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ASSESSMENT OF RIPARIAN VEGETATION SENSITIVITY TO RIVER HYDROLOGY DOWNSTREAM OF A MAJOR TEXAS DAM

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ABSTRACT

Dams may impact the health of downstream riparian vegetation communities through flow modifications such as decreased flood frequency and duration. Without historical vegetation data, however, it is difficult to relate changes in vegetation composition to hydrology patterns downstream of dams. We studied bottomland hardwood forests downstream of Toledo Bend Dam on the Sabine River in Texas and Louisiana to determine their sensitivity to minor changes in river hydrology with a particular focus on floods. Current riparian vegetation was characterized within three topographic zones at three selected sites below the dam. Using 80 years of hydrologic records from two gauging stations downstream of the dam, we evaluated trends in flood frequency, flood duration, peak discharge and total flood discharge in those periods before (1926−1965) and after (1971−2005) dam construction, as well as related flood stage to floodplain elevations to link topography to flood frequency. Plant species diversity in this system is highly dependent on minor changes in elevation, and the proportion of wetland-dependent species changes rapidly with only a few centimeters difference in elevation. Although 50% of trees, shrubs and herbs in the sloughs were wetland adapted, their numbers were only 21% in the levees (74–284 cm higher in elevation) and 14% in the mid-floodplains. Since dam construction, total flood discharge and duration at the most upstream gauge on the Sabine River decreased by 49%. At both gauges, mean discharge was also altered with higher summer flows. Patterns of tree regeneration point to less recruitment by wetland-dependent species in the years following dam construction. These results suggest that minor changes in flood magnitude might limit occurrence of wetland species to the lowest topographic zones and illustrate the need to analyse sensitivity of plants to minor changes in flood characteristics when historical data for the vegetation community are lacking. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: bottomland hardwood forests; dam effects; environmental flows; flood analysis; floodplain vegetation; topographic gradients; Toledo Bend Dam; Sabine River

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INTRODUCTION

Riparian areas provide many ecosystem services, such as flood attenuation, nutrient cycling, carbon dioxide sequestration, sediment deposition, timber production, recreation and wildlife habitat (Sharitz and Mitsch, 1993). Bottomland hardwood forests and deepwater alluvial swamps have developed along rivers in the southeastern United States because of the distinct hydrology, topography and soils (Wharton *et al*., 1982; Osterkamp and Hupp, 2010). These areas, however, are undergoing reduction in size and changes in composition as agriculture, urbanization (Simmons *et al*., 2007), deforestation (Osterkamp and Hupp, 2010), impounded reservoirs (King *et al*., 1998) and other industrial activities encroach upon them (Sharitz and Mitsch, 1993). In these ecosystems, hydrology plays the role of the 'master variable' of ecological communities (Dixon and Turner, 2006), so flood regime changes are often associated with the decline of bottomland hardwood forests.

Riparian plant species are selective as to where they establish because they are sensitive to changes in flooding frequency and duration (Jones *et al*., 1996; Denslow, 2002; Battaglia and Sharitz, 2006; Glaeser and Wulf, 2009; Kupfer *et al*., 2010), as well as soil types (Battaglia and Sharitz, 2006). As floodwaters overtop banks, the coarsest materials deposit closest to the bank, whereas finer materials are dropped out of suspension farther away (Wharton *et al*., 1982). Such overbank deposition creates microtopographic variations across the floodplain that flood more or less frequently, thus influencing vegetation species composition (Wharton *et al*., 1982; Titus, 1990; Sharitz and Mitsch, 1993; Hodges, 1997; Wall and Darwin, 1999; Almquist *et al*., 2002; Naiman *et al*., 2005; Battaglia and Sharitz, 2006; Glaeser and Wulf, 2009; Kupfer *et al*., 2010; Osterkamp and Hupp, 2010). When relating topographic variation to flooding frequency and duration, several authors have noted that changes in elevation of only a few meters or even centimeters can alter the composition,

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richness and diversity of species (Titus, 1990; Sharitz and Mitsch, 1993; Wall and Darwin, 1999; Naiman *et al*., 2005; Glaeser and Wulf, 2009; Kupfer *et al*., 2010). For example, Titus (1990) found that vegetative communities changed from flood tolerant to flood intolerant with an elevation difference of only 20 cm in a Florida swamp.

Plant community composition is formed by past forces acting upon each species; forces, such as geomorphology, climate, hydrology, and soils, shape species composition by preventing the establishment and growth of those species that are not able to withstand the pressures of that environment (Kupfer *et al*., 2010). Riparian ecosystems primarily support wetland species because they have been subjected to periods of inundation or saturation frequently enough to restrict upland species dominance. Trees without adaptations to inundation or saturation will be restricted to the higher riparian elevations, such as levees, that are less flood-prone than the lower topographic areas. The latter may be inundated for weeks to months that may include the growing season. Because bottomland hardwood tree species differ considerably in their tolerance to flooding (Broadfoot and Williston, 1973; Wharton *et al*., 1982; Kozlowski, 2002), changes in flood regime could result in changes in vegetation community assemblages. Therefore, it is critical to assess whether flow alterations on regulated rivers have impacted the riparian plant community.

Several studies have noted that dam effects may include alterations in downstream hydrology, geomorphology, biology and connectivity (Williams and Wolman, 1984; Johnson, 1994, 1998; King *et al*., 1998; Brandt, 2000; Katz *et al*., 2005; Dixon and Turner, 2006; Gordon and Meentemeyer, 2006; Graf, 2006). Depending on climate, geomorphology and the operation schedule of the impounded reservoirs, dams typically reduce flood frequency, total flood discharge, flood duration and peak discharge, as well as altered timing of floods and increased low flows (Williams and Wolman, 1984; Phillips, 2003). Dams may also affect the geomorphology of the river by trapping up to 99% of sediment that flows into the reservoir (Brandt, 2000). The sediment-deprived water that flows out of the dam regains sediment by eroding the bed and banks and incising the channel, resulting in loss of aquatic habitat and connectivity with the floodplain. Hydrologic and geomorphological alterations such as these can seriously harm riparian communities by reducing sediment and nutrient delivery and by reducing the biodiversity of wetland-adapted plants and animals (Graf, 2006). On the other hand, restoring natural flood flows has the potential to enhance riparian plant communities. For example, Anderson *et al*. (2008) found that when a more natural flooding regime returned to a bottomland hardwood forest along the Olentangy River in Ohio, forest productivity increased.

