Locations and Water Features

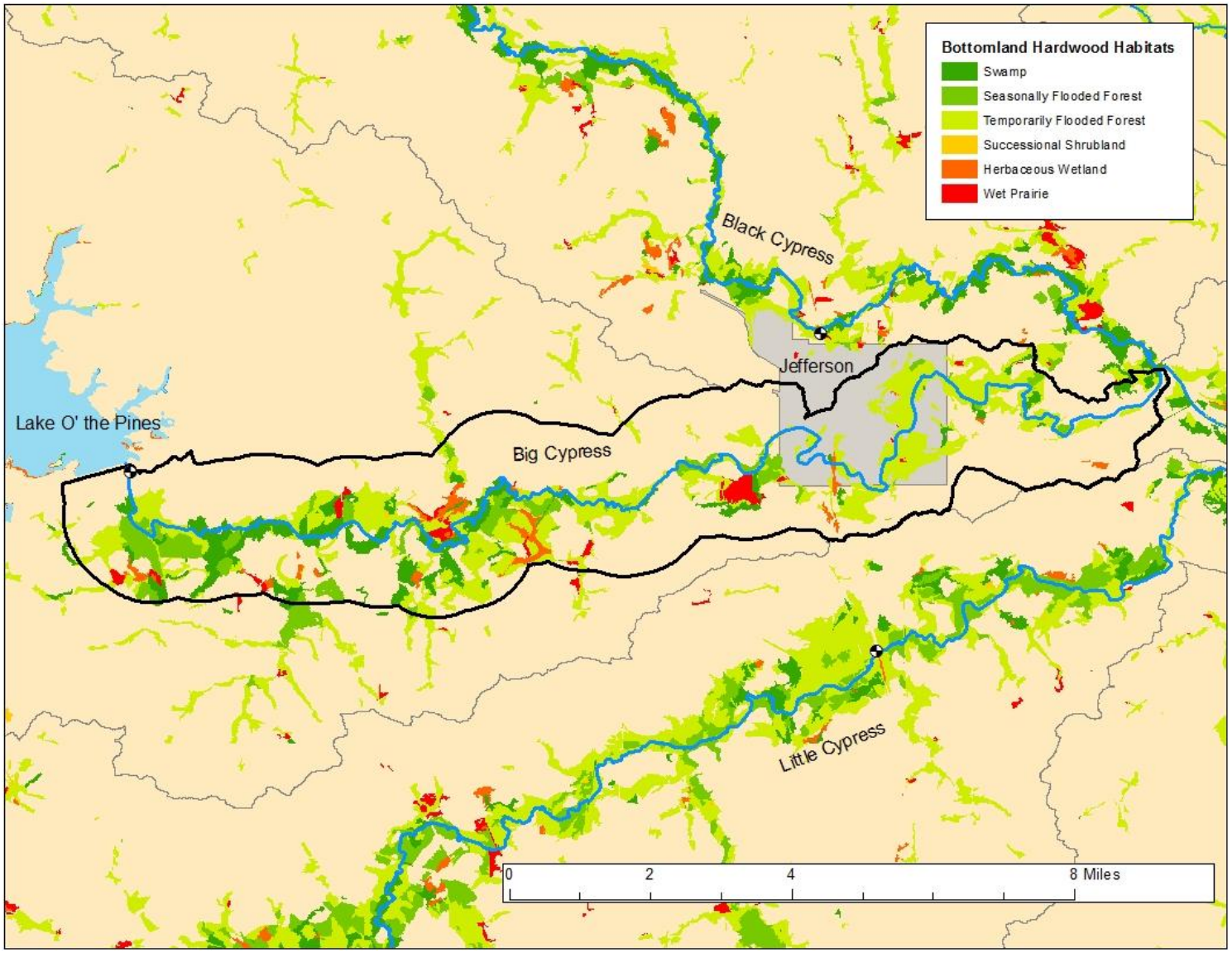


Figure 2 Big Cypress Creek Study Area with Bottomland Hardwood Habitats (Source: TPWD 2009)

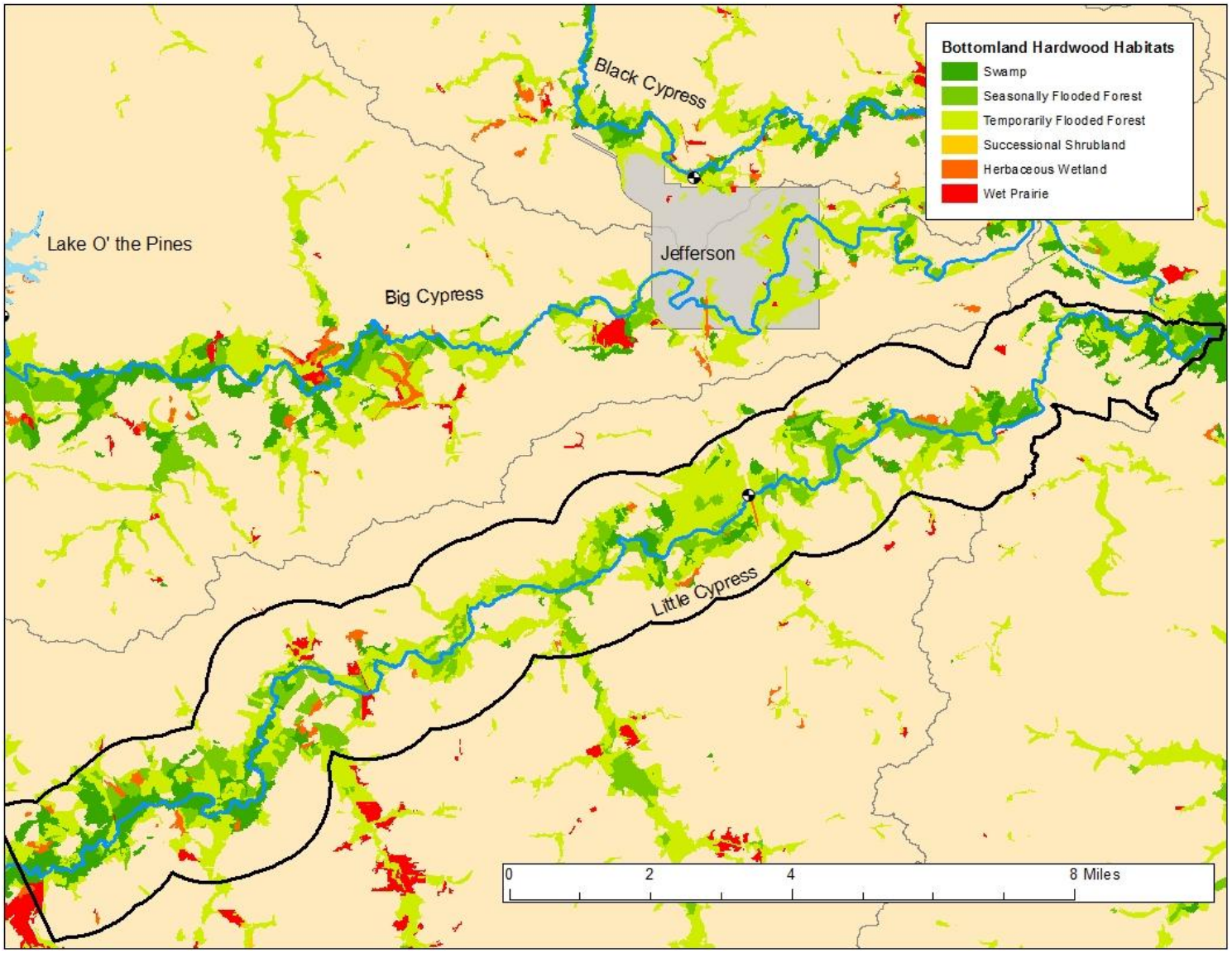


Figure 3 Little Cypress Creek Study Area with Bottomland Hardwood Habitats (Source: TPWD 2009)

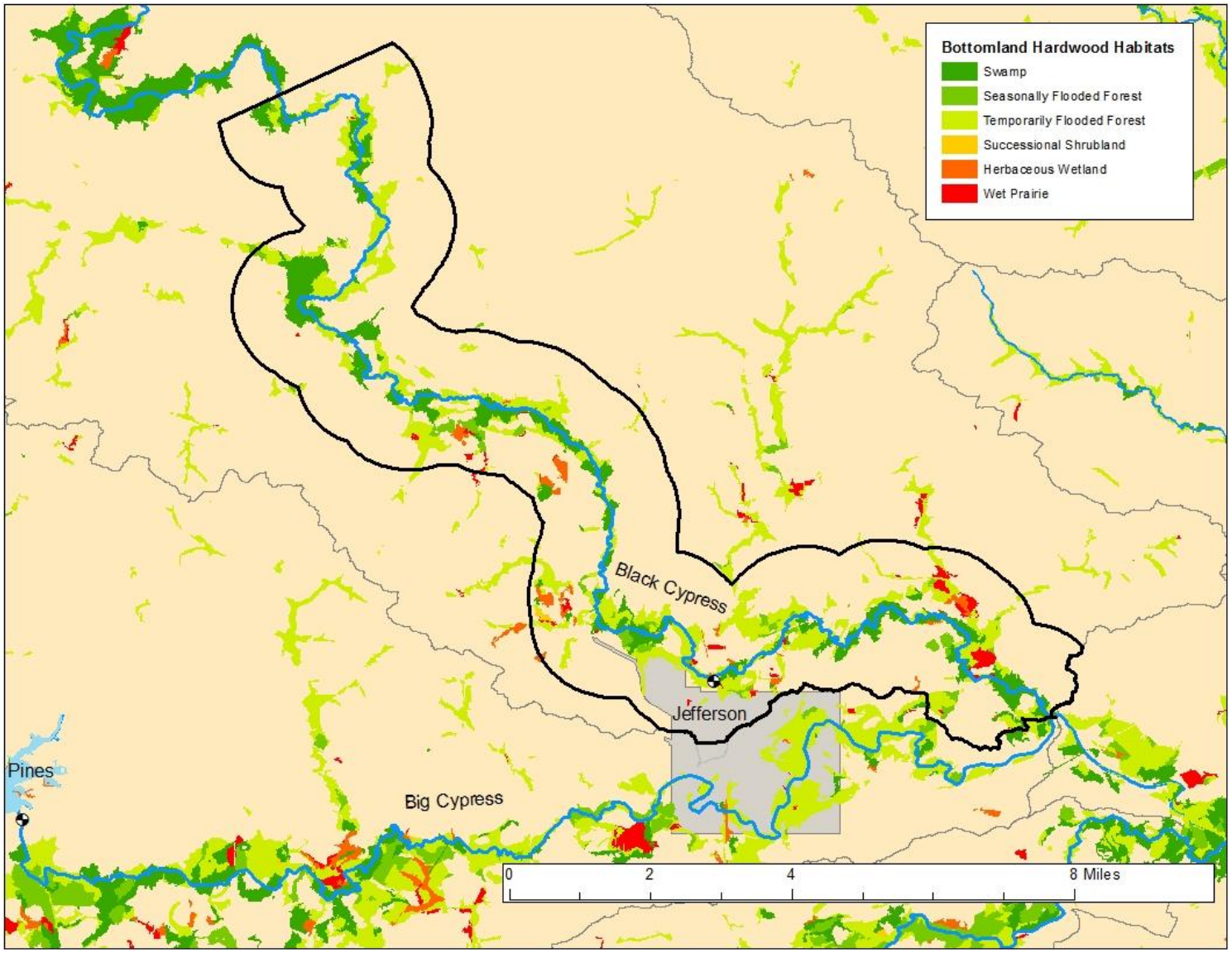


Figure 4 Black Cypress Creek Study Area with Bottomland Hardwood Habitats (Source: TPWD 2009)

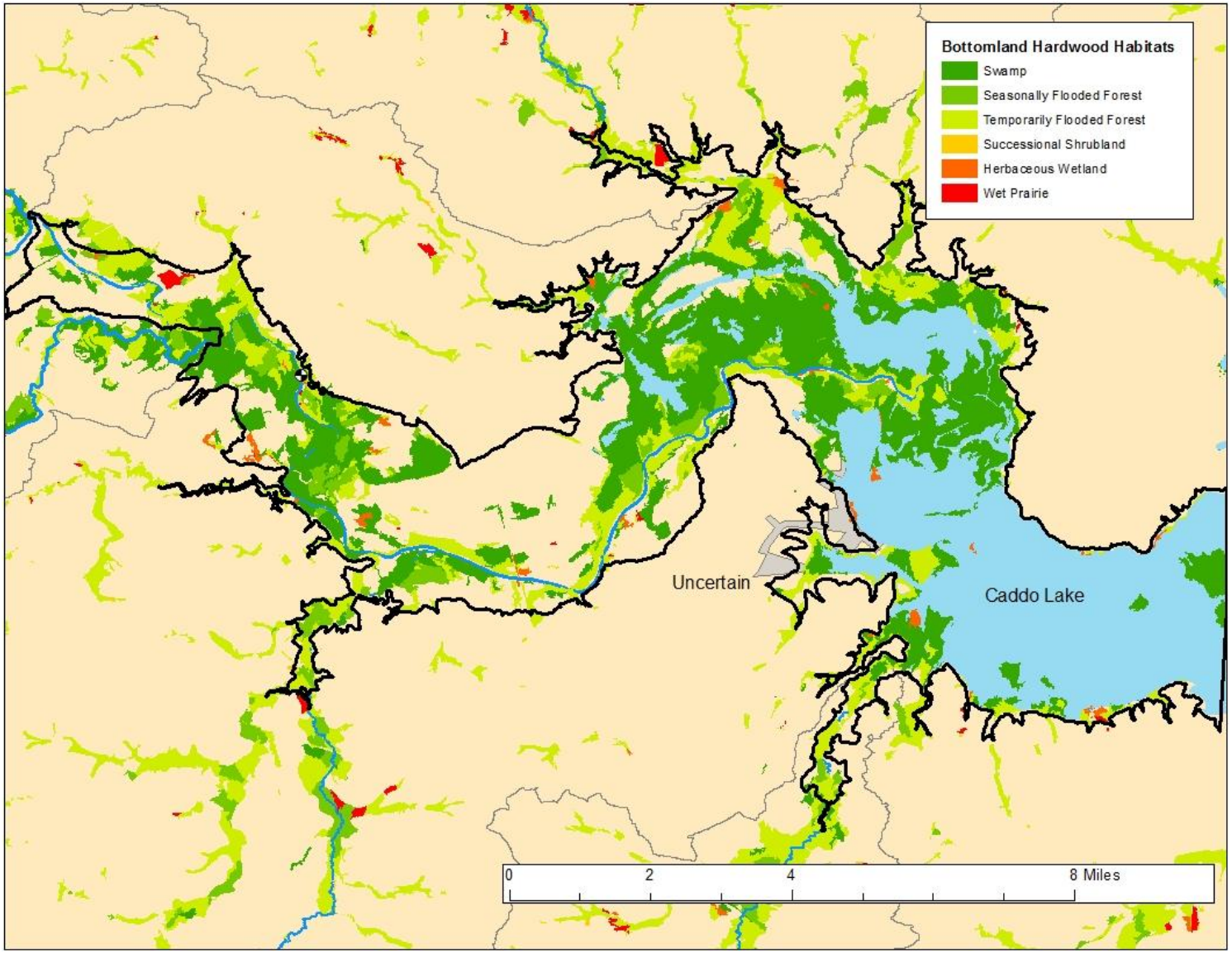


Figure 5 Upper Caddo Lake Study Area with Bottomland Hardwood Habitats (Source: TPWD 2009)

2.1.2 Vegetation Types

The Texas Vegetation Classification Project (TPWD 2009) has performed vegetation mapping of East Texas. TPWD, along with private and agency partners, conducted a multi-year effort to create a new vegetation map of Texas, using the NatureServe Ecological System Classification System (Comer et al. 2003). The basic method was to determine ecological sub-systems or community types then collect satellite data and aerial photos to initiate a supervised classification. Supporting data regarding ecosystems, soils (SSURGO), elevation (DEM), and hydrology were then gathered into a GIS, in order to incorporate the ecological context of mapped sub-systems. Next, plot-based field data were gathered to conjunction with GIS techniques to quantify primarily vegetation variables describing mapping units. Modeling was then employed to implement a decision tree combining remotely sensed biotic and abiotic data into a land-cover classification with a resolution of ten meters.

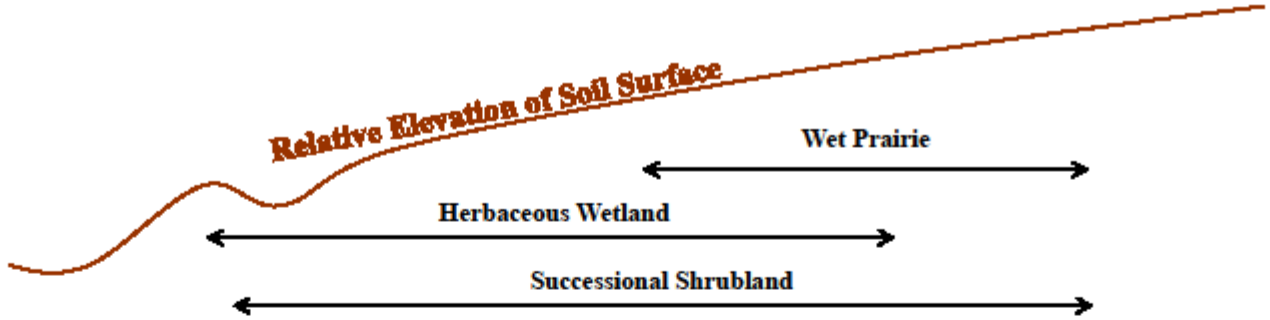
While the TPWD project included mapping of all vegetation types in East Texas, only the riparian types located in the Pineywoods were used for this study. The distinction between what the TPWD project defined as "Small Stream and Riparian" versus "Bottomland" appears to be based on regulatory stream classification and thus is not relevant to this study and was ignored. The Temporarily Flooded Forest types, all of which are made up of species with similar inundation response, were combined into a single category. The GIS data included in this project includes designation of vegetation types listed in Table 1.

Table 1 Riparian Vegetation Types

TPWD GIS Database	Type
Swamp	Swamp
Pineywoods: Baldcypress Swamp	Swamp
Pineywoods: Small Stream and Riparian Baldcypress Swamp	Swamp
Pineywoods: Seasonally Flooded Bottomland Hardwood Forest	Seasonally Flooded Forest
Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest	Seasonally Flooded Forest
Pineywoods:Temporarily Flooded Bottomland Hardwood Forest	Temporarily Flooded Forest
Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest	Temporarily Flooded Forest
Pineywoods: Temporarily Flooded Live Oak Bottomland Hardwood Forest	Temporarily Flooded Forest
Pineywoods: Small Stream and Riparian Live Oak Temporarily Flooded Forest	Temporarily Flooded Forest
Pineywoods: Temporarily Flooded Mixed Pine / Hardwood Bottomland Forest	Temporarily Flooded Forest
Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest	Temporarily Flooded Forest
Pineywoods: Deciduous Successional Bottomland Shrubland	Deciduous Successional Shrubland
Pineywoods: Small Stream and Riparian Deciduous Successional Shrubland	Deciduous Successional Shrubland
Pineywoods: Bottomland Herbaceous Wetland	Herbaceous Wetland
Pineywoods: Small Stream and Riparian Herbaceous Wetland	Herbaceous Wetland
Pineywoods: Bottomland Wet Prairie	Wet Prairie
Pineywoods: Small Stream and Riparian Wet Prairie	Wet Prairie

Associated figure graphically depicts this community diversity in relation to landscape context and hydroperiod.

