Sustainable Rivers Project - Phase 1
Floodplain Inundation – Data Analysis and Monitoring Design
Cypress-Caddo Watershed

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<u>Introduction</u>

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<u>River-Floodplain Ecosystem</u>

Junk et al. (1989) describe the floodplain as the "aquatic-terrestrial transition zone." 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 one constant is that 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 BLH forests improves surface- and groundwater quality, and facilitates the exchange of sediment, nutrients, and biota. As described in more detail in the following sections, 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, producing protein and fiber, sequestering carbon, providing recreation, reducing storm damage, and filtering and redistributing sediment load (Hunter et al. 2008, Opperman et al. 2010).

As described above, spatial and temporal variability of habitats and water movements 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 in this manner. For example, fish migration between spawning and nursery habitats is evolutionarily adapted to floodplain variability. The current study focuses on longitudinal, 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 impact 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 and, furthermore. These forests also serve as buffer-traps for nutrients and sediments carried by upland runoff any time of the year (Gosselink et al. 1981).

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. 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 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 precisely 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 1981b). The relationships between community composition and hydroperiod are briefly summarized for the major BLH forest types of this study in the Study Area description within Methods section.

Hydrology of Bottomland Hardwood Forests

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.

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).

Thirty days annually is the normal duration of natural flooding in BLH forests. 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).

Flood waters 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).

<u>Influence of Overbank Events on BLH Tree Recruitment and Species Diversity</u>

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 influence on wetland vegetation and soil characteristics.

Rood et al. (2005) describe the "flood pulse" as a natural disturbance amenable to management, much like prescribed fire, in order to 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) promoting channel movement and new sedimentation sites to create regeneration sites, and (4) adjusting the rate of flood-water recession. 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.

The importance of following high spring flows that promote seedling establishment with a slow drawdown of flood waters 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, in addition to maintaining the main stream channel by transporting suspended sediment, post-recruitment maintenance flows should provide sufficient moisture in the seedling rooting zone during the growing season.

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). 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).

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.

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.

Ecosystem Processes in Floodplain Forests with Variable Flows

Ecosystem Benefits of Floodplain Forests

Floodplains provide many hydrologic services that benefit ecosystems, including: (1) extractive water supply; (2) in-stream water resources (recreation, transportation, freshwater fisheries, hydropower) (3) flood-damage reduction; (4) aesthetics, education, and tourism; (5) maintenance of estuaries, other aquatic habitats, and future options for adaptive management (Brauman et al. 2007). 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 wetland vegetation and biogeochemical processes in bottomland soils, such as decomposition, sedimentation, and nitrogen cycling (Hunter et al. 2008).

One of the most important ecosystem functions of BLH forests to society is improving water quality through the removal of high nitrogen 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 nitrogen gases such as nitrous oxide. In this fashion, high nitrogen concentrations in river flows are reduced.

Many important BLH ecosystem processes; such as primary production, plant diversity, animal habitat use, and organic matter export; peak with annual flooding (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).

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 $g/m^2/y$, 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 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.

Hydrology and Primary Production

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, nitrogen 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.

BLH tree species are best adapted to intermittent floods, not prolonged floods (Kozlowski 2002). During an extensive study of unregulated floodplains in Mississippi, Alabama, and Arkansas, Rypel et al. (2009) found baldcypress productivity to be positively correlated to May and June discharge amounts and the annual number of floods, and negatively correlated to reduced frequency of annual floods.

In regard to 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 reproduction (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. To be most effective in terms of maintaining BLH tree species and discouraging invasive 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.

Floodplain Hydrology and Productivity of Fish and Wildlife

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 and does not depend upon 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 flood water, with spring spawners targeting the seasonal coincidence of rising flood waters 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. The 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 (Bayley 1995).

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. And long-term mussel productivity likely depends upon occasionally higher flows, which remove accumulated sediments, increase carbon and nutrient inputs from the floodplain, and create new substrate for recruitment.

Water Development Impacts

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 leads 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.

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.