To assess flows needed to maintain riparian health, unaltered ecosystems within the same ecoregion and with the same hydrogeomorphology are needed for comparison. Unfortunately, many rivers have no such unaltered analog. Furthermore, historical records are typically scarce. Thus, there is a strong need for robust *post hoc* research methodologies to link river flows to the health of riparian plant communities. If the only available data convey a 'snapshot' of the community composition at the time of sampling, a composition formed by past forces acting upon these species (Kupfer *et al*., 2010), how can we expect to determine changes in health and, moreover, the causes of such changes? The goal of our project was to relate a *post hoc* vegetation survey to potential changes in riparian health downstream of the Toledo Bend Dam on the Sabine River (Louisiana and Texas). Our study objectives were as follows: (i) to determine the condition of the vegetative communities in the floodplains, and (ii) evaluate whether and by how much the flow regime had changed since dam construction. We then examined these findings to assess whether the floodplain vegetation community has been impacted by the dam. We used microtopography to examine the sensitivity of key wetland-adapted plant species to minor differences in flooding with the expectation that areas lower in elevation had shallower water tables, flooded more frequently and were inundated for longer periods. Current vegetation community condition was assessed by comparing the frequency of wetland and upland species occurrence across elevational gradients. Other authors have discussed the value of using topographic gradients as surrogates for hydrologic gradients (Townsend, 2001; Denslow, 2002; Osterkamp and Hupp, 2010) when extensive floodplain inundation mapping was not conducted, such as that performed by Benke *et al*. (2000). If floods had declined downstream of the dam, one would expect to find a high frequency and dominance of flood-intolerant species because of conditions favorable for their germination and survival at all elevations (Glaeser and Wulf, 2009; Kupfer *et al*., 2010). If hydrologic alterations cause a decline in wetland obligate species, they eventually would be replaced by non-wetland species once the older, larger individuals die, leading to a change in forest composition and structure (Glaeser and Wulf, 2009; Kupfer *et al*., 2010), although this process may take 100–200 years to fully occur (Hughes, 1997). In the absence of long-term data and unimpacted reference sites, assessment of floodplain community composition and structure along topographic gradients provides an effective means to estimate environmental flow requirements for floodplain vegetation communities.

STUDY AREA

Toledo Bend Dam was constructed in 1967 and receives inflow from 75% of the 25,267 km^2 Sabine River watershed

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(Phillips, 2008). Toledo Bend Dam creates Toledo Bend Reservoir, a large lake with a surface area of 735 km^2 and water storage capacity up to 5.52 km^3 (Phillips, 2003). Its capacity is about 1.2 times the average annual inflow (Phillips, 2003). The reservoir is primarily used for hydropower generation, water supply and recreation; it is not designed or operated for flood control (Phillips, 2003).

The study reach extends 237 km between the dam and Sabine Lake estuary (Figure 1) located within the Gulf Coastal Plain ecoregion, with a humid subtropical climate (Phillips, 2008). For several kilometers below Toledo Bend Dam, the river is convergent, sinuous, meandering and strongly influenced by dam operations (Phillips, 2008). Major tributaries include Anacoco Bayou and Big Cow Creek. Further downstream, the river transforms from a single thread channel to a single thread channel with multiple distributaries at high flows, to a fully divergent distributary system beginning 47 river km upstream of Sabine Lake estuary (Phillips, 2008). The lower portion of the river is highly sinuous and deltaic, with only a minor influence of dam releases on flows (Phillips, 2008). For a complete description of the geomorphology of the Sabine River below Toledo Bend Dam, see Phillips (2003, 2008).

Three vegetation study sites were selected for this project: Anacoco Bayou, Big Cow Creek and Sabine Island (Figure 1). The Anacoco Bayou site was located approximately 79 km downstream of the dam and below the confluence with Anacoco Bayou (Figure 1). The Sabine River at this site, located within the coastal plain, is a convergent, single-channel system that is strongly influenced by dam releases (Phillips, 2008). Overbank flow is occasional, but there is low floodplain connectivity (Phillips, 2008). An elevation difference of 284 cm exists between the lowest and highest plots at this site, which is up to 22.83 m above sea level. The major soil types present in the area were Urbo and Mantachie soils, which are composed of clayey and loamy alluvium and somewhat poorly drained (Natural Resources Conservation Service (NRCS), 2011). Soil types were identified from Web Soil Survey maps from the Natural Resources Conservation Service (NRCS).

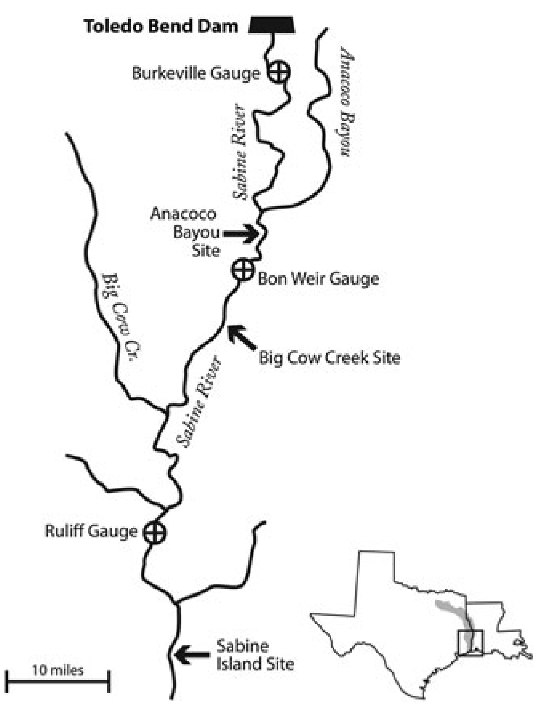

Figure 1. Map showing locations of the three USGS gauges and three study sites along lower Sabine River downstream of Toledo Bend Dam to Sabine Lake Estuary.

The Big Cow Creek site was located 103 km downstream of the dam and upstream of the confluence with Big Cow Creek (Figure 1). This site was logged in 1950. The Sabine River at this site, located within the coastal plain, is a convergent, single-channel system that has multiple channels at high flows and is strongly influenced by dam releases (Phillips, 2008). Overbank flow is occasional, and there is moderate floodplain connectivity (Phillips, 2008). An elevation difference of 258 cm exists between the lowest and highest plots at this site, which is up to 17.43 m above sea level. The major soil types present in the area were Urbo and Mantachie soils in the mid-floodplain and slough plots and Bernaldo-Besner soils on the levees (Natural Resources Conservation Service (NRCS), 2011). Bernaldo-Besner soils are composed of loamy alluvium and are well drained (Natural Resources Conservation Service (NRCS), 2011).