Image of information in Table 1 shows Bottomland Habitat Types in Cypress-Caddo Project Area, Northeast Texas: Landscape Context, Tree Species, and Hydrology



Bottomland Habitat Types:	Stream & Other Open Water	Swamp: Lower Swamp	Swamp: Upper Swamp	Seasonally Flooded Forest	Temporarily Flooded Forest	Transition to Uplands
Dominant Tree Species:	None	Bald cypress	Bald cypress Water elm Overcup oak Sweetgum	Willow oak Water oak Sweetgum Overcup oak	Water oak Sweetgum Loblolly pine Cedar elm	Sugarberry Sweetgum Water oak White oak
Hydrologic Regime [2]:	Permanently Flooded	Intermittently exposed	Semipermanently flooded	Seasonally flooded	Temporarily flooded	Intermittently flooded
Flood Frequency-percent of years [2]:	100%	~ 100%	51-100%	51-100%	11-50%	1-10%
Growing-Season Inundation-total duration [2]:	100% (~ 8 mos.)	~ 100% (~ 8 mos.)	>25% (> 2 mos.)	12.5-25% (1-2 mos.)	2-12.5% (5-30 days)	< 2% (< 5 days)

Footnotes: [1] Diamond, D. 2009. FIA Bottomland Summary: East Texas. Unpub. document, Missouri Resource Assessment Partnership, School of Natural Resources, U. Mo. - Columbia.

[2] Huffman, T., and S.W. Forsythe. 1981. Bottomland hardwood forest communities and their relation to anaerobic soil communities. in: Clark, J.R., and J. Benforado. Wetlands of Bottomland Hardwood Forests, Elsevier Scientific Pub. Co., New York, N.Y., pp. 187-196.

The major BLH forest types within the overall project area are summarized in terms of species composition, relative elevation context, and hydroperiod as follows. Flood frequency and duration (adapted from Huffman and Forsythe, 1981a) are also tabulated for the BLH forest types in Figure 1.

2.1.2.1 Swamps

Often dominated by monocultures of baldcypress, swamps at relatively low surface elevations flood essentially every year and are only intermittently exposed. Slightly higher elevations support upper and backwater swamps, which are semi-permanently flooded (more than two months during the growing season) and receive flood inflows ranging from every year to every other year. In addition to baldcypress, upper swamps are characterized by admixtures of water elm, overcup oak, and sweetgum, while in backwater swamps, tupelo gum and green ash may become co-dominant with baldcypress.

2.1.2.2 Seasonally Flooded Forests

The probability of seasonally flooded BLH forests being flooded in a given year is 51-100 percent. With the natural hydrologic regime relatively undisturbed, these forests are flooded a total of 1-2 months (12.5-25 percent) during the growing season. Species composition is diverse and dominated by various combinations of willow oak, water oak, sweetgum, and overcup oak, with water hickory, laurel oak, and green ash often as co-dominants.

2.1.2.3 Temporarily Flooded Forests

With an annual flood probability of 11-50 percent, these forests experience a total flood duration during the growing season of 5-30 days or 2-12.5 percent. Tree species diversity is high, and is currently characterized by water oak, sweetgum, loblolly pine, and cedar elm, along with sugarberry, ironwood, and other red oaks such as willow oak.

Though currently uncommon in the Coastal Plain and the study area, temporarily flooded forests that are undisturbed and approaching maturity are dominated by elms, ashes, and sugarberry, along with some red oaks (Hodges 1997). The now very uncommon, final successional stage for this community type is characterized by the addition of white oaks and hickories (Hodges 1997).

Timber harvest, agriculture, and altered hydrologic regimes have all contributed to the nearly complete loss of this somewhat drier BLH forest type in east Texas. Such disturbances lead to invasion by sweetgum and red oaks in remaining forests. The current mid-successional composition of these forests in east Texas has been recently quantified by Dewey et al. (2006), who find sweetgum, water oak, and ironwood to be dominant along the Neches River in Tyler County.

2.1.3 Imagery for High Flow Events

In order to meet the objectives of this study, a set of images encompassing a wide range of flow conditions was needed. To focus the search for usable flood inundation imagery, a list of dates for which overbank flows occurred during the growing season was complied.

Estimates of overbank flow were made following a three-step process. The first step relied on an often-cited rule of thumb, based on empirical research, which has found that bankfull flows correspond to discharges with recurrence intervals between 1.2 and 4 years (Leopold et al. 1964). These estimates were calculated as part of the Cypress Flows Project and formed the basis of the Building Blocks recommendations for overbank flows (CLI 2010). Recurrence interval statistics were calculated following procedures defined in Bulletin 17B of the Interagency Advisory Committee on Water Data (1982) assuming a log-Pearson Type III probability distribution. Annual peak

flow data was obtained from the USGS website and calculations were performed in the computer program PEAKFQWin (Flynn et al. 2006).

These initial estimates were compared to flood stage as reported by the National Weather Service (NWS). The NWS reports a range of flood stages of increasing severity from action stage, flood stage, moderate flood stage and major flood stage. For the studied gages, there was general agreement between the NWS levels and the flow-frequency results. Finally, for Big Cypress, these estimates were further refined based on analysis of water level data collected from ten pressure transducers were installed between Lake O' the Pines and Caddo Lake. These instruments were used to record stage data during high flow releases from Lake O' the Pines, resulting in direct observation of overbank flows. These observations led to downward revision to the initial estimates for Big Cypress Creek between Lake O' the Pines and Jefferson (CLI, 2007). Based on this analysis the initial estimates of overbanks thresholds listed in Table 2

Table 2 Initial estimates of flows that begin to result in overbank inundation

Gage	Name	Threshold
7346000	Big Cypress Ck nr Jefferson	2,500
7346045	Black Cypress Bayou at Jefferson	3,000
7346070	Little Cypress Ck nr Jefferson	4,000
7346080	Big Cypress Ck abv SH 43 nr Karnack	6,000

An initial search of Landsat TM scenes, available from USGS Earth Explorer website[1], was made for dates on which daily gage flow records exceeded overbank thresholds. In order to develop relationships for a range of flows, it was also necessary to obtain imagery for dates when flows were below overbank conditions. A second search was conducted to identify imagery for dates when flow rates had remained relatively stable but below overbank levels for several weeks prior to the date of the imagery. All searches were limited to dates that occurred during the winter period when most bottomland hardwood species are without leaves, in order to accomplish the wetted-surface classification of TM data. Thumbnail imagery of each available TM scene was then visually inspected for cloud cover to determine usability. Scenes with little to no cloud cover around designated study areas were considered analyzable and subsequently downloaded. Suitable images for the entire study area were obtained for the dates (sorted in order of increasing total area inundated) listed in Table 3.

[1] http://edcsns17.cr.usgs.gov/EarthExplorer/

Table 3 Dates for which aerial imagery is available

Date	Summed Flow (cfs)	Big Cypress Flow (cfs)	Little Cypress Flow (cfs)	Black Cypress Flow (cfs)	Caddo Lake Elevation (ft)
1/18/2006	52	45	5	3	167
2/9/2008	519	125	229	165	169
2/22/2007	747	130	365	252	169
1/30/1987	1,456	608	521	327	170
2/6/2007	1,690	837	526	327	170
3/9/1995	2,368	850	829	689	170
1/25/1997	2,507	911	796	800	170
1/10/2003	2,828	1,390	1,070	368	170
3/1/2004	3,420	1,210	1,510	700	170
2/21/1995	3,773	2,620	647	506	170
1/7/2002	4,343	3,060	689	594	170
2/5/2001	4,485	2,720	1,030	735	170
2/25/2008	4,589	2,670	1,240	679	170
1/4/2001	4,789	329	3,020	1,440	171
3/1/1998	5,460	2,480	1,830	1,150	171
1/20/1995	6,590	1,790	2,830	1,970	171
1/20/2001	7,730	1,190	4,240	2,300	172
3/9/2001	8,210	3,070	3,500	1,640	175
1/1/1988	10,320	1,300	6,360	2,660	176
Min	52	45	5	3	167
Max	10,320	3,070	6,360	2,660	176

2.2 Data Processing

2.2.1 Mapping wetted area

ERDAS Imagine 2010 software was used to produce inundation maps (Figure 6) based on each suitable LandSat TM scene. All classifications followed the same step-wise methodology, as described below.

1. Acquired LandSat TM imagery within date ranges specified. Import to .img format for bands 1-5 and 7.
2. Mask the area of interest. Masking accomplished using ERDAS Imagine Mask command. Mask image created from shapefile using ESRI ArcGIS Spatial Analyst Feature to Raster command. Resulting continuous image converted to thematic image during sub-setting process, using ERDAS Imagine Subset command.
3. Study-area Landsat TM images were classified into 15-class thematic layer using the ERDAS Imagine unsupervised classification (Isodata) process. Up to 10 iterations were allowed, to meet the 0.95 convergence threshold.
4. Thematic classes were then assigned to either inundated class or not-inundated class by visual interpretation using the raw image in either bands 5, 4, 3 or 4, 3, 2.
5. If one of the original 15 classes was not clearly separable into inundated versus non-inundated classes, a mask was used to subset the original raw imagery and steps 3 and 4 were repeated. This process continued until all thematic classes were separated into either inundated or non-inundated classes.
6. The resulting two-class image was re-coded using either the ERDAS Recode command or a custom model written with ERDAS model builder into a new image with only two thematic classes.

7. The ERDAS Imaging Clump command was then run on the two-class image.
8. The clumped image was then used by the ERDAS Eliminate command to remove all groups of pixels less than one hectare in area, those areas smaller than one hectare are assigned the value of nearby larger clumps.

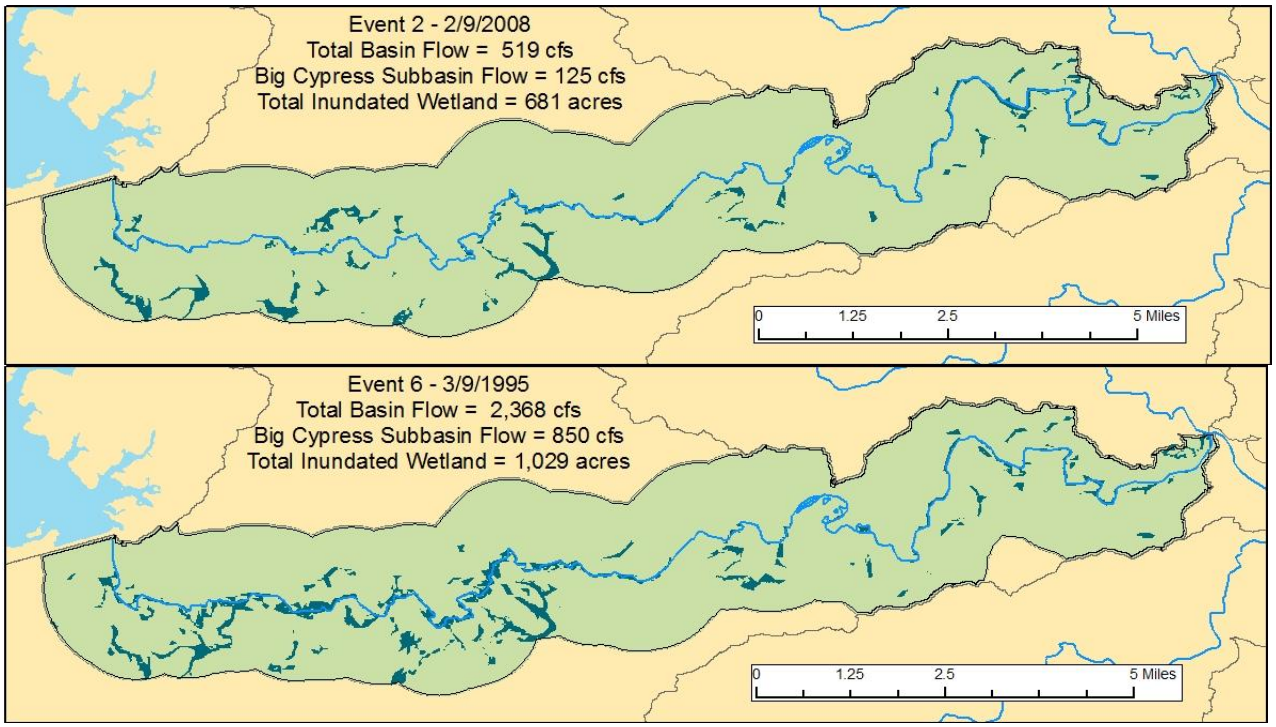


Figure 6a. Displays an example of an increase in areas inundated in the Big Cypress segment as flows increase from 125 cfs to 3,070 cfs. Similar examples for the other study segments are found in Appendix C.

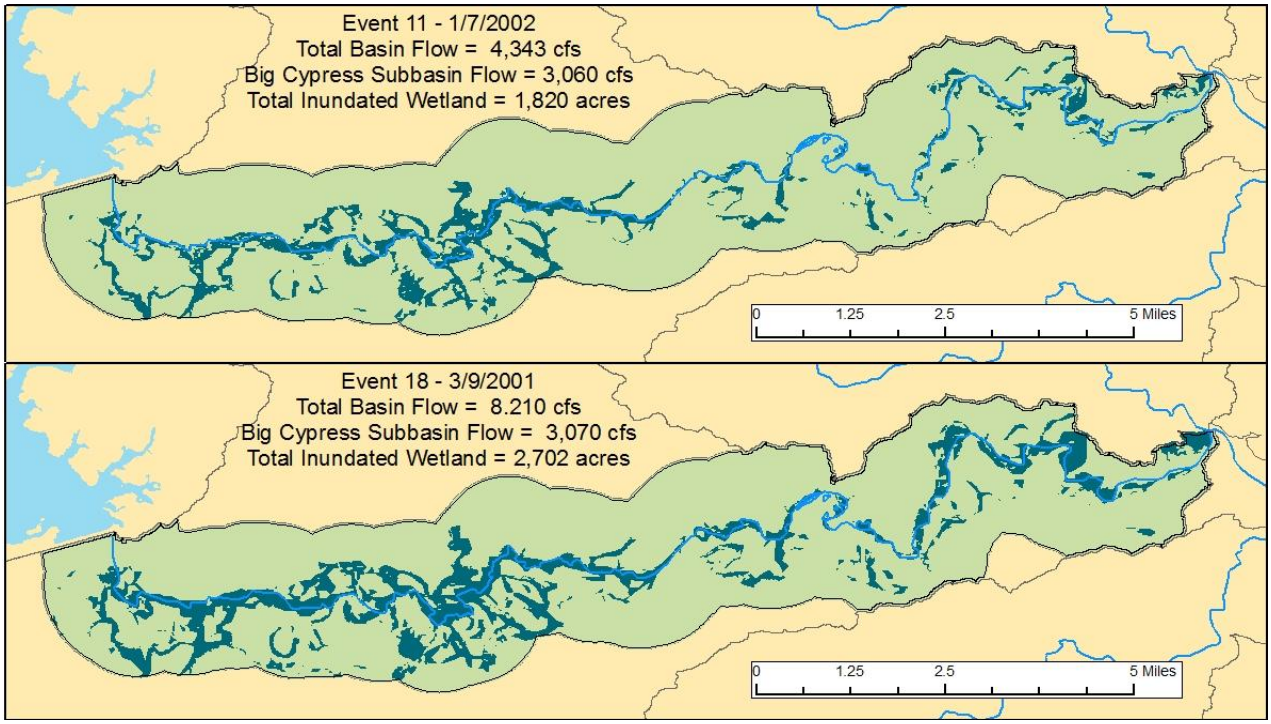


Figure 6b Range of areas inundated in Big Cypress as flows increase from 130 cfs to 3,070 cfs

The area inundated on each date was combined with TPWD vegetation maps to create polygons of area inundated of each vegetation type. Each inundated polygon within the sub-basin defined in Figure 1 was summed to calculate the total area of each habitat type by sub-basin (Table 4 - Table 7).

Table 4 Big Cypress Creek Study Area Inundated (acres)

Date	Total	Swamp	Seasonally Flooded Forest	Temporarily Flooded Forest	Successional Shrubland	Herbaceous Wetland	Wet Prairie	Big Cypress Flow (cfs)
1/18/2006	189	70	7	100	0	12	0	45
2/9/2008	681	282	22	291	0	83	3	125
2/22/2007	776	318	30	311	0	112	4	130
1/4/2001	967	373	48	432	0	110	4	329
1/30/1987	1,396	548	77	663	0	100	7	608
2/6/2007	1,086	491	44	427	0	120	4	837
3/9/1995	1,029	517	37	370	0	102	3	850
1/25/1997	1,576	614	109	718	0	128	8	911
1/20/2001	2,151	803	157	1,002	1	174	13	1,190
3/1/2004	1,598	614	117	712	1	142	13	1,210
1/1/1988	1,741	654	129	851	1	97	8	1,300
1/10/2003	1,462	608	75	656	0	119	4	1,390
1/20/1995	2,053	772	132	967	1	165	15	1,790
3/1/1998	2,343	881	163	1,100	2	179	19	2,480
2/21/1995	2,149	848	135	972	2	175	17	2,620
2/25/2008	1,282	625	58	467	1	129	3	2,670
2/5/2001	2,331	865	164	1,090	1	186	24	2,720
1/7/2002	1,820	754	90	791	2	168	15	3,060
3/9/2001	2,702	910	227	1,333	1	191	38	3,070
Total	5,434	1,141	751	3,086	2	242	212	

Table 5 Little Cypress Creek Study Area Inundated (acres)

Date	Total	Swamp	Seasonally Flooded Forest	Temporarily Flooded Forest	Successional Shrubland	Herbaceous Wetland	Wet Prairie	Little Cypress Flow (cfs)
1/18/2006	116	75	3	34	0	3	0	5
2/9/2008	1,026	558	107	332	0	28	1	229
2/22/2007	1,666	770	220	621	0	53	1	365
1/30/1987	2,743	1,027	474	1,170	1	69	2	521
2/6/2007	1,665	840	179	598	0	47	1	526
2/21/1995	2,681	1,177	385	1,045	0	72	1	647
1/7/2002	2,497	1,133	384	926	0	53	2	689
1/25/1997	2,762	1,122	427	1,117	1	89	7	796
3/9/1995	2,604	1,080	401	1,046	1	75	2	829
2/5/2001	3,137	1,355	488	1,216	0	75	2	1,030
1/10/2003	3,292	1,308	564	1,328	0	89	3	1,070
2/25/2008	2,949	1,331	407	1,129	0	79	2	1,240
3/1/2004	3,287	1,125	641	1,407	1	108	5	1,510
3/1/1998	3,565	1,414	630	1,393	0	121	6	1,830
1/20/1995	3,398	1,318	676	1,288	0	110	6	2,830
1/4/2001	4,912	1,526	1,110	2,106	0	158	11	3,020
3/9/2001	5,323	1,624	1,242	2,275	0	166	17	3,500
1/20/2001	5,309	1,611	1,226	2,299	1	164	8	4,240
1/1/1988	5,260	1,529	1,261	2,274	1	156	39	6,360
Total	7,936	1,745	1,801	4,067	2	199	123	

Table 6 Black Cypress Creek Study Area Inundated (acres)