Methods

The empirical methods employed in this study quantify the dynamic interaction of high and overbank flows with BLH forest habitats. Flood dynamics are not accurately measured by discharge rates or stage elevations of streams, but are best determined by the actual configuration floodplain inundation. This study delineates the extent of temporary aquatic habitats created by these flow events, and links these data to daily discharge rates. By employing a wetted-surface classification of thematic-mapper data for selected dates of the flood hydrograph, the interaction of overbank events with the complex geomorphology and habitat diversity of the floodplain may be quantified.

Benke et al. (2000) find delineation of actual wetted-surface dynamics to be the most important basis for overbank analysis, in order to determine the extent of water-mediated movement of biotic and abiotic resources. These transfers are fundamental to understanding BLH ecosystem services. Linking daily stream discharge to empirical flooded-forest configurations allows flood hydrographs to be directly correlated to vegetation distribution, animal habitats, and ecosystem processes.

During overbank events, this study quantifies the extent of flooded forest relative to previously mapped bottomland hardwood habitats. The method may be described in terms of four steps: study area selection, hydrologic analysis to delineate overbank events, bottomland inundation mapping, and bottomland hardwood vegetation mapping. These steps are described below.

Study Area

Location

Located in northeast Texas and centered on the city of Jefferson, Texas, (32°45′40″ N, 94°20′58″ W), 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 Bayous. Selection of the overall study area is 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 presents the Cypress-Caddo project area, including boundaries for the overall area and its five sub-basin areas, along with USGS stream-gage locations, water features, major roads, towns, etc. Figures 3-6 depict the BLH vegetation types (TPWD 2009) within each of the sub-basin areas, respectively: Upper and Lower Big Cypress Bayou (two study areas), Little Cypress Bayou, Black Cypress Bayou, and Upper Caddo Lake. Table 1 provides the legend for Figures 3-6.

The locations of component sub-basin areas focused on stream segments without the confounding influence of major tributaries downstream of the USGS gage. Basin and sub-basin boundaries were compiled based on a GIS analysis of DEM data and TCEQ river basin delineations (Trungale, 2010, personal communication). Surface water features (lotic and lentic features) are mapped according to the TCEQ Atlas of Texas Surface Waters website: http://www.tceq.state.tx.us/comm_exec/forms_pubs/pubs/gi/gi-316/index.html.

For the Little Cypress and Black Cypress sub-basin study areas, the upstream boundary is a straight line perpendicular to the immediate stream reach. However, in order not to "mix" portions of the upper and lower TCEQ sub-basins at the Ferrells Bridge Dam at Lake of the Pines, the delineated sub-basin boundary is the upper boundary for our upper Big Cypress sub-basin study area.

Study area boundaries encompass the full width of the adjacent floodplain potentially affected by main-channel overbank events. For the Black Cypress, Little Cypress, and upper Big Cypress sub-basin study areas, sub-basin boundaries define the ridge-to-ridge width of the areas. However, for the lower Big Cypress and Caddo Lake sub-basin study areas, the width of the study areas is the outer extent of mapped BLH habitat (TPWD 2009) contiguous with the main water feature (either Big Cypress or Caddo Lake).

Environment

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).

The relatively long growing season supports a diversity of floodplain plant communities. Figure 1 graphically depicts this community diversity in relation to landscape context and hydroperiod. The major BLH forest types within the overall project area are summarized in terms of species composition, relative elevation context, and hydroperiod as follows:

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 semipermanently 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.

Seasonally Flooded BLH 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.

Temporarily Flooded BLH 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, 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.

Hydrologic Analysis to Determine Overbank Events

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). 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 then 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, 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).

Daily gage flow records were reviewed to identify days when flows exceed overbank thresholds. We further limited the list of overbank events to those 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.

This study included a literature review, which defined ecologically important aspects of environmental flows, in addition to flow rate, including frequency, duration, and rate of change.

The results of the literature review are largely reported in the above Introduction section. The overall purpose of this study is to delineate components of the hydrograph important to the maintenance of riparian habitats dependent upon periodic floods. The remote sensing analysis reported here quantified the actual wetted surface configuration for different daily discharge values within overbank events.