The Sabine Island site was located 204 km downstream of the dam within the Sabine Island Wildlife Management Area, managed by the Louisiana Department of Wildlife and Fisheries (Figure 1). An anastomosed channel of the Sabine River surrounds this area, creating an island. The Sabine River at this site, located within a deltaic plain, is fully divergent with multiple distributary channels and experiences only a minor influence from the dam at low flows (Phillips, 2008). Overbank flow is common at Sabine Island with extensive floodplain connectivity (Phillips, 2008). Being in a deltaic plain, this site has a different geomorphology compared with the other two sites and an elevation difference of only 74 cm exists between the lowest and highest plots at this site, which is 1.22 m or less above sea level. The major soil types present in the area were Guyton and Bienville soils on the levees and mid-floodplains and Barbary mucky clay in the sloughs (Natural Resources Conservation Service (NRCS), 2011). Guyton soils are composed of loamy alluvium that are poorly drained, Bienville soils are composed of sandy alluvium that are somewhat excessively drained and Barbary mucky clay is composed of fluid clayey backswamp deposits that are very poorly drained (Natural Resources Conservation Service (NRCS), 2011).

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METHODS

Vegetation

At each site, we established replicate 100-m^2 plots within 500 m of the river channel in a stratified random approach within three topographic zones: levees, mid-floodplains and sloughs (Objective A). Although the floodplain actually is about 1500−4800 m wide, depending on location, we found this area generally encompassed the full range of elevations of the levees and backwater sloughs. It is likely that vegetation community characteristics observed in the 500-m zone reflect characteristics of the entire floodplain, but we cannot extend our result beyond the sampling area. Digital elevation (DEM) data, accurate to the nearest 5-m horizontal resolution and 0.1-m vertical resolution, were downloaded from the Louisiana Atlas Statewide GIS (LSU CADGIS Research Laboratory, 2006) and converted to ESRI ArcMap format. Topographic zones were identified from the DEM by developing a histogram of all elevations within a 500 × 800-m area. Three mid-floodplain plots were selected from areas with elevations near the mean value. Similarly, three slough sampling plots were identified at elevations two standard deviations below average, and three levee sampling plots were identified at elevations two standard deviations above average. Final starting points for each plot were randomly selected on each site within 30 m of the predetermined GPS points acquired from the DEM. Only those areas logged at least 60 years ago, and not disturbed since, were eligible for our surveys.

All trees were measured in every plot. Trees were classified as single-trunked woody perennial vegetation with a diameter at breast height (DBH) of greater than 3 cm (measured to the nearest 0.5 cm) and were recorded by species into one of the following size class categories: 3–15, 16–25, 26–35, 36–45, 46–55, 56–65, 66–75, 76–85, 86–95 and greater than 95 cm.

Shrubs were classified as all multi-trunked woody perennial vegetation and also all single-trunked woody perennial vegetation less than 3 cm DBH. Shrub frequency and dominance was surveyed using a line intercept method along the diagonal line of each plot. Per cent coverage of each species was calculated by dividing the total linear distance of each species (individual measurements taken to the nearest 0.5 cm) by the total distance surveyed (1400 cm). Overlapping canopies of different species were recorded according to the distance each species intersected the line transect. Total distance with no shrub canopy was also recorded. Total per cent shrub canopy cover, or dominance, was calculated according to the following formula: 1 – ([no shrub linear intercept distance / 1400] × 100).

Herbaceous vegetation composition was surveyed using a line point intercept methodology. A 1-meter-long, 1/8-inch diameter pin was set vertically every 1 meter along the 14-m diagonal line of each plot, starting at zero. All species of herbaceous vegetation, woody vines and woody seedlings that touched the pin were recorded. Frequency (number of individuals per plot) was measured as the number of pins touched in each plot. Per cent cover, or dominance, of each herbaceous species was calculated using the following formula: ([number of pins touched by species / 15] × 100). Any species of herb or shrub of notable interest that was not observed in our line intercept was recorded in the notes section of the datasheet.

Key riparian vegetative indicators included age class distribution (using diameter class distribution as a proxy for age), richness, frequency and dominance. Wetland classifications (Obligate-OBL; Facultative Wetland-FACW; Facultative-FAC; Facultative Upland-FACU; and Upland-UPL) for each species were found from various sources, including U.S. Dept of Agriculture-Natural Resources Conservation Service (USDA-NRCS) (2010); U.S. Fish and Wildlife Service (USFWS) (1996); Burns and Honkala (1990); Hook and Brown (1973), and Hook (1984). The occurrence of wetland classification groups among the different topographic plots was analysed for trends in frequency and dominance. Dominance was measured as basal area in m^2/ha for trees, and as per cent cover for shrubs and herbaceous species.

Lastly, we determined which trees were regenerating by examining demographic shifts among groups of tree species by age class using diameter as a proxy. Because not all species reach the same maximum diameter, we grouped them into wetland indicator categories: wetland (FACW, FACW+, FACW-, OBL), neutral (FAC-, FAC, FAC+) and upland (FACU, FACU-, FACU+). Each group's size class distribution was compared using analysis of variance and Tukey's *post hoc* multiple comparisons analysis. Evidence of tree regeneration was evaluated based on size-class distribution within survey plots, assuming that indicator groups with fewer smaller diameter specimens might be declining due to lowered seedling recruitment and survival. If the occurrence of wetland-dependent species is declining, we would expect more upland species in younger age classes and only older specimens of wetland species that depend on flood pulses. Saplings or seedlings found in the shrub or herb survey were assigned an estimated diameter value of 1 cm and included in size-class distribution evaluation. Note that regeneration is generally expected to be low in these closed-canopy forests, but the assumption here is that more regeneration of FAC and FACU trees relative to OBL and FACW trees may indicate that the forest is in transition.

Hydrology

To evaluate whether and by how much the flood flow regime had changed in the period after dam construction (Objective B), we compared flood frequency, duration,

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timing, magnitude and intensity of river discharge from long-term records at two USGS gauging stations. These gauges were located 90 and 180 km downstream of Toledo Bend Dam on the lower Sabine River at Bon Wier (08028500) and Ruliff (08030500), whose records date to 1923 and 1924, respectively (U.S. Geological Survey (USGS), 2001). The USGS gauge located near Burkeville (08026000) approximately 23 km downstream of the dam was excluded because of lack of data before dam construction. To exclude the possibility that differences in climate could have explained the observed differences in hydrology between periods before (1926–1965) and after (1971–2005) dam construction, precipitation data from the corresponding before/after periods were downloaded from the National Climatic Data Center at three sites within or near the Sabine watershed (Greenville and Marshall, TX, and Alexandria, LA) (National Climatic Data Center (NCDC), 2011). Mean annual precipitation at the three sites was compared between periods using a Welch modified two-sample t-test.