Date	Total	Swamp	Seasonally Flooded Forest	Temporarily Flooded Forest	Successional Shrubland	Herbaceous Wetland	Wet Prairie	Black Cypress Flow (cfs)
1/18/2006	52	41	1	7	0	2	0	3
2/9/2008	487	318	2	138	0	21	7	165
2/22/2007	930	530	9	374	0	10	6	252
1/30/1987	1,865	965	38	794	2	43	24	327
2/6/2007	1,560	848	16	618	1	64	14	327
1/10/2003	1,746	949	27	693	1	56	20	368
2/21/1995	1,550	911	15	570	1	34	19	506
1/7/2002	1,688	952	20	635	1	57	23	594
2/25/2008	1,371	849	10	458	0	38	14	679
3/9/1995	1,379	853	11	493	1	11	10	689
3/1/2004	2,006	1,067	42	804	1	71	21	700
2/5/2001	1,899	1,080	21	721	1	54	22	735
1/25/1997	2,116	1,085	47	891	2	67	24	800
3/1/1998	2,161	1,171	31	888	1	52	18	1,150
1/4/2001	2,334	1,207	49	987	1	64	26	1,440
3/9/2001	2,300	1,192	45	961	1	68	33	1,640
1/20/1995	2,458	1,221	50	1,098	2	59	27	1,970
1/20/2001	2,663	1,286	71	1,204	2	65	34	2,300
1/1/1988	2,836	1,296	93	1,307	3	84	53	2,660
Total	4,524	1,532	247	2,422	15	151	157	

Table 7 Upper Caddo Lake Study Area Inundated (acres)

Date	Total	Swamp	Seasonally Flooded Forest	Temporarily Flooded Forest	Successional Shrubland	Herbaceous Wetland	Wet Prairie	Caddo Lake Elevation (ft)
1/18/2006	3,700	3,162	74	434	0	30	0	167.2
2/9/2008	4,728	4,154	48	470	0	54	0	169.0
2/22/2007	5,710	4,951	66	623	0	70	0	169.2
1/30/1987	6,314	5,272	101	858	1	73	8	169.5
1/25/1997	7,529	5,886	221	1,314	6	102	1	169.7
2/6/2007	6,084	5,354	52	609	0	68	0	169.7
1/10/2003	6,877	5,749	149	897	0	81	0	169.8
2/25/2008	6,923	5,656	137	1,055	1	73	0	169.9
3/9/1995	7,974	6,259	209	1,388	4	111	4	170.1
3/1/2004	50	20	3	26	0	1	0	170.3
2/21/1995	7,947	6,370	200	1,260	2	110	5	170.3
1/7/2002	8,302	6,405	259	1,520	5	110	3	170.3
2/5/2001	8,489	6,550	277	1,543	4	108	6	170.4
3/1/1998	9,149	6,675	432	1,895	7	132	8	170.7
1/20/1995	8,763	6,429	462	1,730	6	129	7	171.0
1/4/2001	8,786	6,600	448	1,603	7	124	5	171.2
1/20/2001	9,524	6,735	617	2,008	9	139	15	171.6
3/9/2001	10,477	6,986	830	2,469	7	161	25	174.9
1/1/1988	10,722	6,870	909	2,748	7	154	33	175.6
Total	12,255	7,202	1,098	3,693	11	192	59	

While these results are generally consistent with the expectation; that is increased flows (or lake elevation) result in increased areas of inundation, three additional insights are apparent from these results. First, the vegetation types associated with higher elevations (Successional Shrubland, Herbaceous Wetland and Wet Prairie) are less sensitive to changes in flow. Based on the relative level of accuracy inherent in the method used in this study, these vegetation types were excluded from subsequent analysis. Second, when plotting the Seasonally and Temporally Flooded Forest types (Appendix A), the Temporarily Flooded Forest areas responded to increased flows at lower flow rates than the Seasonally Flooded type (in 2 of the 4 sub-basins). This is contrary to expectations given the life history needs of the species that are believed to make up these habitat types. Perhaps future ground truthing of the vegetation maps could be conducted to explain these results, however at this stage the Seasonally and Temporarily Flooded Forests were combined into a single habitat type. As a results of the above two simplifications, subsequent analysis is limited to the "Swamp" and "Flooded Forest" habitat types. Third and finally, while the flow to inundation relationships are generally positively increasing, some events run counter to this pattern. One reason for this is that this analysis assumes an instantaneous response of area inundated to flow. In reality, the area inundated may be the result of higher flows on preceding days. This issue was investigated by reviewing the daily hydrographs for the days preceding the date on which the LandSat Imagery was obtained. This analysis led to the removal of some dates that appear to have been effected by antecedent flows. (This analysis is presented in Appendix B).

2.3 Regression Analysis

The regression analysis conducted in this study follows the approach taken by Benke (2000). Percentage of total habitat area inundated was regressed against associated USGS gage discharge or in the case of the Upper Caddo Segment against lake level. Following Benke's approach for regression of proportional data, the percent areas were arcsine transformed before developing linear regression. The percentage of habitat type inundated was strongly related to river discharge (or elevation) (r^2 range from 0.60 to 0.86 Figure 7).

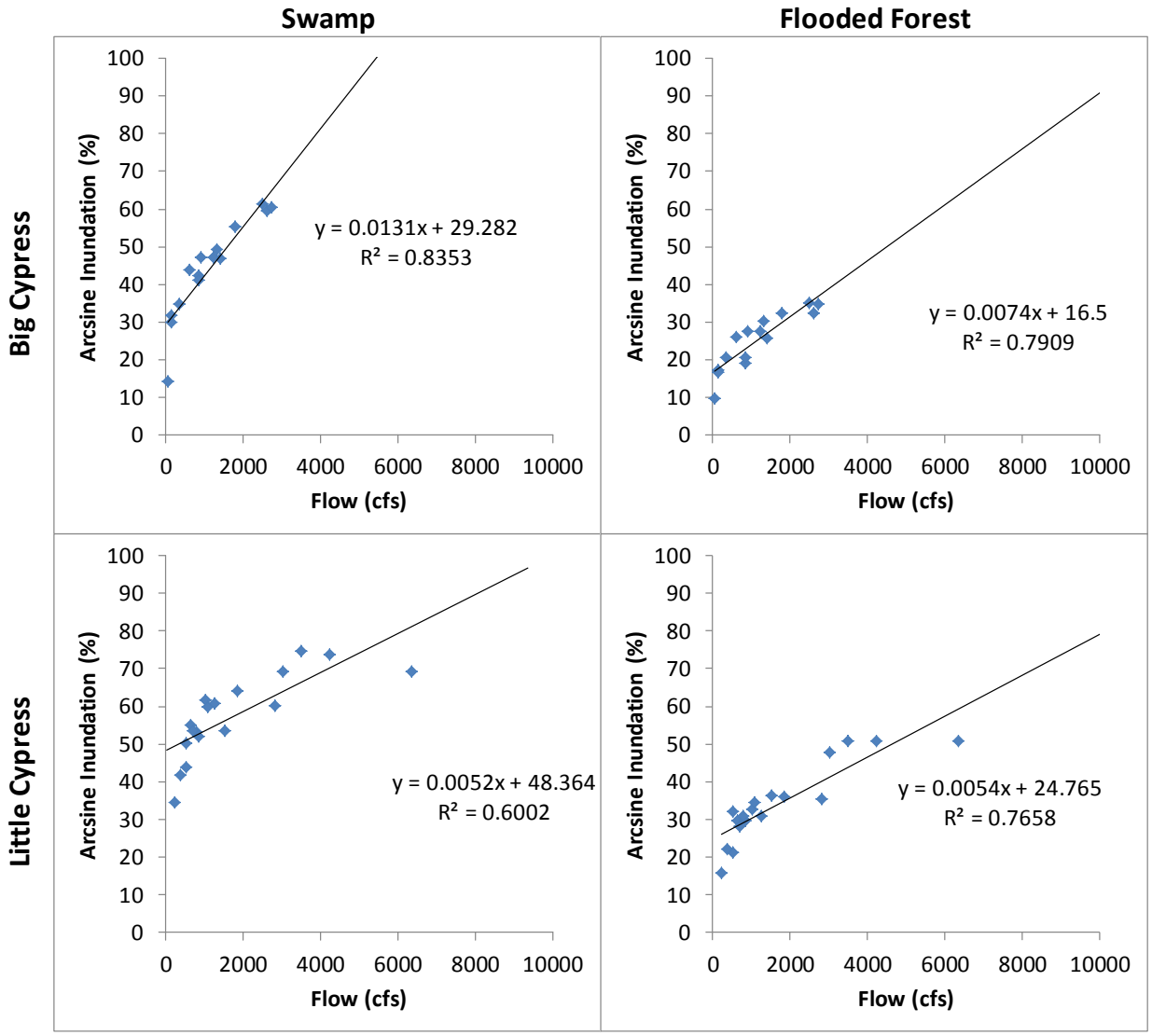


Figure 7 continues on the following page.

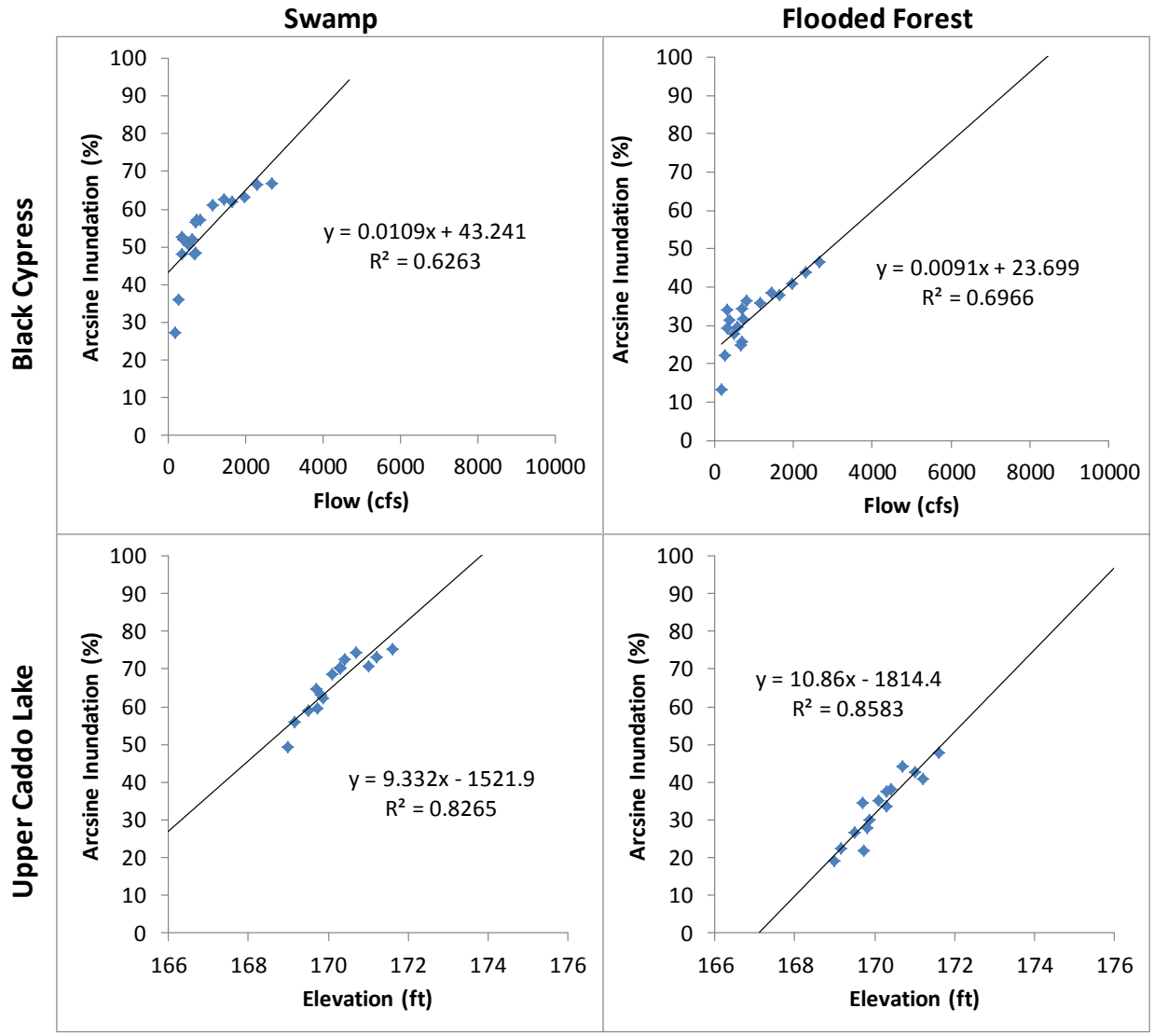


Figure 7 Linear regression of percent of habitat type inundated (arcsine transformed) vs. discharge

Acrsine transformed regression plots may be difficult to interpret (for example the y-axis value of 90 degrees represents 100 percent of the area inundated since sine 90 = 1). In order to make interpretation easier these regressions have been back transformed to display the response in percent area inundated to flow. (Figure 8)

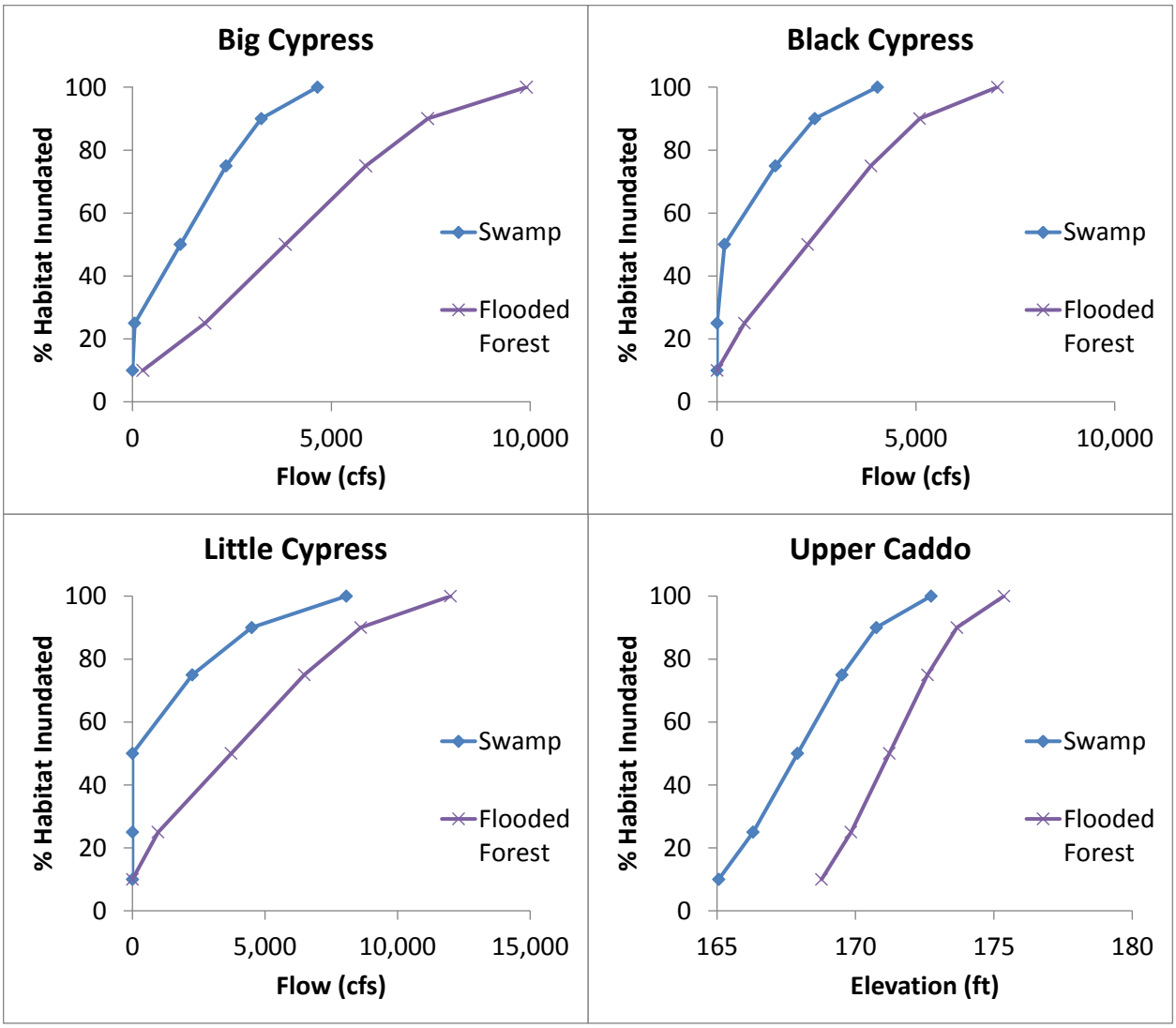


Figure 8 Percent of Habitat inundated vs. Flow (or Elevation)

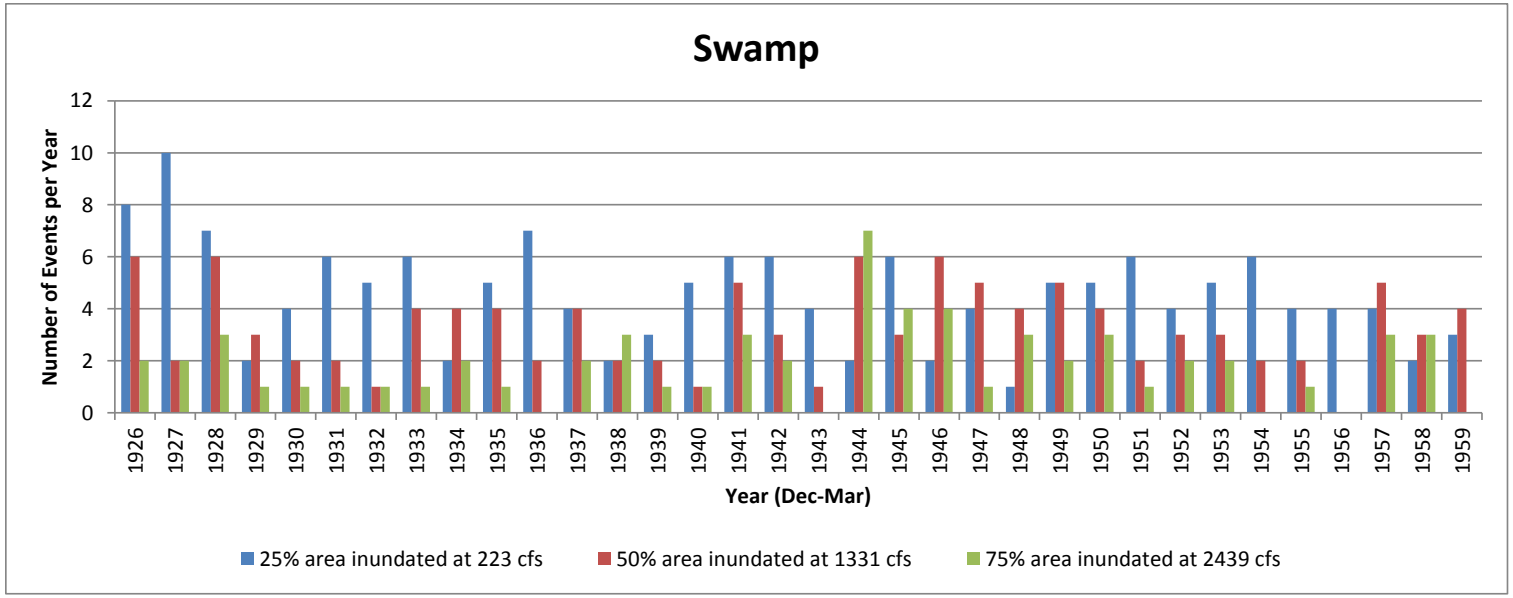
From Figure 8 we can determine the flow magnitudes that would inundate specific percentages of the available habitats. (Table 8) Appendix C provides tables and maps that more specifically illustrate the resulting inundation of habitats in each subbasin study area for a range of flows.