Bottomland Inundation Mapping

At the USGS Earth Explorer website (http://edcsns17.cr.usgs.gov/EarthExplorer/), Landsat TM scenes were searched within overbank-event timeframes determined by the above HEFR analysis for each of the five Cypress-Caddo study areas. Stream reaches and adjacent floodplain areas were selected as study areas based upon USGS gage locations, in such a manner as to minimize anthropogenic floodplain constrictions (i.e., bridge abutments) and major tributaries entering below gage stations. In this manner, study areas encompass stream reaches and their adjacent floodplains, which may be flooded during high-flow and overbank events originating on the main stream channel measured by the respective USGS gage.

To obtain thematic-mapper (Landsat TM) data for these study areas, search locations were delineated using either county name or latitude and longitude values for the USGS gage. During the course of the analysis, all leaf-off scenes (mid-December to mid-March) were searched for 1992 through 2009. 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.

All classifications followed the same step-wise methodology, as described below, using ERDAS Imagine 2010 software.

Classification Steps

1. Acquire LandSat TM imagery within date ranges specified. Import to .img format for bands 1-5 and 7.

2. Mask the area of interest using data provided by GEAA. 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, we used a mask 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.

Bottomland Vegetation Mapping

TPWD, along with private and agency partners, has started 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 is 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 are then gathered into a GIS, in order to incorporate the ecological context of mapped sub-systems. Next, plot-based field data are gathered to conjunction with GIS techniques to quantify primarily vegetation variables describing mapping units. Modeling is 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.

From TPWD in 2010, GEAA obtained the final version of the BLH-forest shape files for Phase 2 (east Texas) of this ecological systems classification project. These data were incorporated into the GIS for this project, in order to quantify the amount of each floodplain vegetation type inundated during high-flow and overbank events. All GIS analyses for this project were performed at GEAA using ESRI ArcGIS 9.3 software with the Spatial Analyst extension.

Regression Analyses to Determine Frequency and Duration of High-Flow and Overbank Events

Regression analysis was performed following the approach described by Benke (2000). Areas of inundated vegetation types were compared to flow rate, volume, and, in the case of the area surrounding Caddo Lake, lake elevation. Preliminary analysis investigated several parameters including the number of days to look back at flows prior to the date on which the TM derived inundation areas were available, the form of the dependent variable (e.g., whether to use percent of total or the absolute magnitude of the area inundated), and the form of the regression equation (linear or logarithmic).

Although the Pearson correlation coefficient (r-squared) suggests that flow rate observed within less than one week prior to the observed inundation explains much of the inundation response, the analysis suggested several areas for improvement. Since the analysis was limited to only high flow events, changes in areas inundated across the range of flows analyzed were relatively modest for most of the vegetation types. This may be explained by the fact that significant areas were inundated at the lower end of the flow range analyzed, and these areas overwhelm the total area inundated at higher flow rates. An estimate of area inundated at base flows would likely resolve this issue. In at least one case (in the Black Cypress study area) there is a very large area that is inundated at all flows observed, and this area accounts for the majority of the inundated area in the Black Cypress analysis. Subsequent analysis will be required to determine at what (lower) flow rate this area is inundated. As a result of these proposed refinements, the regression analysis is still in an early stage and should be refined based on additional analysis at low flow rates to establish a baseline and perhaps some refinements to the study area under consideration.

Preliminary regressions were developed for three vegetation types; swamp, seasonally flooded forests and temporary flooded forests. For the preliminary analysis, we used the maximum peak flow, including the previous two days, as the independent flow variable, and absolute area inundated as the dependent or response variable. Logarithmic regression equations were then applied to the historic hydrology to develop an area of inundation time series for the three vegetation types.

Results

Floodplain Inundation Analysis

This study is one of very few to quantify flood inundation dynamics in relation to average daily river discharge within a BLH forest ecosystem. A total of 44 TM Landsat scenes were classified and usable in delineating and quantifying flooded-forest area. Additional TM data points were classified but rejected primarily due to leaf or cloud interference.