Flood events were defined as periods when discharge equaled or exceeded bankfull discharge for that particular gauge based on the relationship between stream height and elevation near the gauge. Bankfull discharge was 779 m^3/s at Bon Wier and 377 m^3/s at Ruliff (Heitmuller and Greene, 2009). All flood events that occurred before (1926–1965) and after (1971–2005) dam construction were aggregated within 5-year periods for a total of eight and nine sample periods, respectively. We tested whether flood frequency decreased, duration decreased, and peak and total flood discharge decreased in those periods after dam construction using one-tailed Student's *t*-test with a threshold α of 95%. We tested whether the relationship between flood duration and discharge had changed after dam construction by using multiple linear regressions. Finally, we compared the number of floods and mean discharge recorded in each calendar month before and after dam construction using two-tailed Student's *t*-test to evaluate whether the seasonality of flood occurrence and mean discharge had shifted after dam construction. All statistical analyses were done using S-Plus v. 8.2 (Insightful Corporation, Seattle, WA).

We recognize that overbank flooding is not the only source of water in the Sabine River floodplains; other sources include groundwater, coastal backwater effects, tributary flooding and local runoff among others. Our focus in this study was to determine if overbank flooding has been altered and to what extent as a way to examine the present condition of the floodplain vegetation communities. As a way to evaluate these hydrologic components, we examined mean discharges by month as an indicator of changes to the annual hydrograph.

In addition, data from U.S. Geological Survey (USGS) (2001) for average stage height above bankfull for each 5-year period was compared with data for the distribution of elevations in the areas surrounding both gauges. This approach

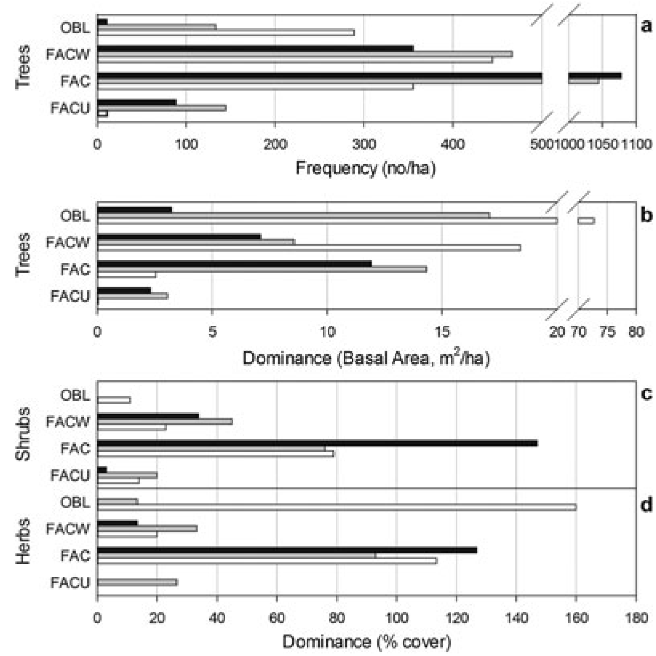

Figure 2. From top: tree frequency (a), tree dominance (b), shrub dominance (c) and herb dominance (d) of individuals in four major wetland indicator classifications (OBL, FACW, FAC, FACU) among all sites grouped by topographic zone: levee (black), mid-floodplain (grey) and slough (white). For trees, frequency is measured in no/ha, and dominance is measured as the total basal area (m^2/ha) in all plots combined. In shrubs and herbs, dominance is measured as % canopy cover in all plots combined.

provides an estimate of the fraction of total area inundated at a given frequency before and after dam construction. Combined with knowledge about the sensitivity of vegetation to minor changes in elevation, this provides insights into both the degree of change that could be expected and the relative size of area it would impact.

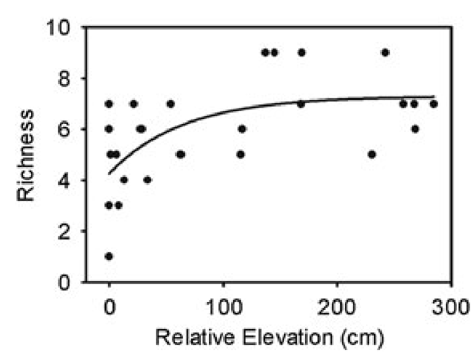

Figure 3. The relationship between tree species richness and relative elevation of plots for all sites combined. Relative elevations were established by using the lowest topographic plot at each site as reference, or zero. The exponential fit equation for richness $(y) = 4.25 + 3.06*(1\text{-}0.98^{\wedge \text{elevation}})$ ($R^2 = 0.37$, $p = 0.004$).

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RESULTS

Vegetation analysis

In general, we observed a shift in plant species composition with elevation on the floodplain. Wetland species (OBL and FACW) of trees, shrubs and herbs were most common in the slough areas and less common at higher elevations where upland species (FAC and FACU) were prevalent (Figure 2). Because of the high species richness occurring on the levees and the comparatively low species richness of OBL species overall, we saw a decline in diversity with decreasing elevation (Figure 3). Whereas 50% of plants were OBL or FACW in the sloughs, their numbers were only 21% in the levees and 14% in the mid-floodplains. Furthermore, wetland species were less common than upland plants across the entire study area. Only 3 of the top 10 tree species, 3 of the top 10 shrub species, and 4 of the top 10 herbaceous species were wetland species (Table I).

Table I. Frequency and dominance of 10 most frequent tree, shrub, and herbaceous species among all sites. Dominance of trees is reported as basal area; dominance of shrubs and herbs are reported as per cent canopy cover. OBL species are indicated by '**'. FACW species are indicated by '*'. All other species are FAC or above