Table 8 Percent of Habitat inundated vs. Flow (or Elevation)

	Big Cypress (cfs)		Little Cypress (cfs)		Black Cypress (cfs)		Upper Caddo (ft)	
Percent Inundated	Swamp	Flooded Forest	Swamp	Flooded Forest	Swamp	Flooded Forest	Swamp	Flooded Forest
10	0	261	175	0	153	267	165	169
25	55	1,821	436	963	383	667	166	170
50	1,204	3,843	873	3,722	766	1,335	168	171
75	2,354	5,866	1,309	6,481	1,149	2,002	170	173
90	3,240	7,426	1,571	8,608	1,378	2,402	171	174
100	4,652	9,912	1,745	11,999	1,532	2,669	173	175

2.4 Time Series Analysis

Time series analysis was conducted to evaluate the durations and frequencies with which the swamp and flooded forests have been inundated. This was done by converting long-term historical gage data from the USGS and Caddo lake elevation data from the Corps of Engineers into a time series of inundated area based on the regression relationships (Figure 7). The relatively long growing season supports a diversity of floodplain plant communities found in the Cypress basin. Since there is an important seasonal component to the inundation, the results of this analysis were limited to inundation that occurs during the growing season. The NOAA office in Shreveport, Louisiana (Carrin et al. 2007) provides data regarding the length of the growing season for the Cypress-Caddo area. According to NOAA, in northeast Louisiana the average date of the first freeze is November 15, while the last is March 10. Therefore, the growing season for the Cypress-Caddo project area is approximately March 11 to November 14 (~ 249 days). However, NOAA-Shreveport has recorded freezing temperatures as early as October 19 and as late as April 11 (NCDC, 2006). This analysis includes flows occurring between March 1 and November 31.



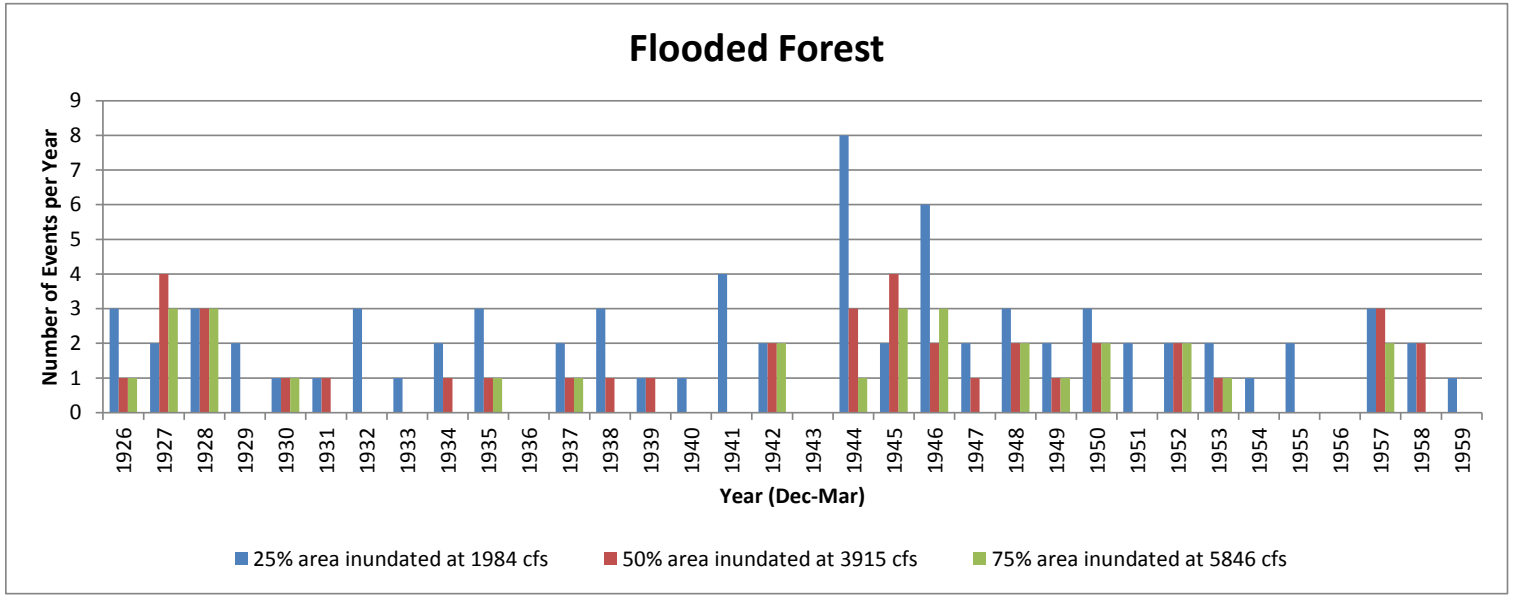
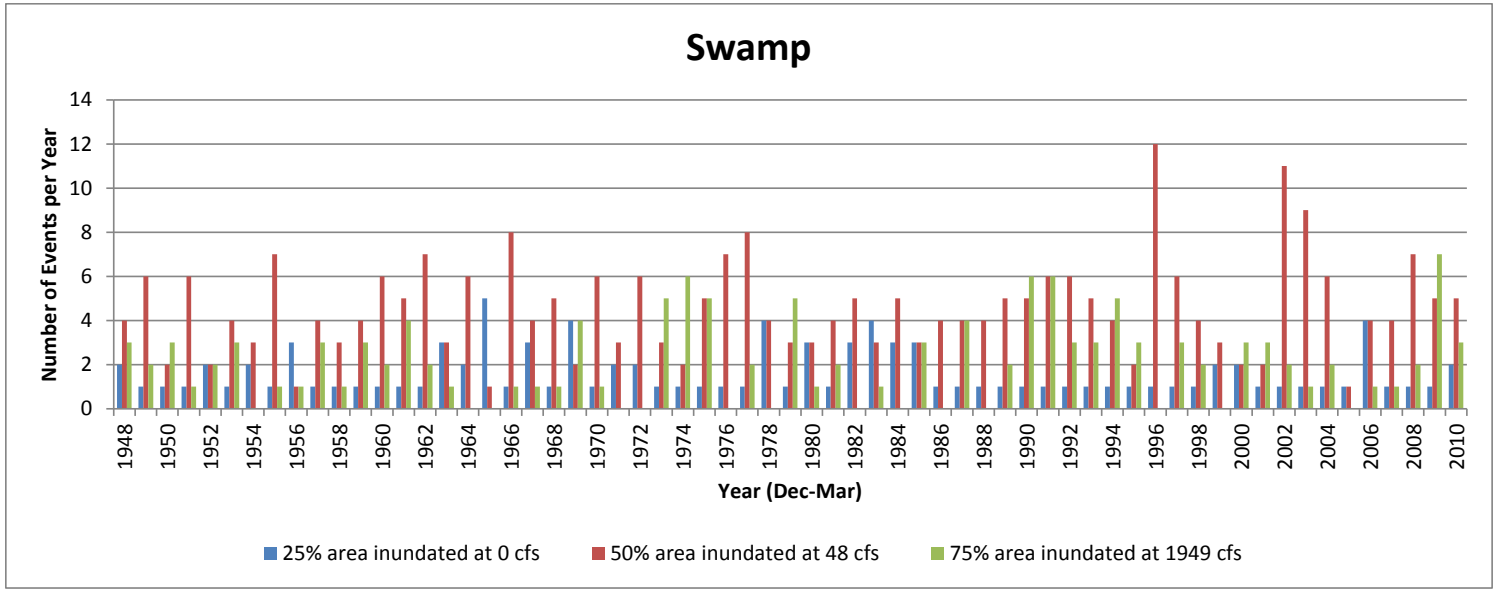


Figure 9 Big Cypress (pre-LOP) - Number of inundation events per year



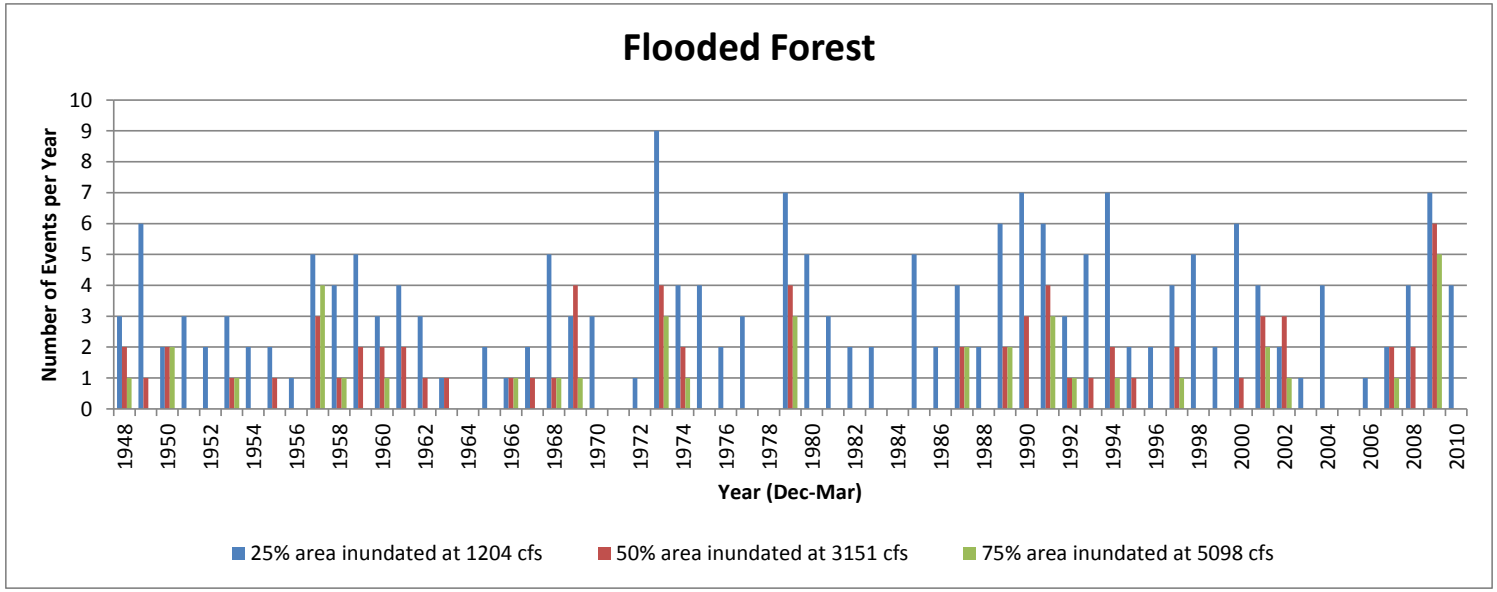
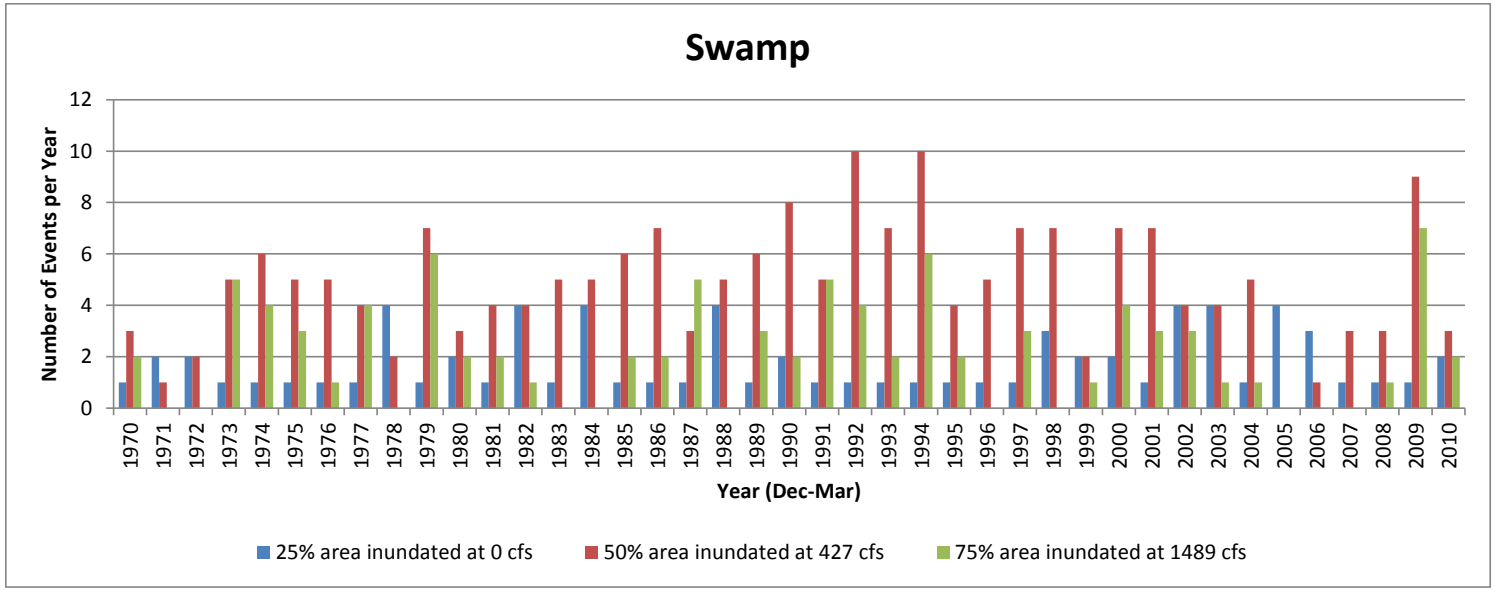


Figure 10 Little Cypress - Number of inundation events per year



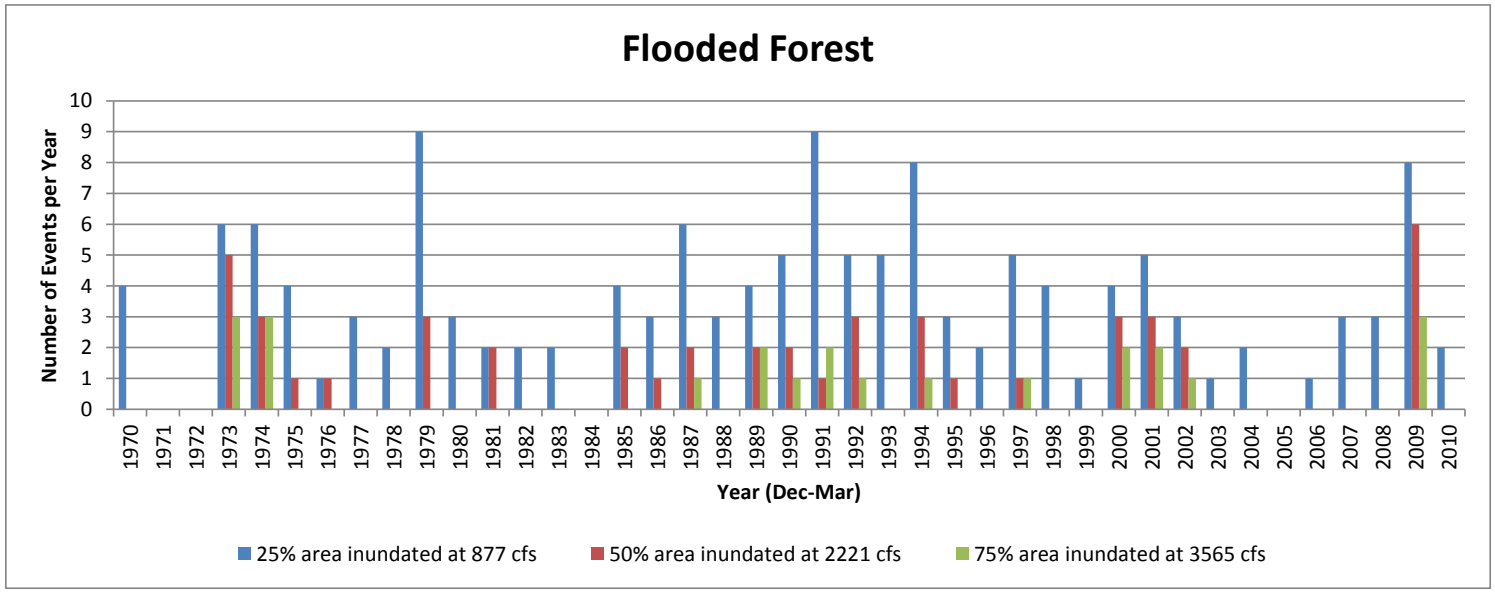
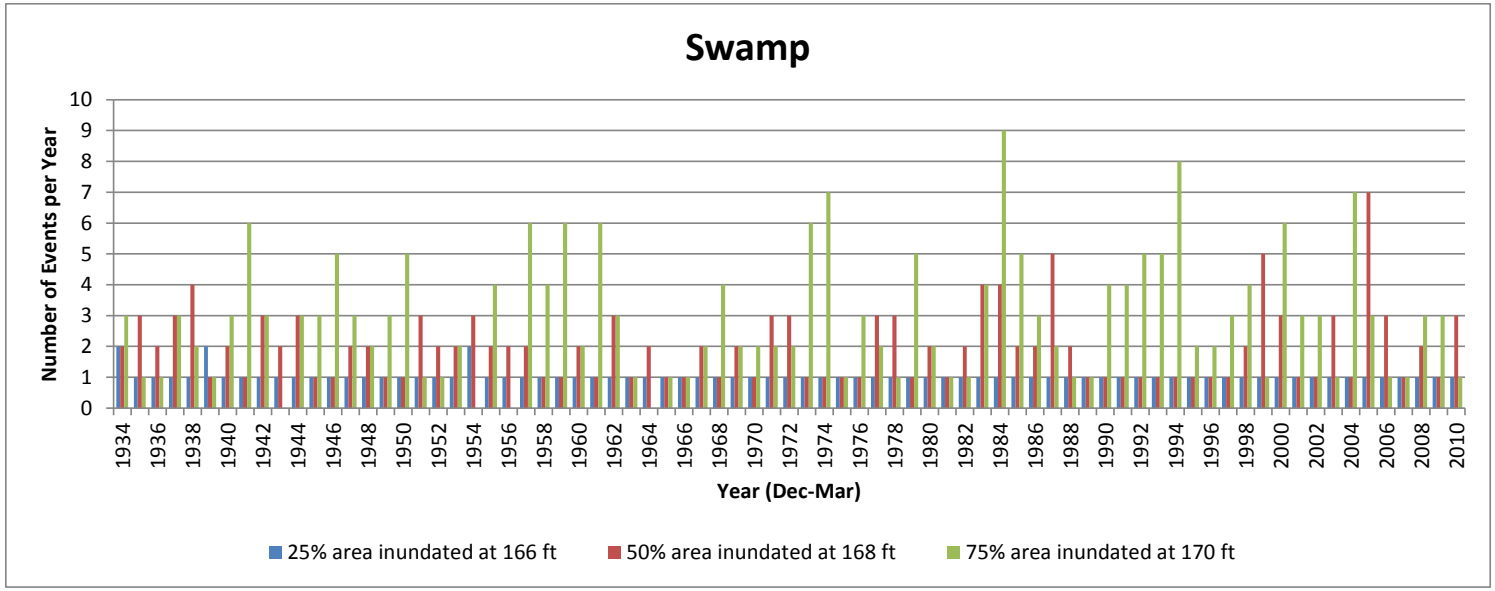