Classification results for each of the 44 delineated flow events are presented in Appendix A. For each event, summary information is tabulated, including mean daily discharge rate, TM date, and inundation (relative percent and area) for total BLH forest and each BLH habitat. Though not included in this report, the wetted-surface shapefiles created for each flow event graphically depict the empirical results. Such graphics may more effectively communicate environmental choices and eventual outcomes during the planning process (Rood et al. 2005).

This study included an extensive literature review, the results of which are graphically summarized in Figure 1 (Bottomland Habitat Types in Cypress-Caddo Project Area, Northeast Texas - Landscape Context, Tree Species, and Hydrology). This detailed figure presents the overall thesis of this study, in regard to relationships among the 15 east Texas BLH forest types examined in this study, dominant tree species, respective hydrologic regimes (including flood duration and frequency), and landscape contexts.

Table 2 (Bottomland Habitat Types within Five Cypress-Caddo Sub-basin Study Areas: Nomenclature, Acronyms, and Distribution) identifies which BLH forest types occur in each of the five study areas, and defines their acronyms as used in Figure 1 and Table 3. An overview of the five Cypress-Caddo study areas and a results summary are provided in Table 3 (Study Area Overview and Results Summary). The usable number of classified flood-inundation dates per study area ranged from four to 13. Table 3 also lists the ranges for daily discharge and percent BLH-forest inundation covered by results for each study area.

Appendices B and C compile the results of field-plot measurements (Diamond 2009a and 2009b, respectively), which were used to ground-proof the TPWD Pineywoods BLH types (TPWD and TNRIS 2009) falling within the study areas. Appendix B provides quantitative data for basal area and density of mature forest tree species, including relative basal area, relative density and frequency of occurrence (Diamond 2009a). Additional data on forest structure is provided by Appendix C, in terms of canopy cover and frequency for tree, shrub, and herbaceous species within the BLH forest types (Diamond 2009a). In this manner, these two appendices provide detailed information on species diversity and structural characteristics used to define the BLH forest types.

Extrapolation of Frequency, Duration, and Timing of High-Flow and Overbank Events

Linear or logarithmic regressions developed for three habitat types (vegetation classes) at all study areas are presented in Appendix D. These results are presented in terms of total area inundated and percent of total available area. A review of these preliminary results and, in particular, the relatively modest response in the percent of habitat observed for seasonally and temporarily flooded forests has suggested potential areas for improvement in subsequent analysis and these results should be viewed as preliminary. Numbers labeling the points correspond to the dates of the events in Appendix A.

Appendix E includes two sets of plots for the three primary study sites for which flow recommendations were developed in the Cypress Flows Project. These figures are based on data limited to the growing season from March 11th to November 14th The upper plot includes historical flow frequencies and several horizontal lines for various flow rates that have been considered in the Cypress Flows Project. The lower plot shows the frequencies of the percent of the total habitat area inundated for swamp, seasonally flooded, and temporarily flooded forests. These results were generated based on application of the regression equations to historic hydrology to develop inundation area time series. As the regressions are considered preliminary these figures are for demonstration purposes. Analysis of inter- and intra- annual inundation patterns, including timing and duration, will be developed in subsequent phases of this project.

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) nitrogen, (2) water clarity and/or sediment load, and (3) phosphorus.

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). Figure 7 (Cypress-Caddo SRP Project: Proposed Riparian Study Sites Above Caddo Lake) depicts the preliminary locations of riparian study sites (three primary sites and five secondary or alternate sites) on Big Cypress, Little Cypress, and Black Cypress Bayous. In order to place these proposed riparian sites in context with related efforts, this figure also depicts the sites in relation 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):

Class:	Description:	Class:	Description:
1	all limbs and fine branches present, all bark remaining, sound sapwood, hard heartwood;	4	few branch stubs;
		5	no branch stubs;
		6	broken main bole;
2	few limbs, no fine branches, broken top;	7	decomposed;
		8	fallen;
3	only limb stubs;	9	stump.