	All sites combined		Anacoco Bayou		Big Cow Creek		Sabine Island	
Tree species	**Frequency (no/ha)**	**Basal area (m^2/ha)**	**Frequency (no/ha)**	**Basal area (m^2/ha)**	**Frequency (no/ha)**	**Basal area (m^2/ha)**	**Frequency (no/ha)**	**Basal area (m^2/ha)**
Carpinus caroliniana	2300	10.53	1033	3.67	567	1.87	700	5.0
**Acer rubrum*	1133	12.33	0	0.00	433	2.67	700	9.7
Liquidambar styraciflua	1133	30.67	367	4.33	467	15.33	300	11.0
Triadica sebifera	967	3.67	0	0.00	67	0.33	900	3.3
Quercus nigra	933	19.00	400	8.00	367	5.33	167	5.7
Carya sp	700	14.00	700	14.00	0	0.00	0	0.0
Ilex opaca	533	2.53	500	2.33	33	0.20	0	0.0
**Ulmus americana*	467	16.00	233	8.67	0	0.00	233	7.3
Diospyros virginiana	467	1.93	133	0.33	233	1.33	100	0.3
***Taxodium distichum*	433	147.33	100	110.33	0	0.00	333	37.0
Shrub/sapling species	**All sites combined**		**Anacoco Bayou**		**Big Cow Creek**		**Sabine Island**	
	Frequency	**Canopy cover (%)**	**Frequency**	**Canopy cover (%)**	**Frequency**	**Canopy cover (%)**	**Frequency**	**Canopy cover (%)**
Triadica sebifera	12	63	1	0.40	3	13	8	50
Ilex vomitoria	11	49	6	36	5	14	0	0
Carpinus caroliniana	10	35	2	4	2	16	6	15
**Sabal minor*	9	51	0	0	0	0	9	51
Viburnum dentatum	7	66	0	0	7	66	0	0
**Acer rubrum*	7	36	0	0	3	26	4	10
Quercus nigra	4	15	0	0	0	0	4	15
Ostrya virginiana	3	10	2	9	0	0	1	1
***Cephalanthus occidentalis*	2	8	2	8	0	0	0	0
Frangula caroliniana	2	25	0	0	0	0	2	25
Herb species	**All sites combined**		**Anacoco Bayou**		**Big Cow Creek**		**Sabine Island**	
	Frequency	**% Cover**	**Frequency**	**% Cover**	**Frequency**	**% Cover**	**Frequency**	**% Cover**
Toxicodendron radicans	17	113	5	33	1	6	11	73
Campsis radicans	13	86	0	0	11	73	2	13
***Phanopyrum gymnocarpon*	13	86	0	0	0	0	13	86
Vitis rotundifolia	9	60	6	40	3	20	0	0
***Rhynchospora cf inundata*	8	53	0	0	0	0	8	53
Smilax bona-nox	6	40	0	0	4	26	2	13
Polygonum sp.	5	33	2	13	0	0	3	20
***Rhynchospora corniculata*	5	33	0	0	0	0	5	33
**Onoclea sensibilis*	4	26	0	0	0	0	4	26

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Sloughs supported more tree and herbaceous biomass than higher floodplain elevations, whereas shrubs were more dominant on levees. In the sloughs, OBL trees had the greatest total basal area (72.7 m^2/ha), followed by FACW species (18.4 m^2/ha; Figure 2b). OBL trees were also the most dominant group on the mid-floodplains (basal area of 17.1 m^2/ha), while FAC tree species were most dominant on the levees (basal area of 11.9 m^2/ha). FAC shrub species dominated all three topographic zones, but reached greatest canopy cover (147%) on the levees (Figure 2c). By contrast, OBL shrub species had only 11% canopy cover in sloughs, as compared to 14% canopy cover for FACU species. As with trees, OBL herbaceous species dominated the slough areas (160% cover), but had minimal dominance on the mid-floodplains and none on the levees (Figure 2d).

The most pronounced delineation between wetland and nonwetland species along an elevational gradient was found at the most upstream site, Anacoco Bayou, where FAC and FACU trees were generally excluded from the sloughs, whereas OBL and FACW trees were virtually restricted to the sloughs (Figure 4a,b). The slough areas at this site were characterized by very large bald cypress (*Taxodium distichum*, 31-163 cm DBH), yet no bald cypress saplings or seedlings were detected. Furthermore, only five herbaceous species were found, three of which were exclusive to the slough areas (Figure 4d). Only one OBL shrub species was found at Anacoco Bayou, buttonbush (*Cephalanthus occidentalis*), which like OBL trees was restricted to the slough areas (Figure 4c). Levees at Anacoco Bayou had more diverse plant composition than sloughs or mid-floodplains (Figure 4a). We

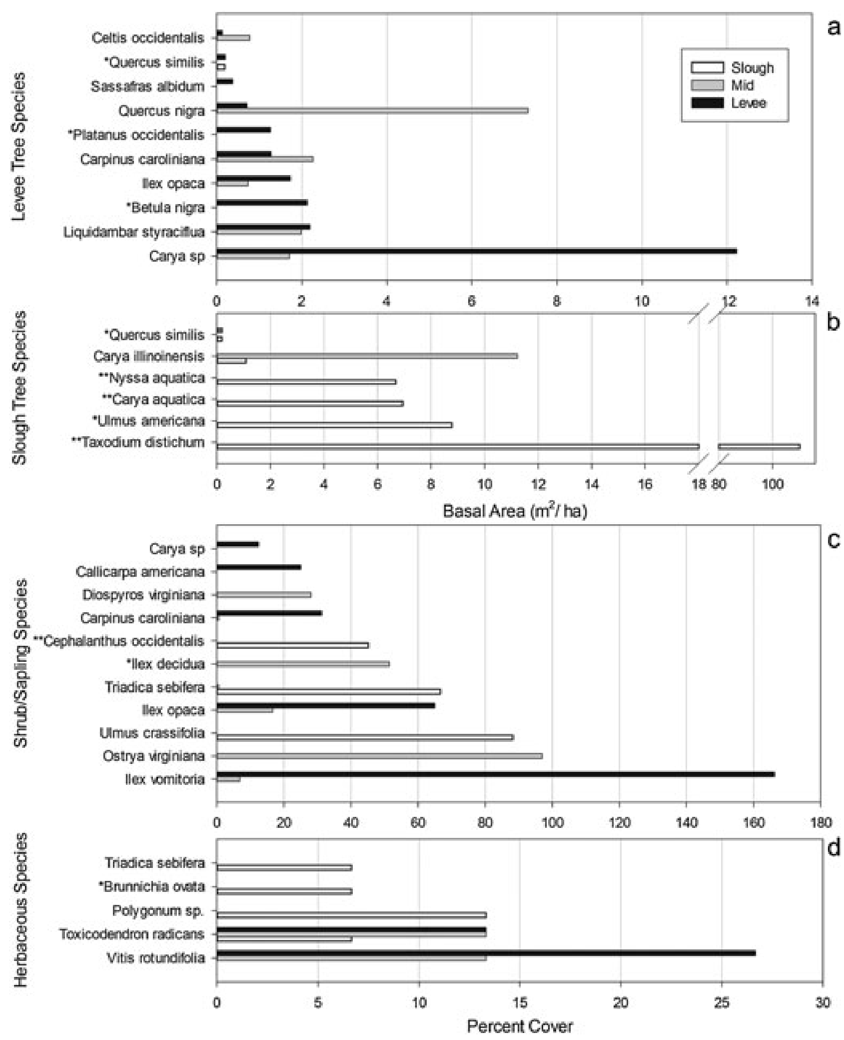

Figure 4. At the Anacoco Bayou site, dominance of all tree species found on the levee (a) and slough (b) plots, and dominance of shrub/sapling (c) and herb (d) species. OBL species are indicated by '**'. FACW species are indicated by '*'. For trees, dominance is measured as the total basal area (m^2/ha) in all plots combined. For shrubs and herbs, dominance is measured as % canopy cover in all plots combined. Dominance in sloughs indicated by white bars, on mid-floodplains by grey bars, and on levees by black bars.