Figure 11 Black Cypress - Number of inundation events per year



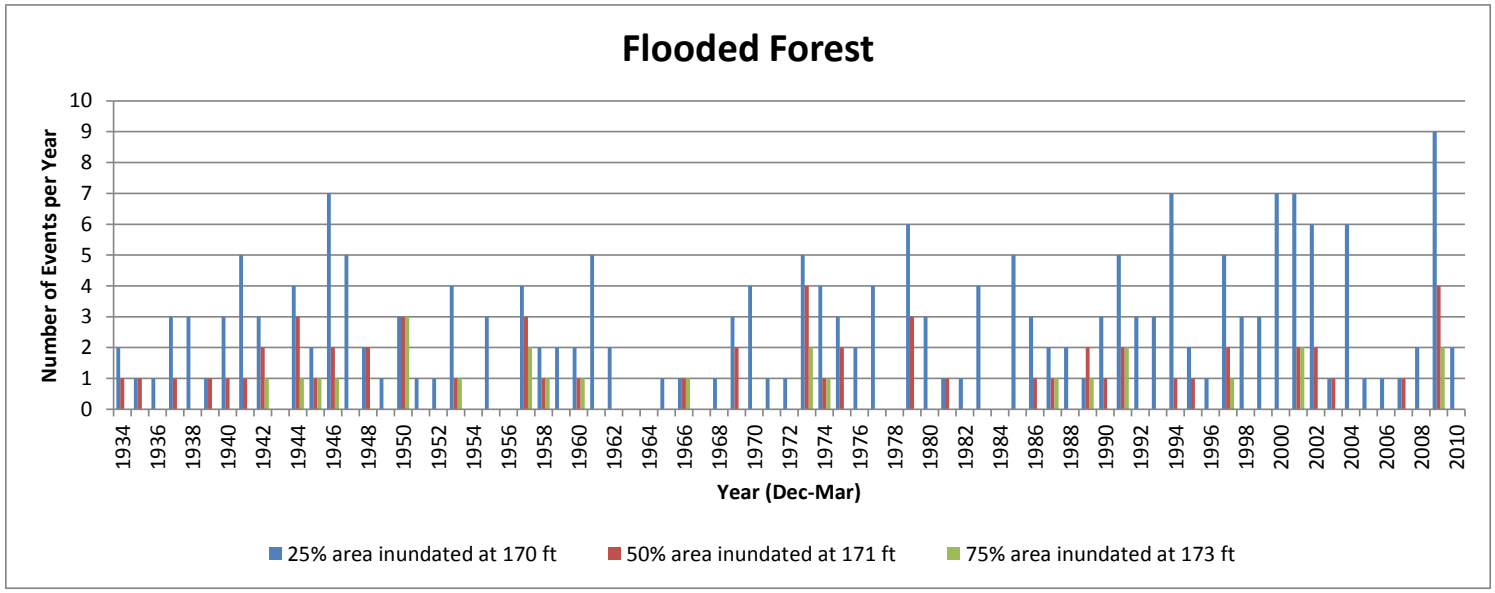
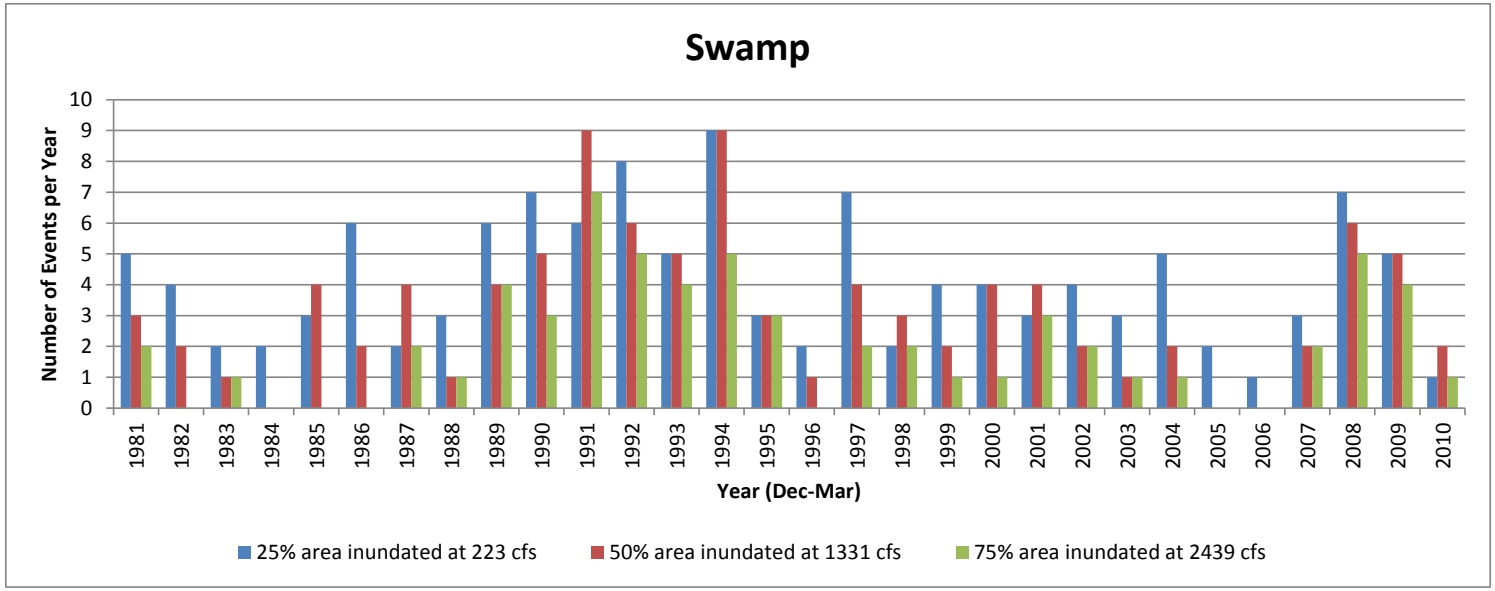


Figure 12 Upper Caddo - Number of inundation events per year



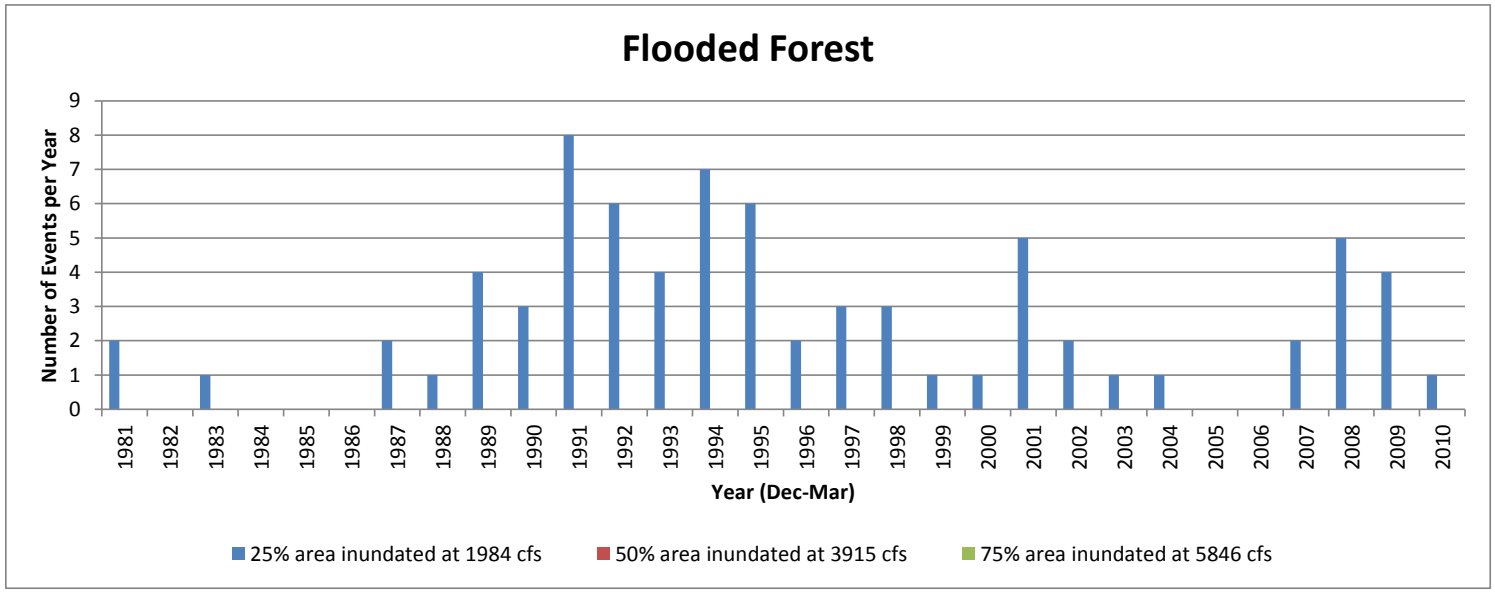


Figure 13 Big Cypress (post-LOP) - Number of inundation events per year

3 RESULTS

3.1 FREQUENCY AND DURATION OF INUNDATION FOR NATURAL SYSTEMS

Although each have different periods of record, a comparison of time series analysis among the Little, Black and upper Caddo study (all assumed generally intact natural systems) show remarkable consistency. In all three systems up to 50 of the swamp areas and 25 percent of the Flood Forest areas are inundated almost every year (90 percent of years) and these events tend to last for about 2 weeks. As percent inundation of swamp areas increases the frequency drops as expected, but again fairly consistently among the three areas with 90 percent of the areas inundated in about half the years for a few days to a week and 100 percent of the areas inundated in about one-third of the years for a few days. For Flooded Forests, about 50 percent of the areas are inundated in about half of the years, 75 percent in a third of the years and the entire Flooded Forest habitat is inundated about 15 percent of the years.

Little	Swamp					Flooded Forest				
Percent of Total Acres	25	50	75	90	100	25	50	75	90	100
% of years with 1 or more events	100%	100%	78%	51%	29%	92%	54%	35%	29%	17%
Median # Events/yr	1.0	4.0	2.0	1.0	0.0	3.0	1.0	0.0	0.0	0.0
Median Duration		17	6	4	3	9	5	4	2	3

Black	Swamp					Flooded Forest				
Percent of Total Acres	25	50	75	90	100	25	50	75	90	100
% of years with 1 or more events	100%	98%	73%	49%	32%	90%	49%	32%	27%	15%
Median # Events/yr	1.0	5.0	2.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0
Median Duration		11	4	4	3	7	4	3	3	2

Upper Caddo	Swamp					Flooded Forest				
Percent of Total Acres	25	50	75	90	100	25	50	75	90	100
% of years with 1 or more events	100%	100%	95%	52%	22%	90%	47%	23%	19%	13%
Median # Events/yr	1.0	2.0	3.0	1.0	0.0	2.0	0.0	0.0	0.0	0.0
Median Duration			18	12	10	15	10	11	14	8

Average	Swamp					Flooded Forest				
Percent of Total Acres	25	50	75	90	100	25	50	75	90	100
% of years with 1 or more events	100%	99%	82%	51%	27%	91%	50%	30%	25%	15%
Median # Events/yr	1.0	3.7	2.3	0.7	0.0	2.7	0.3	0.0	0.0	0.0
Median Duration		14	9	7	5	10	6	6	6	4

For these natural systems, these might serve as targets to maintain the currently healthy systems for future planning studies.

3.2 FREQUENCY AND DURATION OF INUNDATION FOR MODIFIED SYSTEM (BIG)

Since the construction of Lake o' the Pines, flows in Big Cypress are almost never above 3,000 cfs. Although many years see releases of 3,000 cfs (> 77 percent) which inundates about three-quarters of the swamp habitat, about one quarter of swamp habitat is never inundated by overbank flows (presumably this swamp persists via local rainfall and runoff – perhaps try to identify these areas and try to evaluate the health of these swamps). The situation for Flooded Forest habitat appears more dire, as these habitats require greater than 3,000 cfs for

inundation of much of the habitat area (only 25 percent of the Flooded Forest habitat is inundated with significant frequency) which means that the majority of flooded Forest habitat is never inundated via overbank flows from Big Cypress.

Average Natual Systems	Swamp					Flooded Forest				
Percent of Total Acres	25	50	75	90	100	25	50	75	90	100
% of years with 1 or more events	100%	99%	82%	51%	27%	91%	50%	30%	25%	15%
Median # Events/yr	1.0	3.7	2.3	0.7	0.0	2.7	0.3	0.0	0.0	0.0
Median Duration		14	9	7	5	10	6	6	6	4

Big Pre	Swamp					Flooded Forest				
Percent of Total Acres	25	50	75	90	100	25	50	75	90	100
% of years with 1 or more events	100%	97%	85%	71%	59%	91%	65%	47%	41%	38%
Median # Events/yr	4.5	3.0	2.0	1.0	1.0	2.0	1.0	0.0	0.0	0.0
Median Duration	19	11	8	6	5	9	4	4	4	3

Big Cypress Regulated	Swamp					Flooded Forest				
Percent of Total Acres	25	50	75	90	100	25	50	75	90	100
% of years with 1 or more events	100%	90%	77%	7%	0%	80%	0%	0%	0%	0%
Median # Events/yr	4.0	3.0	2.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0
Median Duration	28	13	10	16		10				

With respect to the question of how to develop flow magnitude, duration and frequency targets for Big Cypress, the above analysis presents at least two options for consideration. One would be to rely on the pre Lake o' The Pines results for Big Cypress and the other would be to consider the results from the other unregulated systems. It would be expected that the vegetation community would have responded to similar inundation patterns and the results from these two analyses would be generally consistent. For inundation areas up to about 75 percent of the swamp area and 50 percent of the Flooded Forest areas the results are generally consistent, it is only at very high flows where the frequencies of occurrence begin to diverge between the two analyzes. These frequency differences can be explained in part by the periods of record available for the different gages. The natural systems statistics are made up of varying gage records, though all include at least the period 1969 – 2010, whereas the Big Cypress pre Lake o' the Pines period is 1925-1959. It is worth noting that the results are surprising in that the early period includes the drought of record but has higher frequency of meeting the higher flow rates than the statistics for the natural systems. In any event, the results of this analysis confirm the consensus reached at the initial Cypress Flows Workshop (2005); that flows higher that 3,000 cfs would be necessary to maintain intact riparian systems. They also confirm the refinement to high flow pulse recommendations made based on analysis of pressure transducer data (USGS) which showed that some riparian connective occurs at flows in the range of 1,500 – 2,000 cfs.

3.3 FREQUENCY AND DURATION OF INUNDATION BASED ON PROPOSED BUILDING BLOCKS

A proposal for implementation of the recommended flows will be discussed at the Cypress Flows Project meeting in December 2011. As the details of this procedure are finalize and incorporated into reservoir operations and water availability models, the resulting flows from these simulations will be use to create inundation time series for potential future scenarios.

4 Discussion

4.1 Linking Stream Discharge and Inundation Area within BLH Forests

Using Landsat TM data from 1987 through 2008, this study analyzed the effect of daily discharge on floodplain inundation within the overall study area with a cumulative river reach length (main channels of Big Cypress, Little Cypress, and Black Cypress Bayous) of 140.52 mi (226.65 km), and a total BLH forest area of 56,220 ac (22,752 ha). Note that the Lower Big Cypress Bayou study area is completely encompassed by the Upper Caddo Lake study area (Figure xxx. The extensive area and long period of analysis (21 years) greatly exceed previous published studies that have quantified daily inundation dynamics within floodplains.

The published research that is most similar to the current effort (Benke et al. 2000) used successive aerial photography flown 1984-1985 along a 6.3-km reach of the Ogeechee River in Georgia. The Benke et al. (2000) study determined flood-inundation areas using the photography, which allowed regression with daily river discharge, and subsequent extrapolation of flooded-forest area for a 58-year record (1938-1995) of daily discharge from a single USGS gage.

The current study's thesis is that the distribution of mapped BLH forest types closely coincides with the areal distribution of hydrologic regimes. The literature review identifies linkages between bottomland habitat distributions and flood regimes (Figure 1). The BLH forest-hydroperiod relationship is sufficiently documented by study results (Appendix A) to permit the TPWD BLH forest maps to essentially substitute for the extent of corresponding flood regimes, as defined in Figure 1. Examination of Appendix A reveals a consistent sequence of flood inundation according to the relative soil-surface elevation and landscape context of TPWD BLH types.

4.2 Historical Flow Regimes

An analysis of the historic flow patterns in the basin was the basis for the development of instream flow recommendations in the Cypress Flows Project (Winemiller et al. 2005, Trungale 2010). The analysis presented in this report can be considered an overlay to these preliminary recommendations that can be used to validate or refine the preliminary recommendations. Linking stream discharge to inundation area within BLH forests provides a means for measuring the effect of these flows on the forest ecology. As noted above, these results should be re-analyzed in subsequent phases of this project. However, the preliminary results appear to confirm several expectations as to the relationship between flow and inundation of BLH forests.

Figure E-1 indicates that flows regulated by Lake O' the Pines (post), regularly inundate significant areas of swamps (>70 percent of the available areas). However, inundation of seasonally and temporarily flooded forests is limited to less than 30 percent of the available areas under the post Lake o the Pines regulated flow regime. Assuming this finding is confirmed in subsequent data analyses, support is provided for the original Building Blocks recommendation for more infrequent but much higher flow recommendations. Furthermore, the data suggest that a failure to produce these higher (10-20 year recurrence flows) could lead to invasion of upland species into these seasonally and temporarily flooded forests; a hypothesis that might be confirmed with long term monitoring.

Results from analysis of data from Little and Black Cypress also suggest that significant percentages of swamp habitats are inundated at moderate high flow pulse levels. However, the data also indicate only very high flows, which continue to occur infrequently, inundate large percentages of the seasonally and temporarily flooded forests.

One finding that is contrary to expectations is that temporarily flooded forests appear to respond to lower flow rates than seasonally flood forests, in some areas. This finding will be addressed in subsequent study phases.

The data developed in this study can be used to investigate intra- and inter- annual inundation patterns including time and duration of inundation. These will be addressed in subsequent phases of this study, once the initial regressions are re-evaluated.

4.3 Holistic Management of Riparian Water Resources

In terms of sustaining society, a hectare of floodplain is second in value only to a hectare of estuary (Costanza et al. 1997). Water management needs new direction, as floodplains become more threatened and, thus, increasingly important for meeting a variety of human, environmental, and ecological services. Gosselink et al. (1990) conclude that reduction of the cumulative impacts of altered river hydrology is so vital that landscape-scale regulation is now required across political boundaries, such as state and national borders. Whether or not regulatory in nature, a shift is essential from a water supply outlook to holistic management of water resources (Hughes and Rood 2003).

A holistic approach necessarily incorporates water conservation and prioritization of water allocation. Floodplain infrastructure changes may be required in order to gain multiple benefits from increasingly limited water resources. An example would be the replacement of constructed flood-defense barriers with a natural flood-management plan utilizing floodplains for supplemental water storage, while enhancing ecosystem services. In this manner, society simultaneously gains the multiple benefits of reduced flood elevation and velocity, base flow maintenance, groundwater recharge, and ecosystem services (Gosselink et al. 1990). Restoration of riparian ecosystem services, while reducing flood damage, has more widespread ramifications, such as increased primary and secondary biotic production and associated economic returns downstream. Rood et al. (2005) find that systemic restoration of more natural flow dynamics benefit a much larger area of the floodplain than manufactured corrections.

The quantification of the flow regime, including high and overbank flows, is the first priority for ecologically sustainable water management within floodplains (Richter et al. 2003). Since it is critical for the maintenance of native biodiversity and natural ecosystem processes, an accurate determination of the flow regime provides important upfront guidance for all subsequent steps aimed at resolving conflicts between extractive and ecosystem needs. Richter et al. (2003) strongly recommend this approach instead of treating ecological impacts as regulatory questions after water development plans are brought forward. The current project introduces an empirical approach not only for accurately quantifying high and overbank flows, but also for specifying their interactions with BLH habitats.

Basic to the systemic restoration of river-floodplain ecosystems is permitting flow variation according to the natural hydrograph, which may necessitate different flow prescriptions for dry, normal, and wet years (Rood et al. 2005). The pragmatic approach is to augment regulated flows during high-flow years, in order to compensate for water diversions required during low-flow years. As discussed above, the reproductive requirements of BLH tree species need only be satisfied some years (Hughes and Rood 2003), so there is flexibility in meeting both the between-year variability of environmental flows and the stakeholder priorities.