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

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 impact BLH forest health and the benefits that healthy forests have on water quality

Discussion

Linking Stream Discharge and Inundation Area within BLH Forests

Using Landsat TM data from 1992 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 2). The extensive area and long period of analysis (17 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.

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% of the available areas). However, inundation of seasonally and temporarily flooded forests is limited to less than 30% 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.

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 has emerged 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).

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:

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.

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.

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.

References

Amoros, C., and G. Bornette. 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater Biology 47: 761–776.

Bayley, P.B. 1995. Understanding large river-floodplain ecosystems. BioScience 45(3): 153-158.

Bedinger, M.S. 1981. Hydrology of bottomland hardwoods in southeastern United States. In: Clark, J.R., and J. Benforado (eds.). Wetlands of Bottomland Hardwood Forests. Elsevier Scientific Publishing Co., New York, N.Y.

Bendix, J., and C.R. Hupp. 2000. Hydrological and geomorphological impacts on riparian plant communities. Hydrological Processes 14: 2977-2990.

Benke, A.C., I. Chaubey, G.M. Ward, and E.L. Dunn. 2000. Flood pulse dynamics of an unregulated river floodplain in the southeastern U.S. coastal plain. Ecology 81(10): 2730-2741.

Brauman, K.A., G.C. Daily, T.K. Duarte, and H.A. Mooney. 2007. The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services. Annu. Rev. Environ. Resour. 32:67–98.

Bridgham, S.D., J.P. Megonigal, J.K. Keller, N. B. Bliss, and C. Trettin. 2006. The carbon balance of North American wetlands. Wetlands 26: 889-916.

Carrin, G., J. DeBerry, and J. Hansford. Cited 2007. Climate of Shreveport, Louisiana. National Weather Service Office, Shreveport, LA. [Available online at http://www.srh.noaa.gov/ssd/techmemo/sr230.pdf]

Chin, A., L.R. Laurencio, and A.E. Martinez. 2008. The hydrologic importance of small- and medium-sized dams: Examples from Texas. The Professional Geographer 60(2): 238-251.

Comer, P., D. Faber-Langendoen, R. Evans, S. Gawler, C. Josse, G. Kittel, S. Menard, M. Pyne, M. Reid, K. Schulz, K. Snow, and J. Teague. 2003. Ecological Systems of the United States: A Working Classification of U.S. Terrestrial Systems. NatureServe, Arlington, Virginia.

Connor, W.H., R.T. Huffman, and W. Kitchens. 1990. Composition and productivity in bottomland hardwood forest ecosystems: The report of the vegetation workgroup. In: Gosselink, J.G., L.C. Lee, and T.A. Muir (eds). Ecological Processes and Cumulative Impacts: Illustrated by Bottomland Hardwood Wetland Ecosystems. Lewis Publishers, Inc., Chelsea, Michigan.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. Oneill, J. Paruelo, R.G. Raskin, P. Sutton, and M. van den Belt. 1997. The Value of the World's Ecosystem Services and Natural Capital. Nature 387:253-260.

Crespo Consulting Services, Inc. 2009. Trinity and San Jacinto River Basins BBEST Instream Flow Study. Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process. Prepared for: Texas Water Development Board, Austin, TX.

Dewey, J.C., S.H. Schoenholtz, J.P. Shepard, and M.G. Messina. 2006. Issues related to wetland delineation of a Texas, USA, bottomland hardwood forest. Wetlands 26(2): 410-429.

Diamond, D. 2009a. FIA Bottomland Definition Summaries. Unpublished manuscript, Missouri Resource Assessment Partnership (MoRAP), School of Natural Resources, University of Missouri, Columbia, MO.

Diamond, D. 2009b. FIA Bottomland Summaries. Unpublished manuscript, Missouri Resource Assessment Partnership (MoRAP), School of Natural Resources, University of Missouri, Columbia, MO.

Flynn, K.M., Kirby, W.H., and Hummel, P.R., 2006, User's Manual for Program PeakFQ Annual Flood-Frequency Analysis Using Bulletin 17B Guidelines: U.S. Geological Survey, Techniques and Methods Book 4, Chapter B4; 42 pgs.