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also found one FACW shrub species on the mid-floodplains, possumhaw holly (*Ilex decidua*).

At Big Cow Creek (middle site), 33% of the tree species present were wetland species, compared with 42% wetland species at Anacoco Bayou. As compared with Anacoco Bayou, the topographic gradient was less steep at Big Cow Creek site and the delineation between wetland and nonwetland species was less evident. Only one individual OBL tree was observed, Carolina ash (*Fraxinus caroliniana*), which was so large that it dominated the overall trend at Big Cow Creek (Figure 5b). At this site, FACW tree species were present at every topographic level, whereas nonwetland tree growth was limited in the sloughs. Also, the presence of FACW seedlings and saplings indicates some tree regeneration is occurring at this site, the extent of which is unknown (Figure 5c). However, trumpet creeper vine (*Campsis radicans*), a FAC herb species, had more than three times the dominance of the rest of the species that occurred within the slough areas (Figure 5d).

The most downstream site, Sabine Island, had much higher plant diversity than the other two sites, in large part because of wetland species, which comprised 53% of all plant species at this location. This site also had the lowest elevation gradient of all three sites. Even though there was only 0.6 meters of

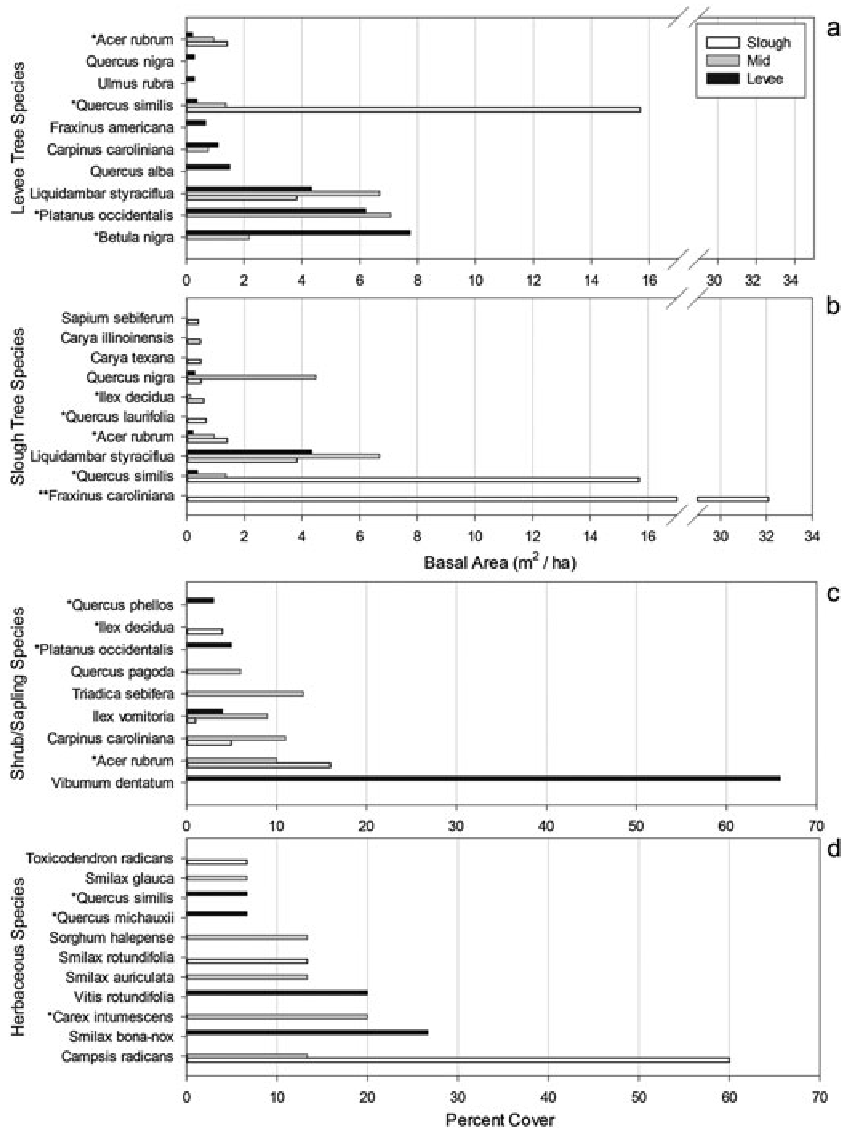

Figure 5. At Big Cow Creek site, dominance of all tree species found on the levee (a) and slough (b) plots, and dominance of shrub/sapling (c) and herb (d) species. OBL species are indicated by '**'. FACW species are indicated by '*'. For trees, dominance is measured as the total basal area (m^2/ha) in all plots combined. For shrubs and herbs, dominance is measured as % canopy cover in all plots combined. Dominance in sloughs indicated by white bars, on mid-floodplains by grey bars, and on levees by black bars.

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elevation difference between the lowest plot and the highest plot, there was a dramatic difference in the species composition between them. The sloughs supported mostly wetland plants, except Chinese tallow (*Triadica sebifera)*, poison ivy (*Toxicodendron radicans*) and greenbriar (*Smilax bona-nox*). Of the ten tree species present in the sloughs, seven were wetland species (4 OBL, 3 FACW – See Figure 6b), but we observed only one sapling each of OBL trees bald cypress and water elm (*Planera aquatica*; Figure 6c). On the levees, only four of the 11 tree species were wetland types (1 OBL, 3 FACW – See Figure 6a). Also, wetland herb species dominated the sloughs and were present on the mid-floodplains but not present on the levees (Figure 6d).

Given the slow recruitment of saplings in established forests, it is no surprise that we found little evidence of tree regeneration in recent decades; however, a comparison of tree diameter size class distributions strongly suggests that wetland species regeneration was lower than regeneration of FAC species in the years following dam construction (Figure 7). Size-class distributions among all tree species revealed that wetland tree species were, on average, 13.5 cm larger ($p < 0.01$) than FAC species. There was no size difference between FAC and upland (FACU) species or between upland and wetland species. Only seven species (13 individuals) of wetland tree seedlings or saplings with diameters less than 3 cm were detected.