The restoration of the natural flow regime during high-flow years is practical, since these years provide enough water to maintain BLH forest habitats, while meeting both short-term economic purposes and long-term environmental and socioeconomic requirements (Rood et al. 2005). As discussed above, regulated high and overbank flows, timed to match the life histories of most biota, should be followed by gradual drawdowns and

subsequent maintenance flows to protect vulnerable juvenile life stages. Effective planning for the timing, frequency, and duration of higher flows also supports short-term processes such as fish spawning (a trigger variable) and long-term processes such as riparian forest regeneration (Opperman et al. 2010).

In terms of maintaining the compositional integrity of BLH tree communities and preventing the encroachment of upland and exotic species, overbank flows after foliage emergence are most effective (Gosselink et al. 1981). Flood tolerance differences among tree species are most pronounced after photosynthesis begins in early spring. Remote sensing work accomplished during this project indicates that on average foliage emergence within the Cypress-Caddo basins begins in mid-March, which coincides with the average start (March 11) of the growing season (Carrin et al. 2007).

4.4 Recommendations for Future Research

According to Rood et al. (2005), the most important goal of future research and application within floodplains is improving the calculation for the ecological benefits of restoration. Their other top priority for future studies is determining how to effectively "resize" rivers and their floodplains, in order to maximize necessary ecosystem processes within an altered flow regime. The current data analysis provides an example of how to achieve both of these priorities. The wetted-surface classification of thematic-mapper data quantifies the interaction of high-flow and overbank events with the full range of floodplain habitats. In this manner, the functional response of the floodplain ecosystem to different stream discharge values is directly measured.

Regression analyses of percent inundation (floodplain, total BLH forest habitat, selected BLH forest types) versus stream discharge are needed for additional river basins, in order to derive inundation-discharge relationships, which are broadly applicable. These relationships may then be extrapolated to the long-term record for daily discharge for USGS gages across a range of hydrologic regimes. Flood-duration curves could be developed from the discharge record and the inundation-discharge relationship. For example, Benke et al. (2000) plotted discharge and inundation against the percentage of time that a selected discharge value was equaled or exceeded, in order to produce discharge-duration and inundation-duration curves, respectively. Taking this further, if relative percent values for discharge were modeled based on hydrologic "breakpoints", the inundation-duration relationship may be extrapolated to other gages, in addition to those selected for direct discharge-inundation analysis.

Another recommendation for future applied research is to develop a more holistic and collaborative approach to maintain essential high and overbank flows, which incorporates the following biological considerations to modify inundation-duration relationships derived through the above empirical and regression analyses:

4.4.1 Ecological Flow Prescriptions

In order to match most organisms' life histories, high and overbank flow events should be specified according to requisite discharge values and their frequency, timing, and duration. These ecological flow prescriptions should include gradual drawdowns and subsequent maintenance flows to protect vulnerable juvenile life stages.

4.4.2 Importance of Early Spring Flows

The above prescriptions should also stipulate the probability of high and overbank flows in early spring, which are important for maintaining BLH habitats. The current data analysis emphasizes the importance of overbank flows early in the growing season in order to sustain BLH forests, which provide essential ecosystem services within the floodplain. Peer-reviewed literature also identifies annual early spring (late March and early April) overbank flows with a duration of two to four weeks as critical to the survival of seasonally flooded BLH forest habitats within the southeastern United States, including east Texas.

4.4.3 Key BLH Habitats as Benchmarks for Determining Regulated Flows

For restoring habitat diversity and ecosystem processes, regulated flows regimes should target the health of seasonally and temporarily flooded hardwood forests, with the latter being more protective due to its topographic context. Baldcypress and other swamps, with the possible exception of backswamps, flood more frequently and for longer duration than other habitats more sensitive to the maintenance of overbank flows and connections with the river discharge regime.

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APPENDIX A SEASONALLY AND TEMPORALLY FLOODED FOREST

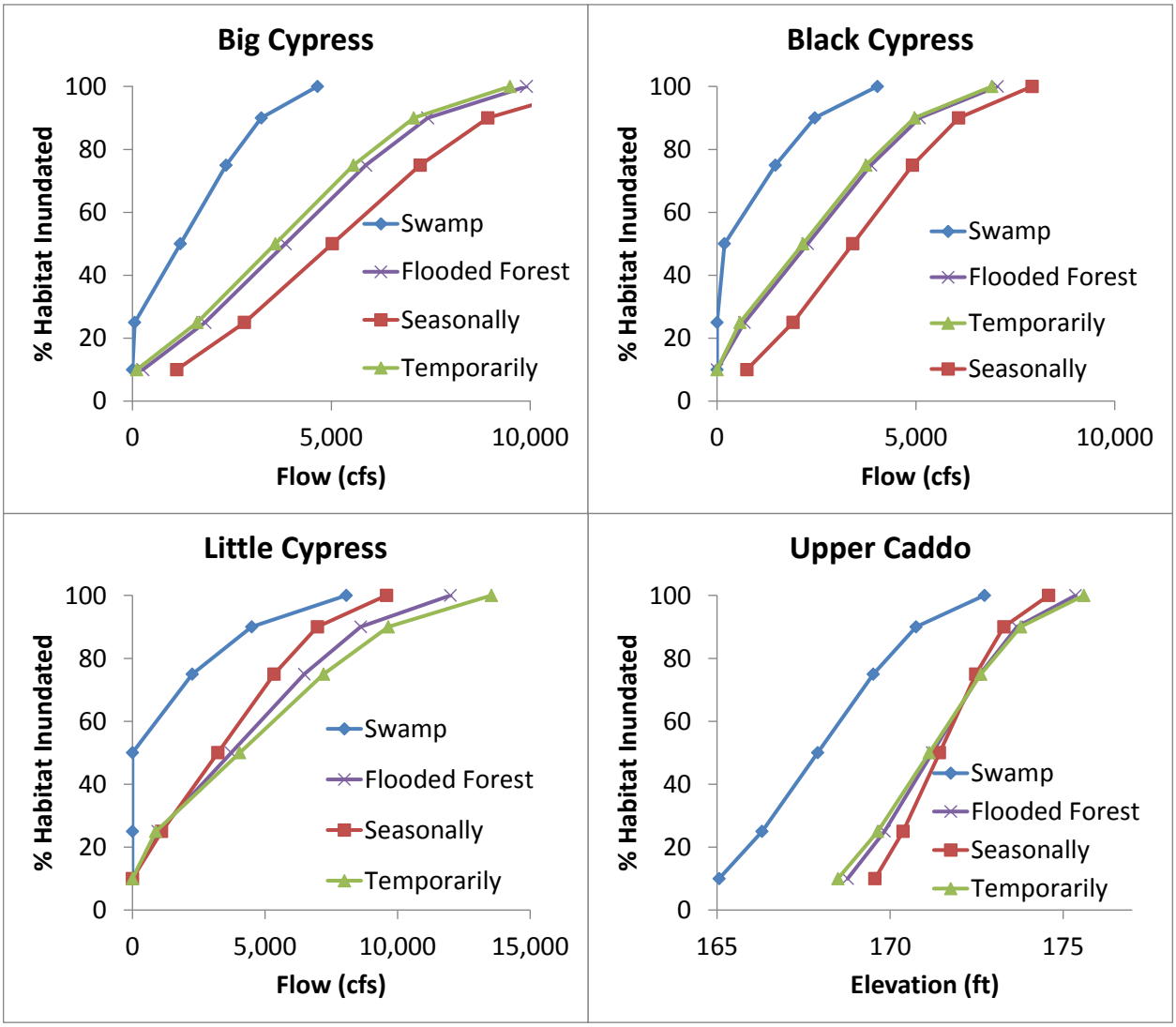

Figure A1 Relationship between habitat type inundated and discharge

APPENDIX B ANTECEDENT HYDROLOGY

Antecedent hydrology was examined to evaluate whether some data should be excluded from the analysis to develop regressions. Dates were excluded when flows on the days preceding the date of the satellite imagery were highly variable. For the Big Cypress study this analysis included reviewing flows in the other basins.

For Big Cypress events number 9, 11, 12 and 19 were not included in the development of the regression equations. Event number 9 and 19 were sharply falling and rising on the days prior to the imagery. Flow for events 11 and 12 was relatively steady in Big Cypress however the inundation response in Big Cypress is contrary to expectations and review of the hydrographs for Little and Black Cypress suggest that storms not captured by the gage measurements just below Lake O' Pines were affecting the area of inundation.

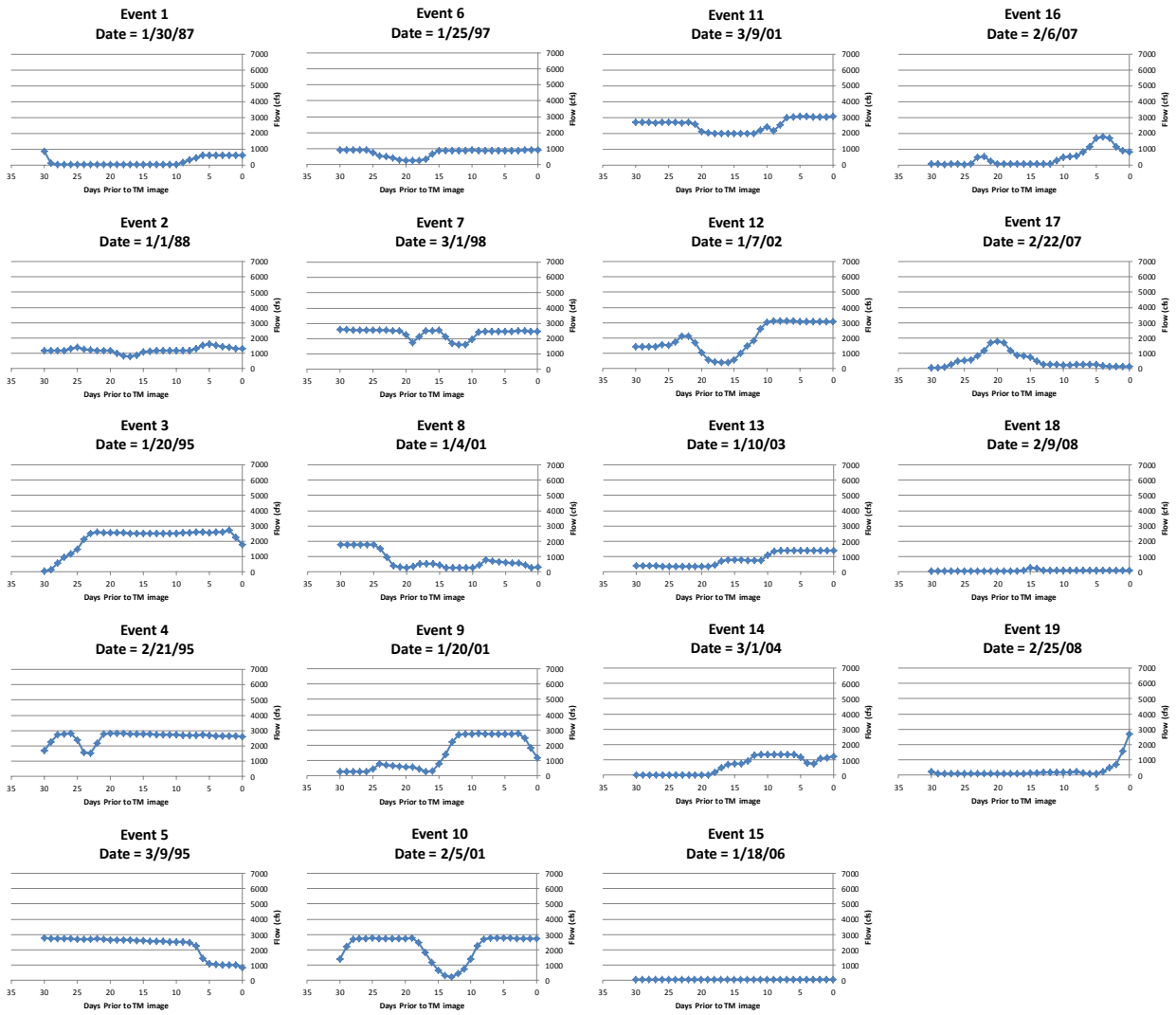

Figure 14 Big Cypress

Only event 15 was removed from the Little Cypress regression. Flow on this day was essentially zero.

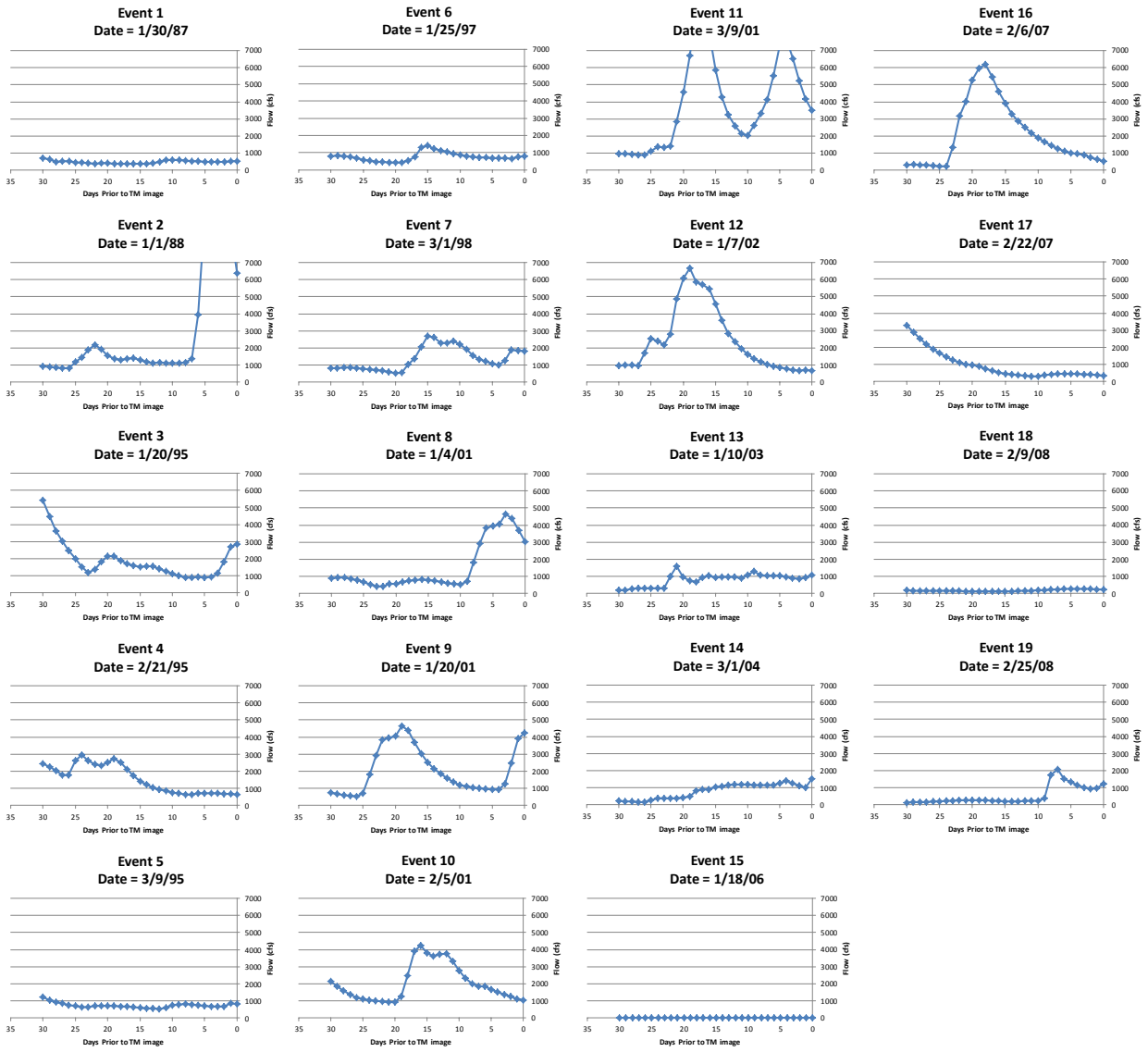

Figure 15 Little Cypress

Only event 15 was removed from the Black Cypress regression. Flow on this day was essentially zero.

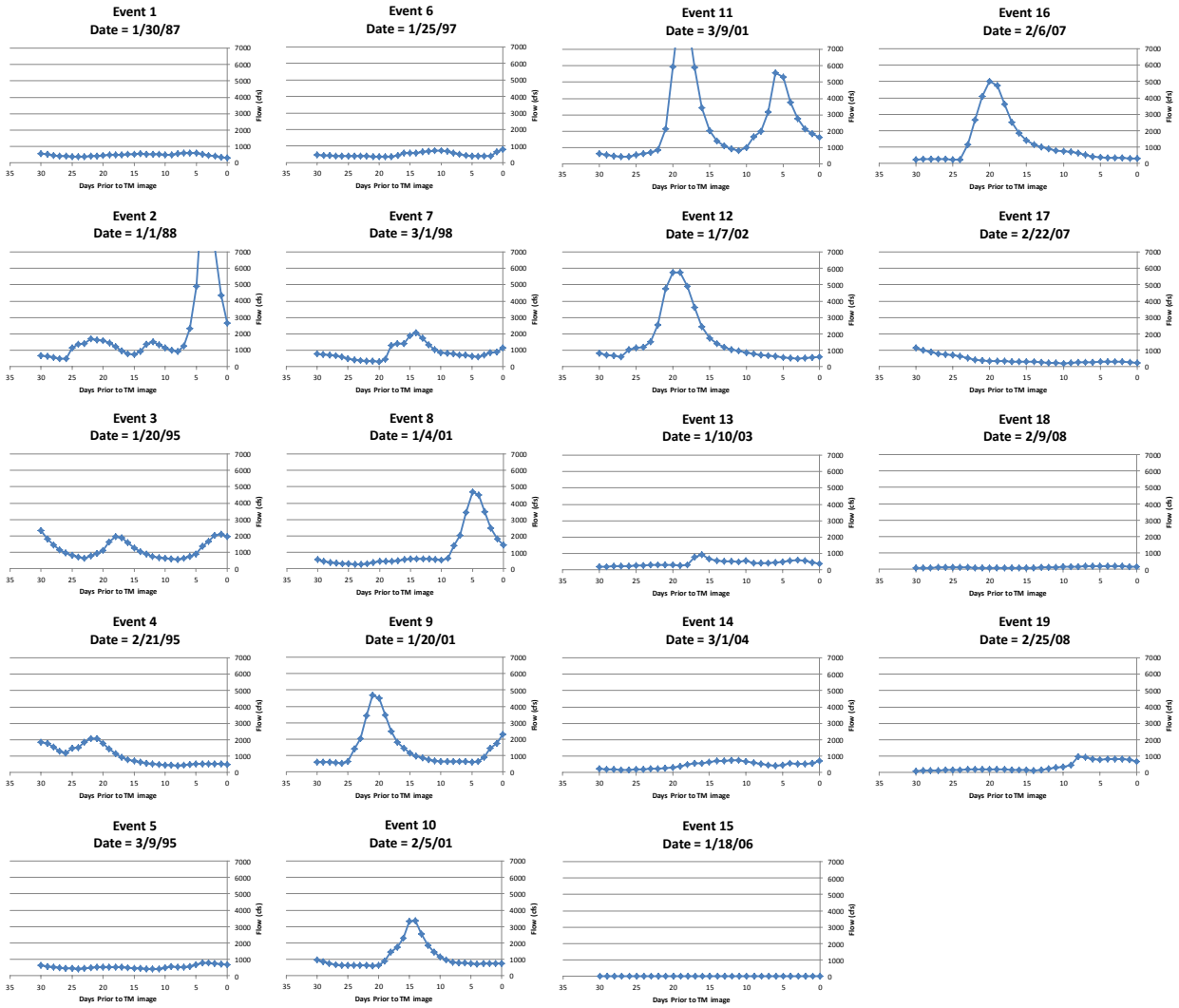

Figure 16 Black Cypress

Events 2, 11, 14, and 15. Event 11 had heavy cloud cover making it unsuitable for analysis. The other events were either very high or very low elevations. At these extremes the flow acrsin regression of elevation to percent inundation is not linear, thus care should be taken when extrapolating the regressions to these elevations.