Gleick, P. H. 1998. The world's water 1998–1999: The biennial report on freshwater resources. Island Press, Washington, D.C.

Gosselink, J.G., 1981. Ecological factors in the determination of riparian wetland boundaries. In: Clark, J.R., and J. Benforado (eds.). Wetlands of Bottomland Hardwood Forests. Elsevier Scientific Publishing Co., New York, N.Y.

Gosselink, J.G., B.A. Touchet, J. Van Beek, and D. Hamilton. 1990. Bottomland hardwood forest ecosystem hydrology and the influence of human activities: The report of the hydrology workgroup. In: Gosselink, J.G., L.C. Lee, and T.A. Muir (eds). Ecological Processes and Cumulative Impacts: Illustrated by Bottomland Hardwood Wetland Ecosystems. Lewis Publishers, Inc., Chelsea, Michigan.

Heitmeyer, M.E. 2006. The importance of winter floods to mallards in the Mississippi Alluvial Valley. The Journal of Wildlife Management 70(1): 101-110.

Hodges, J.D. 1997. Development and ecology of bottomland hardwood sites. Forest Ecology and Management 90: 117-125.

Huffman, T., and S.W. Forsythe. 1981a. 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, NY.

Huffman, R.T., and S.W. Forsythe, 1981b. Ecological factors in the determination of riparian wetland boundaries. In: Clark, J.R., and J. Benforado (eds.). Wetlands of Bottomland Hardwood Forests. Elsevier Scientific Publishing Co., New York, NY.

Hughes, F.M.R., and S.B. Rood. 2003. Allocation of river flows for restoration of floodplain forest ecosystems: A review of approaches and their applicability in Europe. Environmental Management 32(1): 12-33.

Hunter, R.G., S.P. Faulkner, and K.A. Gibson. 2008. The importance of hydrology in restoration of bottomland hardwood wetland functions. Wetlands 28(3): 605-615.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood-flow frequency: Bulletin 17B of the Hydrology Subcommittee, Office of Water Data Coordination, U.S. Geological Survey, Reston, Va., 183 p.

Jones, R.H., R.R. Sharitz, P.M. Dixon, D.S. Segal, and R.L. Schneider. 1994. Woody plant regeneration in four floodplain forests. Ecological Monographs 64: 345-367.

Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems. In: Dodge, D. P. (ed.). Proceedings of the International Large River Symposium. Can. Spec. Publ. Fish. Aquat. Sci. 106.

King, S.L., and J.A. Allen. 1996. Plant succession and greentree reservoir management: Implications for management and restoration of bottomland hardwood wetlands. Wetlands 16(4): 503-511.

Kozlowski, T.T. 2002. Physiological-ecological impacts of flooding on riparian forest ecosystems. Wetlands 22(3): 550-561.

Lemmon, P. E. 1956. A spherical densimeter for estimating forest overstory density. Forest Science 2:314-320.

Lemmon, P. E. 1957. A new instrument for measuring forest overstory density. Journal of Forestry 55:667-668.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial Processes in Geomorphology. W. H. Freeman and Co., San Francisco.

Maser, C., S. P. Cline, K. Cromack, Jr., J. M. Trappe, and E. Hansen. 1988. What we know about large trees that fall to the forest floor. in: Maser, C., R. F. Tarrant, J. M. Trappe, and J. F. Franklin (eds.). From the Forest to the Sea: A Story of Fallen Trees. USDA Forest Service, Pacific Northwest Forest and Range Experimental Station, General Technical Report PNW-GTR-229, chapter 2, p.25-46.

McKnight, J.S., D.D. Hook, O.G. Langdon, and R.L. Johnson. 1981. Flood tolerance and related characteristics of trees of the bottomland forests of the southern United States. In: Clark, J.R., and J. Benforado (eds.). Wetlands of Bottomland Hardwood Forests. Elsevier Scientific Publishing Co., New York, N.Y.