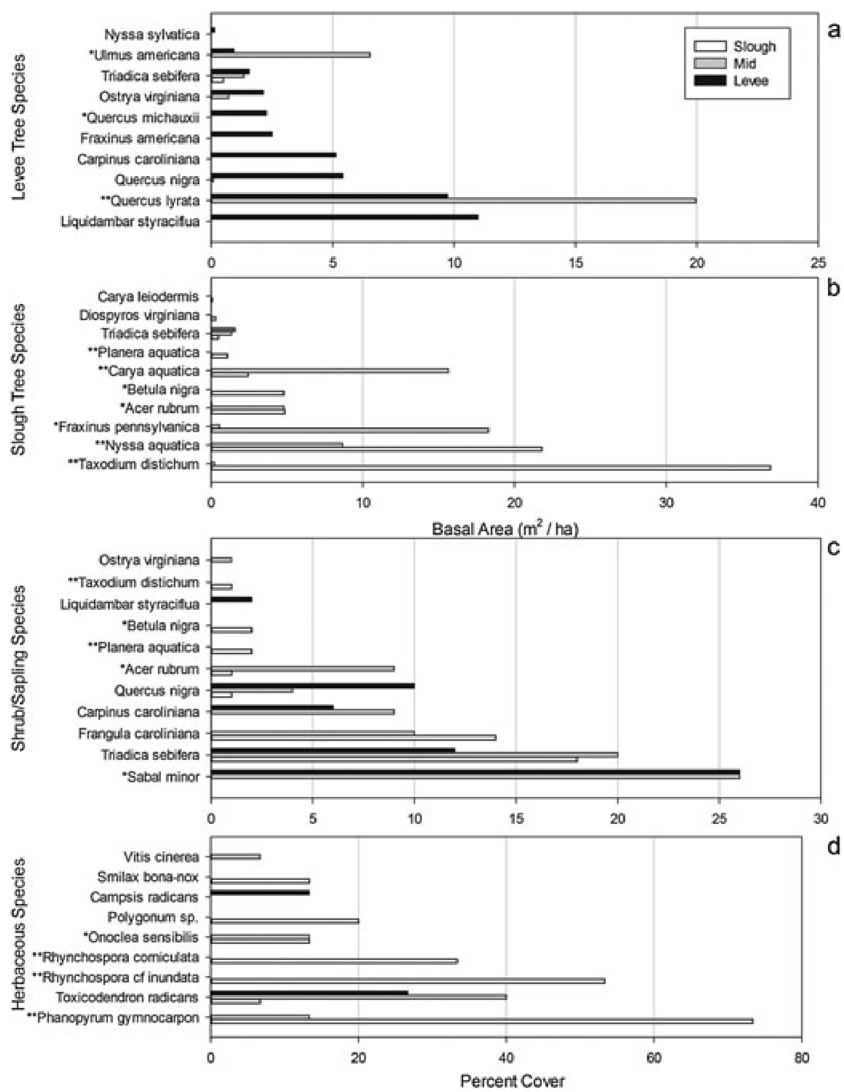

Figure 6. At Sabine Island site, dominance of all tree species found in the levee (a) and slough (b) plots and dominance of shrub/sapling (c) and herb (d) species. OBL species are indicated by '**'. FACW species are indicated by '*'. For trees, dominance is measured as the total basal area (m^2/ha) in all plots combined. For shrubs and herbs, dominance is measured as % canopy cover in all plots combined. Dominance in sloughs indicated by white bars, on mid-floodplains by grey bars, and on levees by black bars.

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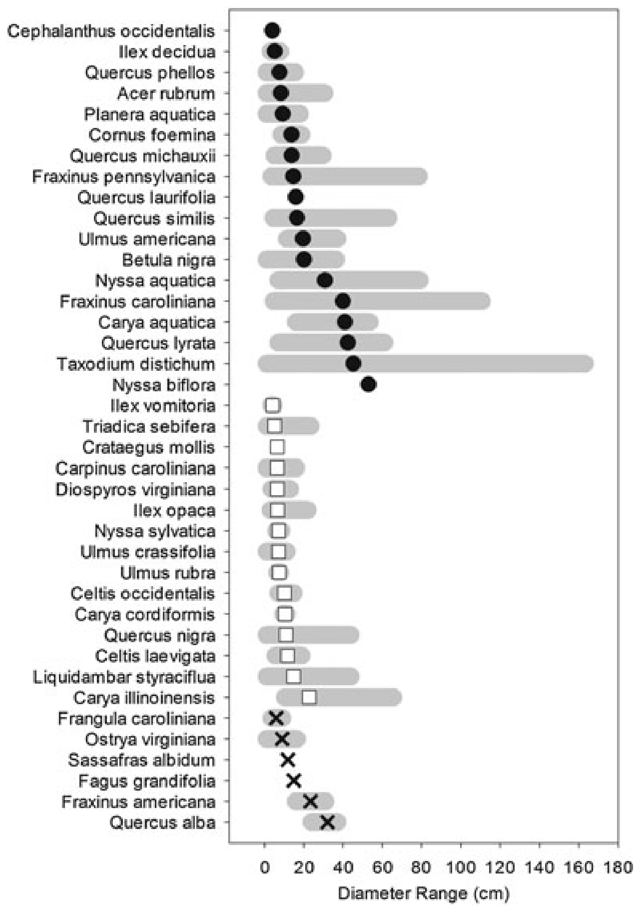

Figure 7. Size distribution means, found as diameter at breast height (DBH) in cm, of OBL and FACW (black circle), FAC (white square), and FACU (black X) tree species. Grey lines represent the range of DBH found for each species.

Hydrologic analysis

A significant change in hydrology occurred at the Bon Wier gauge, where total flood discharge was reduced 49% in the post-dam period from $398.7 \pm 173.5\, m^3$ per flood event to $195.4 \pm 51.1\, m^3$ per flood event ($p < 0.05$). Flooding duration decreased 49% in the post-dam period from 13.6 ± 5.0 days to 6.7 ± 1.6 days ($p < 0.01$). There was no difference in flooding frequency ($p < 0.1$) or peak discharge ($p > 0.05$) between the pre-dam and post-dam periods. For the relationship between duration and discharge, no difference was found between the pre-dam and post-dam periods ($p > 0.05$). Monthly trends at Bon Wier followed a similar pattern before and after dam construction, the only exception being February with 10 floods occurring in the 34-year post-dam period compared with 4 floods in the 39 years prior to the dam being built ($p < 0.05$).

No significant changes in flood frequency, total flood discharge, flood duration and peak discharge were detected at Ruliff. No significant changes were found in either the relationship between duration and discharge or monthly trends at Ruliff before and after dam construction.

Evaluating mean discharges at both gauges showed significant increases in base flows during the summer months after dam construction (Figure 8). Average discharge at Bon Wier increased 1.8 times during July ($p < 0.01$), 2.2 times during August ($p < 0.01$) and 2.8 times during September ($p < 0.001$). At Ruliff, average discharge increased 1.6 times in August ($p < 0.05$) and 2.2 times in September after dam construction ($p < 0.01$).