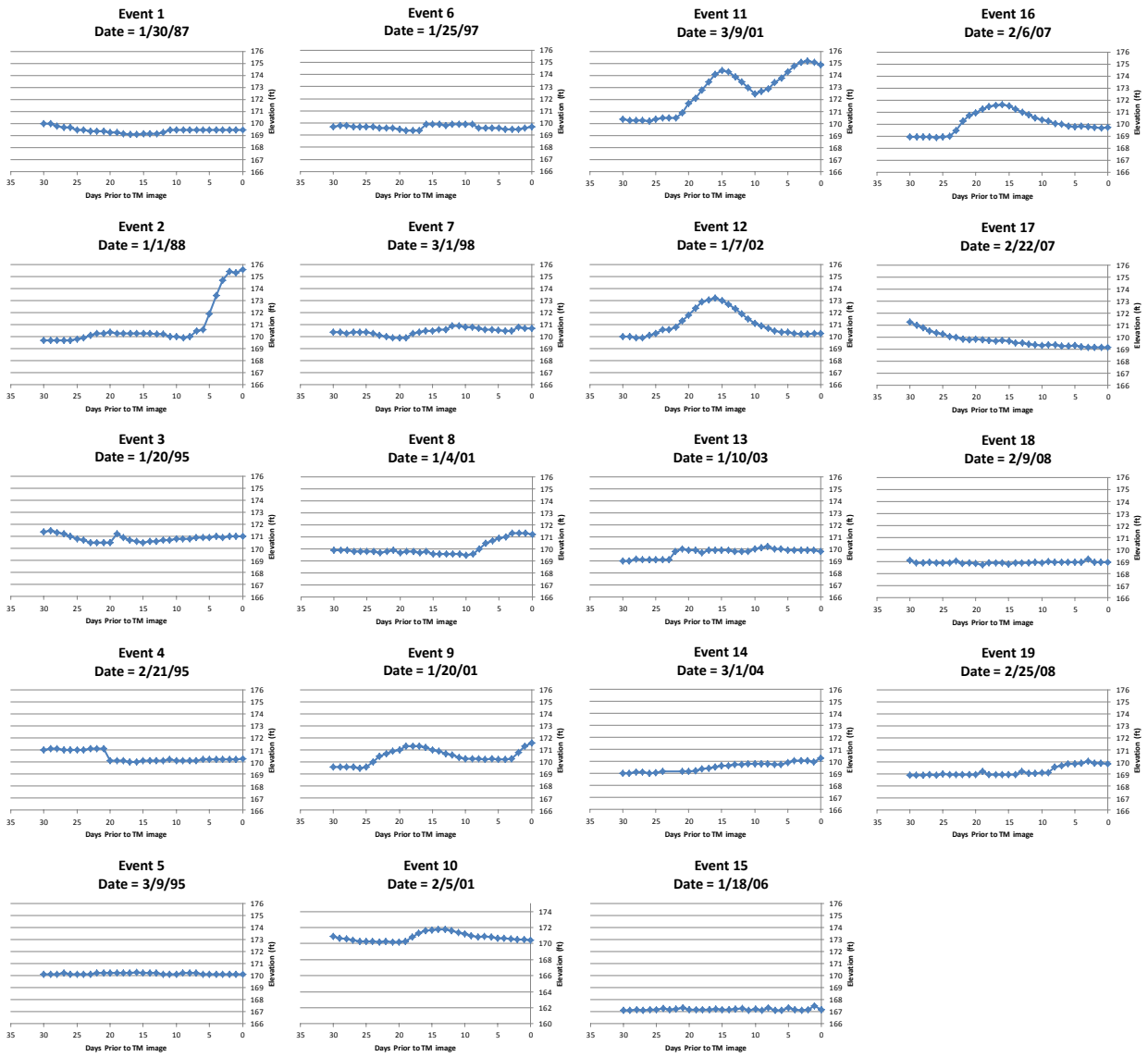

Figure 17 Caddo Lake

APPENDIX C INUNDATION TABLES AND MAPS

Contained in the Appendices below are a series of four maps depicting inundations of habitat in each subbasin study area for a spectrum of hydrologic events. For consistency, the hydrologic events were sorted in ascending order of total basin flow. Because events affected each study area uniquely, different events were selected for each study area where appropriate to show a broad spectrum of habitat inundation. Complete datasets for all events studied are provided in the corresponding tables for each study area and events used in the map series are noted in red text.

Appendix C.1 Big Cypress

Appendix C.2 Little Cypress

Appendix C.3 Black Cypress

Appendix C.4 Caddo Lake

APPENDIX C.1 BIG CYPRESS

Event	Date	Total Habitat Area	Swamp	Seasonally Flooded Forest	Temporarily Flooded Forest	Successional Shrubland	Herbaceous Wetland	Wet Prairie	Big Cypress Flow (cfs)	Total Basin Flow (cfs)
1	1/18/2006	189	70	7	100	0	12	0	45	52
2	2/9/2008	681	282	22	291	0	83	3	125	519
3	2/22/2007	776	318	30	311	0	112	4	130	747
4	1/30/1987	1,396	548	77	663	0	100	7	608	1,456
5	2/6/2007	1,086	491	44	427	0	120	4	837	1,690
6	3/9/1995	1,029	517	37	370	0	102	3	850	2,368
7	1/25/1997	1,576	614	109	718	0	128	8	911	2,507
8	1/10/2003	1,462	608	75	656	0	119	4	1,390	2,828
9	3/1/2004	1,598	614	117	712	1	142	13	1,210	3,420
10	2/21/1995	2,149	848	135	972	2	175	17	2,620	3,773
11	1/7/2002	1,820	754	90	791	2	168	15	3,060	4,343
12	2/5/2001	2,331	865	164	1,090	1	186	24	2,720	4,485
13	2/25/2008	1,282	625	58	467	1	129	3	2,670	4,589
14	1/4/2001	967	373	48	432	0	110	4	329	4,789
15	3/1/1998	2,343	881	163	1,100	2	179	19	2,480	5,460
16	1/20/1995	2,053	772	132	967	1	165	15	1,790	6,590
17	1/20/2001	2,151	803	157	1,002	1	174	13	1,190	7,730
18	3/9/2001	2,702	910	227	1,333	1	191	38	3,070	8,210
19	1/1/1988	1,741	654	129	851	1	97	8	1,300	10,320
Total Habitat in Basin		5,434	1,141	751	3,086	2	242	212		

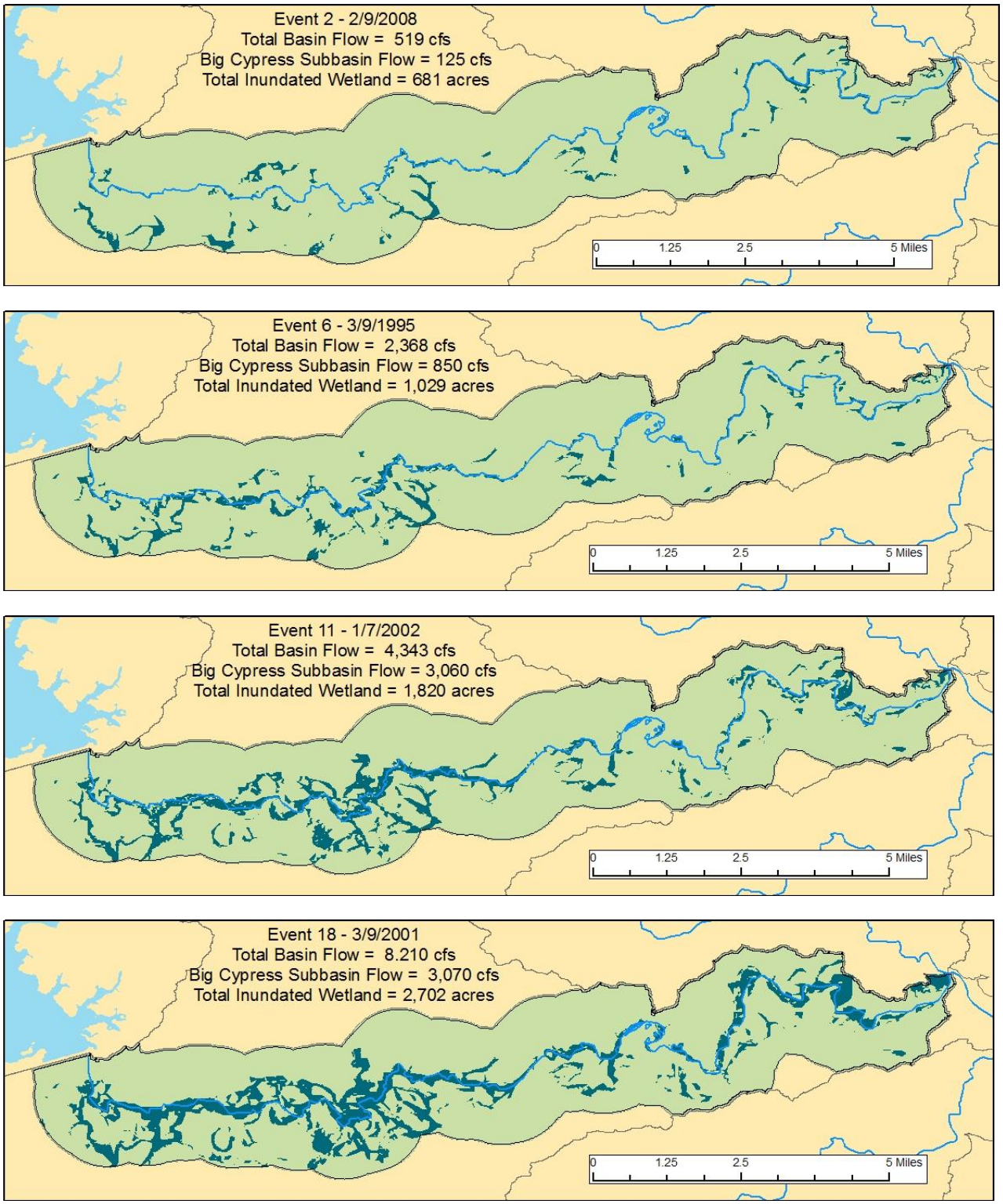

Figure C1 Inundation of habitats for a spectrum of hydrologic conditions, Big Cypress Subbasin

APPENDIX C.2 LITTLE CYPRESS

Event	Date	Total	Swamp	Seasonally Flooded Forest	Temporarily Flooded Forest	Successional Shrubland	Herbaceous Wetland	Wet Prairie	Little Cypress Flow (cfs)	Total Basin Flow (cfs)
1	1/18/2006	116	75	3	34	0	3	0	5	52
2	2/9/2008	1,026	558	107	332	0	28	1	229	519
3	2/22/2007	1,666	770	220	621	0	53	1	365	747
4	1/30/1987	2,743	1,027	474	1,170	1	69	2	521	1,456
5	2/6/2007	1,665	840	179	598	0	47	1	526	1,690
6	3/9/1995	2,604	1,080	401	1,046	1	75	2	829	2,368
7	1/25/1997	2,762	1,122	427	1,117	1	89	7	796	2,507
8	1/10/2003	3,292	1,308	564	1,328	0	89	3	1,070	2,828
9	3/1/2004	3,287	1,125	641	1,407	1	108	5	1,510	3,420
10	2/21/1995	2,681	1,177	385	1,045	0	72	1	647	3,773
11	1/7/2002	2,497	1,133	384	926	0	53	2	689	4,343
12	2/5/2001	3,137	1,355	488	1,216	0	75	2	1,030	4,485
13	2/25/2008	2,949	1,331	407	1,129	0	79	2	1,240	4,589
14	1/4/2001	4,912	1,526	1,110	2,106	0	158	11	3,020	4,789
15	3/1/1998	3,565	1,414	630	1,393	0	121	6	1,830	5,460
16	1/20/1995	3,398	1,318	676	1,288	0	110	6	2,830	6,590
17	1/20/2001	5,309	1,611	1,226	2,299	1	164	8	4,240	7,730
18	3/9/2001	5,323	1,624	1,242	2,275	0	166	17	3,500	8,210
19	1/1/1988	5,260	1,529	1,261	2,274	1	156	39	6,360	10,320
Total		7,936	1,745	1,801	4,067	2	199	123		

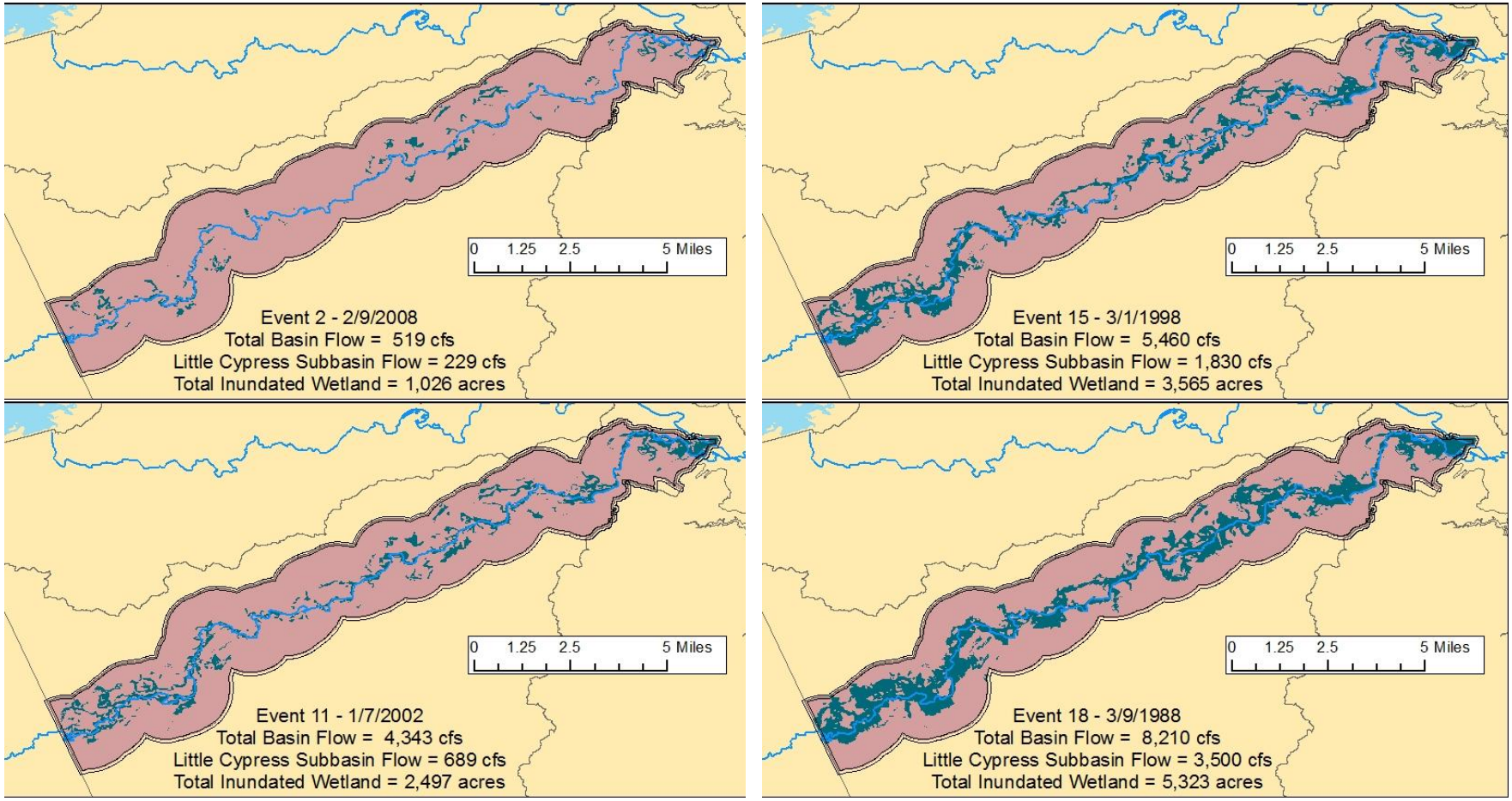

Figure C2 Inundation of habitats for a spectrum of hydrologic conditions, Little Cypress Subbasin

APPENDIX C.3 BLACK CYPRESS

Event	Date	Total	Swamp	Seasonally Flooded Forest	Temporarily Flooded Forest	Successional Shrubland	Herbaceous Wetland	Wet Prairie	Black Cypress Flow (cfs)	Total Basin Flow (cfs)
1	1/18/2006	52	41	1	7	0	2	0	3	52
2	2/9/2008	487	318	2	138	0	21	7	165	519
3	2/22/2007	930	530	9	374	0	10	6	252	747
4	1/30/1987	1,865	965	38	794	2	43	24	327	1,456
5	1/25/1997	2,116	1,085	47	891	2	67	24	800	1,690
6	2/6/2007	1,560	848	16	618	1	64	14	327	2,368
7	1/10/2003	1,746	949	27	693	1	56	20	368	2,507
8	2/25/2008	1,371	849	10	458	0	38	14	679	2,828
9	3/9/1995	1,379	853	11	493	1	11	10	689	3,420
10	3/1/2004	2,006	1,067	42	804	1	71	21	700	3,773
11	2/21/1995	1,550	911	15	570	1	34	19	506	4,343
12	1/7/2002	1,688	952	20	635	1	57	23	594	4,485
13	2/5/2001	1,899	1,080	21	721	1	54	22	735	4,589
14	3/1/1998	2,161	1,171	31	888	1	52	18	1,150	4,789
15	1/20/1995	2,458	1,221	50	1,098	2	59	27	1,970	5,460
16	1/4/2001	2,334	1,207	49	987	1	64	26	1,440	6,590
17	1/20/2001	2,663	1,286	71	1,204	2	65	34	2,300	7,730
18	3/9/2001	2,300	1,192	45	961	1	68	33	1,640	8,210
19	1/1/1988	2,836	1,296	93	1,307	3	84	53	2,660	10,320
Total		4,524	1,532	247	2,422	15	151	157		