Mitsch, W.J., and W.G. Rust. 1984. Tree growth responses to flooding in a bottomland forest in northeastern Illinois. Forest Science 30(2): 499-510.

National Climatic Data Center, 2006: Shreveport, LA General Climate Summary - Shreveport, Louisiana Local Climatological Data, 2005 Annual Summary with Comparative Data, 8 pp.

Opperman, J.J., R. Luster, B.A. McKenney, M. Roberts, and A.W. Meadows. 2010. Ecologically functional floodplains: connectivity, flow regime, and scale. J. American Water Resources Assoc. 46 (2): 211-226.

Richter, B.D., R. Mathews, D. L. Harrison, and R. Wigington. 2003. Ecologically sustainable water management: Managing river flows for ecological integrity. Ecological Applications 13(1): 206–224.

Robertson, A.I., P. Bacon, and G. Heagney. 2001. The responses of floodplain primary production to flood frequency and timing. Journal of Applied Ecology 38: 126-136.

Rood, S.B., G.M. Samuelson, J.H. Braatne, C.R. Gourley, F.M.R. Hughes, and J.M. Mahoney. 2005. Managing river flows to restore floodplain forests. Frontiers in Ecology and the Environment. 3(4): 193-201.

Rypel, A.L.,W.R. Haag, and R.H. Findlay. 2009. Pervasive hydrologic effects on freshwater mussels and riparian trees in southeastern floodplain ecosystems. Wetlands 29(2): 497-504.

Science Advisory Committee (SAC). 2009. Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology, Report # SAC-2009-01-Rev1. Austin, TX.

Smock, L.A., J.E. Gladden, J.L. Riekenberg, L.C. Smith, and C.R. Black. 1992. Lotic macroinvertebrate production in three dimensions: channel surface, hyporheic, and flood-plain environments. Ecology 73: 876-886.

Stallins, J.A., M. Nesius, M. Smith, and K. Watson. 2009. Biogeomorphic characterization of floodplain forest change in response to reduced flows along the Apalachicola River, Florida. Published online in Wiley InterScience (http://dx.doi.org/10.1002/rra.1251).

Streng, D.R., J. S. Glitzenstein, and P. A. Harcombe. 1989. Woody seedling dynamics in an east Texas floodplain forest. Ecological Monographs 59: 177-204.

Texas Commission on Environmental Quality. Cited 2010. Atlas of Texas Surface Waters, http://www.tceq.state.tx.us/comm_exec/forms_pubs/pubs/gi/gi-316/index.html.

Texas Instream Flow Program (TIFP). 2008. *Texas Instream Flow Studies: Technical Overview*. Prepared by Texas Commission on Environmental Quality, Texas Parks and Wildlife

Department, and Texas Water Development Board. TWDB Report No. 369, May 2008, Austin, Texas.

Texas Parks and Wildlife Department and Texas Natural Resources Information System. 2009. Texas Ecological Systems Classification Project Phase II. http://www.tpwd.state.tx.us/landwater/land/maps/gis/tescp/index.phtml#Comer

Thoms, M.C., M. Southwell, H.M. McGinness. 2004. Floodplain-river ecosystems: Fragmentation and water resources development. Geomorphology 71: 126-138.

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

Trungale Engineering and Science, 2010. Environmental Flow Regime Analysis and Recommendations Report, Cypress Flows Project, Austin, Texas.

USFWS. 1985. Department of Interior Final Concept Plan: Texas Bottomland Hardwood Preservation Program. USFWS, Albuquerque, NM, May 1985.

Walton, R., J.E. Davis, T.H. Martin, and R.S. Chapman. 1996. Hydrology of the Black Swamp wetlands on the Cache River, Arkansas. Wetlands 16(3): 279-287.

Winemiller, K.O., A. Chin, S.E. Davis, D.L. Roelke, L.M. Romero, and B.P. Wilcox. 2005. Summary Report Supporting the Development of Flow Recommendations for the Stretch of Big Cypress Creek below Lake O' the Pines Dam. Final Project Report to the Caddo Lake Institute and The Nature Conservancy.