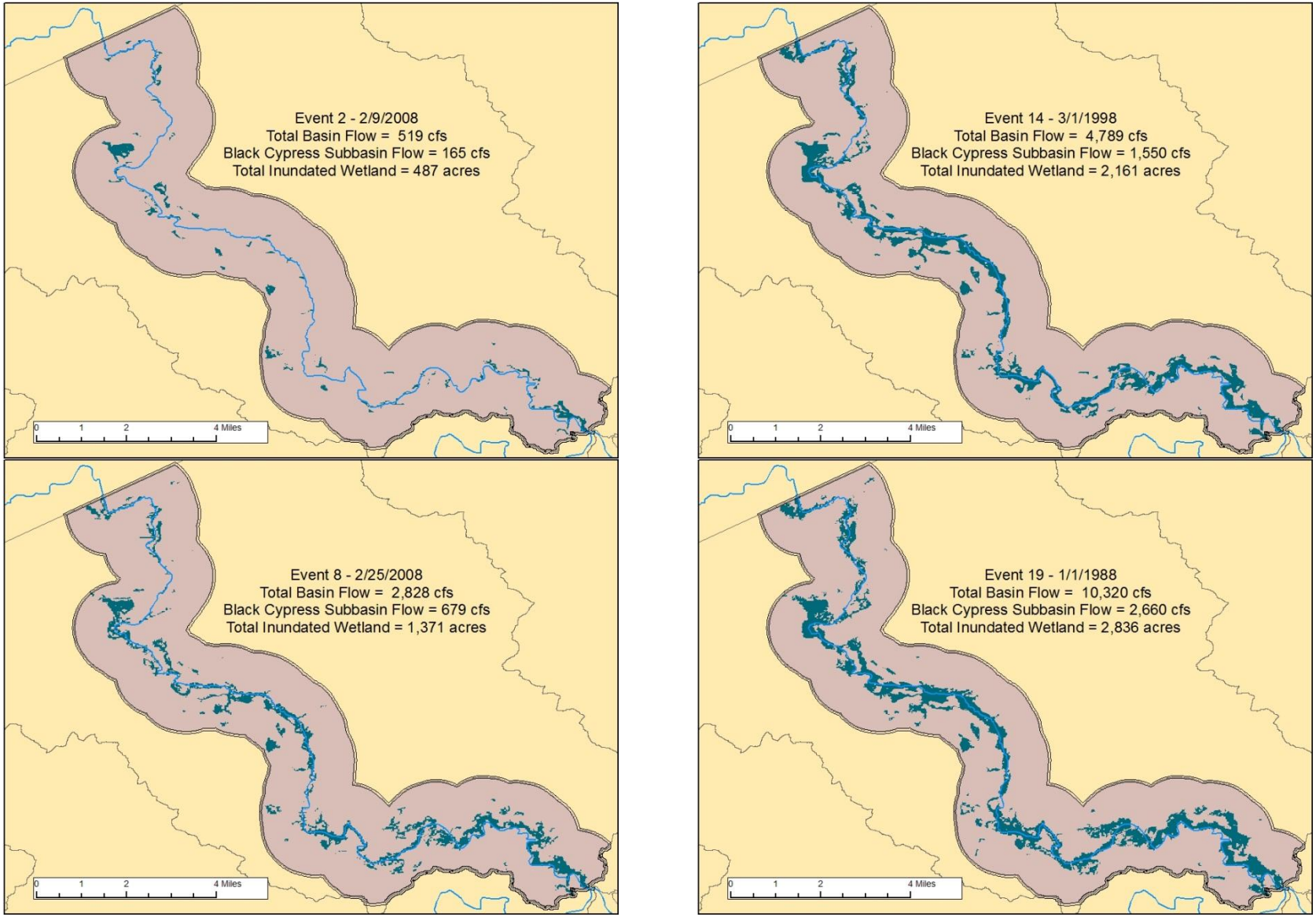

Figure C3 Inundation of habitats for a spectrum of hydrologic conditions, Black Cypress Subbasin

APPENDIX C.4 CADDO LAKE

Event	Date	Total	Swamp	Seasonally Flooded Forest	Temporarily Flooded Forest	Successional Shrubland	Herbaceous Wetland	Wet Prairie	Caddo Lake Elevation (ft)	Total Basin Flow (cfs)
1	1/18/2006	3,700	3,162	74	434	0	30	0	167	52
2	2/9/2008	4,728	4,154	48	470	0	54	0	169	519
3	2/22/2007	5,710	4,951	66	623	0	70	0	169	747
4	1/30/1987	6,314	5,272	101	858	1	73	8	170	1,456
5	1/25/1997	7,529	5,886	221	1,314	6	102	1	170	1,690
6	2/6/2007	6,084	5,354	52	609	0	68	0	170	2,368
7	1/10/2003	6,877	5,749	149	897	0	81	0	170	2,507
8	2/25/2008	6,923	5,656	137	1,055	1	73	0	170	2,828
9	3/9/1995	7,974	6,259	209	1,388	4	111	4	170	3,420
10	3/1/2004	50	20	3	26	0	1	0	170	3,773
11	2/21/1995	7,947	6,370	200	1,260	2	110	5	170	4,343
12	1/7/2002	8,302	6,405	259	1,520	5	110	3	170	4,485
13	2/5/2001	8,489	6,550	277	1,543	4	108	6	170	4,589
14	3/1/1998	9,149	6,675	432	1,895	7	132	8	171	4,789
15	1/20/1995	8,763	6,429	462	1,730	6	129	7	171	5,460
16	1/4/2001	8,786	6,600	448	1,603	7	124	5	171	6,590
17	1/20/2001	9,524	6,735	617	2,008	9	139	15	172	7,730
18	3/9/2001	10,477	6,986	830	2,469	7	161	25	175	8,210
19	1/1/1988	10,722	6,870	909	2,748	7	154	33	176	10,320
Total		12,255	7,202	1,098	3,693	11	192	59		

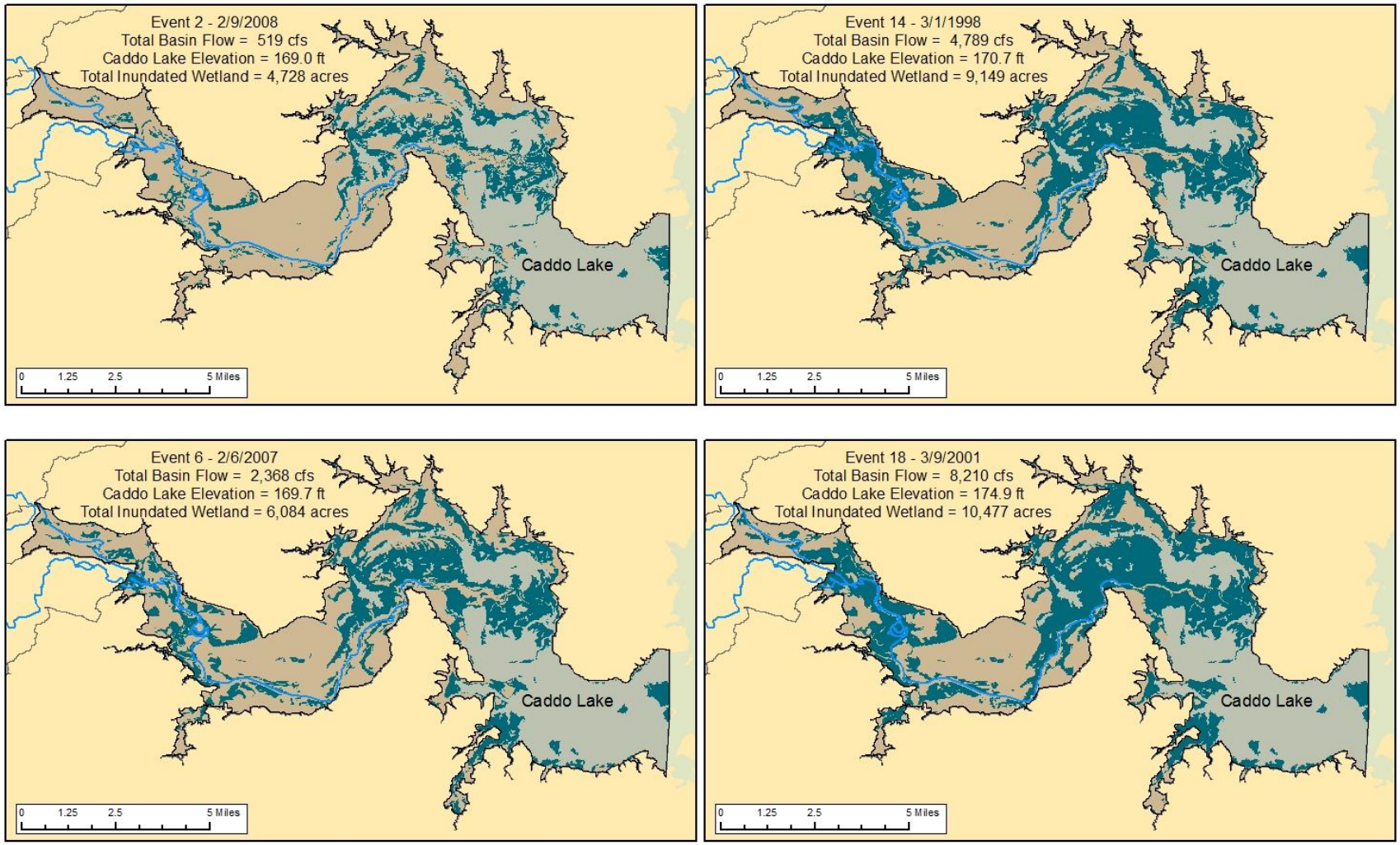

Figure C4 Inundation of habitats for a spectrum of hydrologic conditions, Caddo Lake

APPENDIX D MONITORING PLAN

The implementation of regulated flows for floodplain restoration should include prior baseline inventories and ongoing ecological and environmental monitoring, in order to allow adaptive management (Rood et al. 2005). The Texas Instream Flows Program (TIFP 2008) includes monitoring based on key indicators. The habitat-inundation data presented in this report provide the basis for establishing a stratified random design for baseline inventories and subsequent monitoring. The literature review, overbank-flow inundation analyses, and the Big Cypress Bayou/Caddo Lake TIFP process (Trungale, J., personal communication, 2010) all identify the following indicators for each of the five TIFP categories recommended for baseline and monitoring activities related to the health of BLH forest ecosystems. This study's direct approach for linking daily discharge to flooded-forest surface area lends itself to measuring response of several of the following indicators.

Biology

The overall health of floodplain processes may be best determined by the status of seasonally and temporarily flooded BLH forests, with the latter being more protective of the overall river-floodplain ecosystem, due to landscape context (Figure 1). Baldcypress and other swamps, with the possible exception of backswamps, may not be the primary basis for determining ecosystem health. Swamp habitats flood more frequently and for longer duration than BLH habitats at higher elevations, which are more vulnerable to reductions in overbank flows and intermittent connections with the stream discharge regime. Recommended biological indicators of BLH ecosystem health, in order of priority, are: (1) tree seedling and sapling establishment, (2) species diversity within each forest strata (tree, shrub, herbaceous), and (3) encroachment by upland and exotic plant species.

Hydrology

As discussed above in detail, the most important hydrologic measure of BLH forest health is similarity to the natural flow regime (frequency, duration, etc.), including seasonal overbank flows. The important indicator is probability of annual early spring (late March and early April) overbank flows with a duration of two to four weeks within seasonally flooded BLH forest habitat.

Water Quality

Important water quality objectives in determining functional status of BLH forest ecosystems may include comparative analyses in rising versus falling floodwaters. Proposed key indicators are: (1) N, (2) water clarity and/or sediment load, and (3) P.

Geomorphology

In order of priority, the most important geomorphologic indicators of BLH forest health may be: (1) the overbank flow regime, including inundation area, extent of flooding for each BLH forest type, and stage elevation; (2) lateral channel movement, lateral and point bar establishment, and floodplain sedimentation processes; and (3) wood-debris volume, transport, and recruitment.

Connectivity

Continuance of river-floodplain connections critical to BLH forest processes may be best indicated by frequency, duration, and timing of flooding for each BLH forest type, with comparison to the general hydrologic regime for

each type (Figure 1). If monitoring funds are limited, focus on those BLH forest types particularly sensitive to connectivity, such as backswamps and temporarily flooded hardwood forests. These habitats provide early warning of hydrologic separation of river and floodplain.

Permanent Vegetation Plots

Due to the long lifespan of BLH tree species, the appropriate indicators of BLH forest change are understory species and the regeneration dynamics of seedlings and young saplings (Hughes and Rood 2003). Preliminary locations of riparian study sites (three primary sites and five secondary or alternate sites) on Big Cypress, Little Cypress, and Black Cypress Bayous have been selected. In order to place these proposed riparian sites in context with related efforts, some of these site were selected in reasonable proximity to existing COE HEC-RAS monitoring sites and USGS-CLI temporary elevation benchmarks. Additional riparian study sites are proposed downstream for managed conservation areas (TPWD, USFWS, etc.) on Big Cypress Bayou and upper Caddo Lake. Within these study sites, plant-community composition (species and structure) is measured within permanent vegetation plots during field surveys.

The purpose of inventorying and monitoring riparian vegetation within the study area is to identify the extent and condition of existing habitats, and determine future deviations from this baseline. The initial baseline survey will populate data sets for comparison to subsequent data collections. In this manner, the proposed riparian methodologies will quantitatively assess plant communities, in order to establish a baseline by which the functional status of river-floodplain connectivity may be determined now and in the future. Vegetation variables, calculated for each community type and each component species, include size class distribution, species richness and diversity, stem density, basal area, and percent canopy cover. An important component of the vegetation inventory is verification of plant species identification through the archiving of voucher specimens.

Spatial configuration of riparian plant communities is based on the TPWD/NatureServe Vegetation Classification System database. As described above, this database is the basis for entering floodplain habitats and land uses into a GIS for each Study Site, in order to analyze their condition, including community type, structure, patch size distribution, fragmentation, and hydrologic connectivity. The project GIS is the basis for sampling habitat patches of each community using a stratified-random design for the efficient, statistically valid acquisition of vegetation data. In this manner, 50-m transects are randomly located along a survey line, which is perpendicular to the river and spans the full width of a given habitat patch.

To facilitate comparison with other riparian habitat assessments in Texas, the vegetation analyses described below are similar to those currently proposed for implementation by one of the authors (Hayes) for the interagency Middle and Lower Brazos River Sub-Basin Study Design Workgroup. The field methods for each vegetation strata (tree, shrub, and herb) include:

Transect Benchmarks

The precise location of each end of the 50-m transects is recorded by GPS coordinates and by triangulation from witness trees or other prominent features. As appropriate, labeled iron-rebar sections (0.5-in diameter, 18 in long) will also be driven flush to the ground surface at each end of the central 50-m transect, in order to serve as permanent benchmarks. Benchmarks will increase the precision of relocating sampling locations in the future, as facilitated by metal detectors and/or witness-tree triangulation. Particularly for transect data, the use of the same sampling locations significantly increases the statistical power of change detection, when subsequent sampling is compared to baseline conditions.

Tree Strata

Within a 10 m X 50 m plot centered on each of the random selected 50-m transects, the diameter at breast height (DBH) is recorded by species for both live and dead woody perennial vegetation (trees and vines) with at least one stem equal to or greater than 5 cm DBH. In this manner, multi-stemmed trees with at least one stem equal to or greater than 5.0 cm DBH are included along with single-stemmed trees. Diameter measurement is to the nearest 1.0 cm, rounded as appropriate. For multi-stemmed trees, DBH and basal area (BA) are calculated based on the respective sum totals for stems having a DBH equal to or greater than 5 cm.

The data collected for species in the tree strata are sorted and analyzed according to the following size-class categories: 5-15 cm, 16-25 cm, 26-35 cm, 36-45 cm, 46-55 cm, 56-65 cm, 66-75 cm, 76-85 cm, 86-95 cm, and greater than 95 cm. In this way, all trees within 5 m of either side of the center 50-m transect are analyzed according to 10-cm size classes.

DBH Measurement: In the USA, diameter at breast height (DBH) is defined as the average stem diameter, outside bark, at 1.37 m (4.5 ft) above the ground on the high side of the tree, disregarding any bark-litter mound at the base of tree. For consistent measurement, the steel diameter tape must be level and pulled taut.

For irregular trees, DBH is measured by the following method. When swellings, deformities, or branches occur at 4.5 ft (137 cm) above the ground, take DBH above irregularity, where normal stem form ceases to be affected. If trunk forks immediately above DBH height, measure DBH immediately below swelling caused by fork. For forks below true DBH, each stem DBH is normally measured above fork. The exception is when normal DBH height is too close to fork so that it is influenced by swelling associated with the fork, in which case the DBH is measured immediately above such swelling. In this manner, more than one DBH may be recorded per tree, including multiple trunks. For swell-butted stems, DBH is measured above swell if swell is at normal DBH height.

Snag Class: A snag class, adapted from Maser (1988), is recorded for dead vegetation within the tree strata. Snags are defined as standing dead woody vegetation, with an angle greater than 45 degrees relative to the horizontal. The snag classes are defined primarily according to structural integrity and decay. In order of progressive deterioration, the following nine classes are arranged numerically from the most recently killed snags with highest structural integrity (class 1) to the oldest and most decayed snags (class 9):

Densimeter Measurements: Canopy closure is estimated using spherical densimeters at four points (5 m, 15 m, 25 m, and 35 m) along each 50-m center transect line. The densimeter (Lemmon Forest Densimeter, model A, Bartlesville, OK) is held level atop a rod at a height of 1 m. Within each grid square etched on the concave mirror of the densimeter, the area of open canopy is estimated in each quarter square, with a possible score of zero (completely closed canopy) to one (completely open canopy) for each quarter square. Allowing a possible score per square of 0 to 4, this method, as modified from Lemmon (1956, 1957), increases resolution and repeatability. The total count for the 24 grid squares so enumerated is multiplied by 1.042 (24 squares x maximum score of 4 x 1.042 = 100 percent) to obtain percentage of overhead area not occupied by canopy. The difference between this and 100 is an estimation of percent canopy cover. Four such cover estimates obtained per 50-m transect are averaged to obtain a cover estimate for each randomly located transect.

Shrub Strata

Shrub composition and relative abundance is quantified using a line-intercept method. Shrubs are defined as woody perennial plants, either single- or multi-trunked, with a canopy height greater than 1 m and no stem equal to or greater than 5 cm DBH. The linear distance, to the nearest cm, that the canopy of each live shrub intersects

the center 50-m transect line is recorded. Percent coverage of each species is calculated by dividing the total linear distance of each species by 5000 cm. Overlapping canopy of different species is recorded according to distance each species intersects the line transect. Total distance with no shrub canopy is also recorded. Total percent shrub canopy cover is calculated according to the following formula: 1 – (no shrub linear intercept distance / 5000).

Herb Strata

Canopy cover for plant species within the herb strata is determined using a point intercept method along the center 50-m transect. Every meter along the transect (total of 51 points from 0-50 m), a 1-m long, 1/8 inch diameter "pin" is set vertically. All species of herbaceous vegetation (herbs, grasses, sedges, rushes, ferns, mosses, etc.), along with woody vines and woody seedlings less than one meter in height, that touch the pin are recorded.

In addition to live vegetation within the herb strata, "touches" are recorded for the following microhabitat features, in order to assess the functional status of each habitat patch:

Moss on bare mineral soil
Moss on dead fallen wood
Moss on rocks
Bare rock
Woody debris, coarse (> 20 cm. dia.)
Woody debris, medium (10 < 20 cm. dia.)
Woody debris, fine (0.5 < 10 cm. dia.)
Wet depressons (non-vegetated, gray/gley litter)
Semi-wet depressions (sparsely vegetated)
Other vegetated wetland (sedges, etc.)
Root tip-ups
Tree bole > 5 cm. DBH
Bare mineral soil
Forest floor (organic litter layer)
Other notable non-vegetation feature (identify)

Percent cover of each herb-stratum species and microhabitat feature is calculated using the formula: (# pins touched by species or feature / 51) * 100.

Calculations for Vegetation and Microhabitat Features

Several variables for both species and strata are calculated from the above data, including basal area (tree strata), canopy cover (shrub and herb strata), density (all strata), and frequency (all strata). Frequency is calculated as percent of 5-m segments along the long axis of the forest-structure plot occupied by a given species or microhabitat. In addition, relative importance is defined as the average of either percent relative basal area (tree strata) or percent relative canopy cover (shrub and herb strata), percent relative density, and percent relative frequency, where the percent relative value equals the value for the species divided by the sum of values for all species times 100.

Water Quality Monitoring

Water quality both affects and is affected by BLH composition. The Texas Clean Rivers Program includes monitoring sites within the study areas included in this report. These data will be evaluated to develop a monitoring program to access critical parameters that might affect BLH forest health and the benefits that healthy forests have on water quality.