The lowest floodplain elevations apparently remained inundated for longer durations in the post-dam period at both Bon Wier and Ruliff (Figure 9). At Bon Wier, the total inundation time of elevations above 18.3 m was similar in the pre-dam and post-dam periods. These higher elevations represent the majority of the floodplain area at that site. At Ruliff, although the total inundation time of elevations above 5.6 m was similar, the majority of the floodplain experienced increased inundation post-dam period. We found no evidence that differences in annual precipitation could have explained the observed differences in hydrology between periods before (1926−1965) and after (1971−2005) dam construction ($p > 0.05$).

DISCUSSION

Because bottomland hardwood forests depend on episodic large floods to inundate vast expanses of the floodplain, deposit sediment and deliver nutrients, there is, as described previously, a potential for changes in flood patterns to impact ecosystem status. However, not all dams alter the

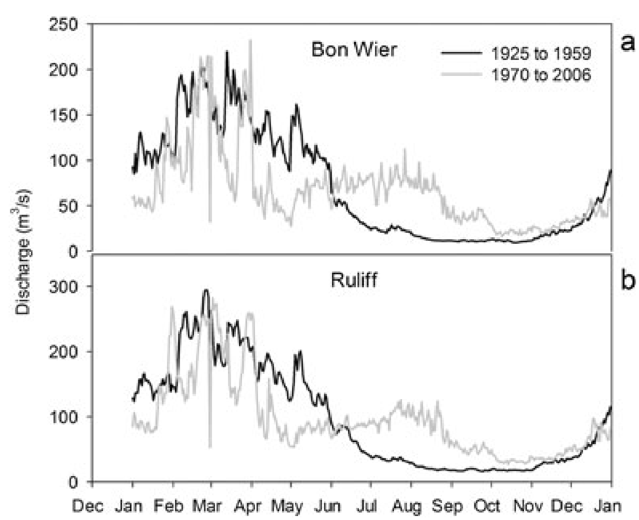

Figure 8. Mean discharge (in m^3/s) by calendar month before (1925–1959) and after (1970–2006) at Bon Wier (a) and Ruliff (b) gauges.

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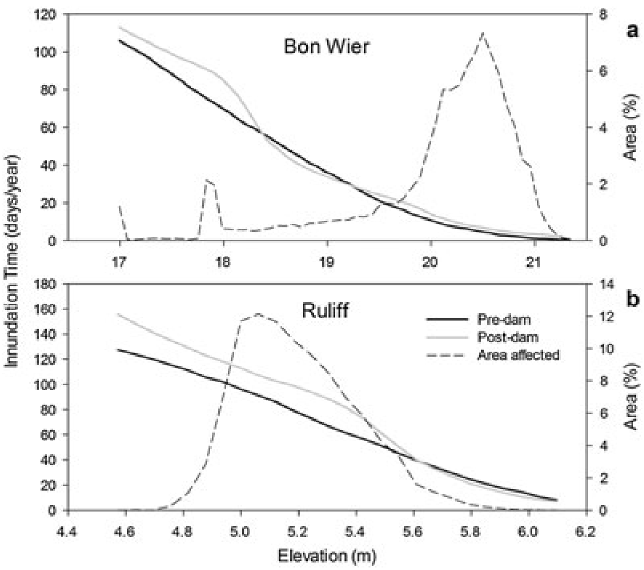

Figure 9. Time of inundation (days/year) for floods and the % of floodplain area affected (dashed line) across varying elevations in the pre-dam (black line) and post-dam (grey line) periods.

hydrology in the same way (Phillips, 2003; Graf, 2006). On the Sabine River, we found that whether the site was close to the dam or far away, they all exhibited a similar pattern: wetland plants dominated lower topographic areas, whereas upland species dominated higher areas (Table II). We found that vegetation patterns among the various topographic plots did not differ greatly from the most upstream to the most downstream sites. Wetland species dominance changed from 42%, to 33%, to 53% with increasing distance from the dam, and the greatest diversity was found at the most downstream site. Without prior data before dam construction, we cannot speculate whether these values were higher in the past or that the dam has had any effect on these values; however, upland species are more common than wetland species in these particular riparian wetlands upstream of the Sabine Island site. Furthermore, results for the site closest to the dam were potentially skewed by a few very large remnant specimens of bald cypress. These trees were clearly present before the dam was built and clearly not regenerating at the time of this survey.

Closer to the dam, several aspects of hydrology and geomorphology had changed significantly after the dam (Phillips, 2003, 2008), but these changes may not have been sufficient to alter plant composition. Although tree regeneration was low overall, FAC species regeneration apparently is outpacing OBL species regeneration. For example, once an old-growth bald cypress tree dies, it is not clear whether bald cypress or any other wetland-specific tree will take its place. We recognize that certain wetland tree species grow much larger than many upland species, such as American hornbeam (*Carpinus caroliniana*), and that regeneration in these systems is low and influenced by numerous factors (Streng *et al*., 1989). Also, trumpet creeper vine, a FAC herb species, had more than three times the dominance of the other species in the slough areas, which may indicate that desiccation is occurring at this site. This herbaceous species would likely respond faster to changes in hydrology that affect soil moisture, and the current tree species on the site

Table II. Summary of results

Question	*Finding*
Vegetation	
Did community composition differ among topographic gradients between sites?	Yes, wetland species dominated sloughs but not mid-floodplains or levees.
Did richness differ with elevation?	Yes, least diversity in the sloughs.
Is there an indication that fewer wetland species are regenerating after the dam was built?	Yes, FAC species had smaller mean diameters than wetland species.
Surface hydrology	
Did flood peaks decline after the dam was built?	No
Did flood size decline after the dam was built?	Yes, but only at Bon Wier
Did flood duration decline after the dam was built?	Yes, but only at Bon Wier.
Did flood frequency decline after the dam was built?	No
Did the seasonal timing of flows change after the dam was built?	No, except more floods in February at Bon Wier.
Did average flows differ after the dam was built?	Yes, increase in mean flows in July, August and September at Bon Wier; increase in mean flows in August and September at Ruliff.
Did the relationship between flood size and duration differ after the dam was built?	No
Did the area of inundation decrease after the dam was built?	No

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possibly represent past wetland conditions (Dewey *et al.*, 2006). Continued monitoring is needed to evaluate regeneration in this bottomland hardwood forest.

Work carried out by Streng *et al.* (1989) allows predictions about expected species composition changes based on timing and intensity of flooding. Many factors affect regeneration of southern bottomland hardwood forests species such as flooding intensity and timing, elevation, light availability, proximity to adults and drought among others that determine the distribution and survival of seedlings on an annual basis (Streng *et al.*, 1989). Also of importance are differences in emergence of light-seeded versus heavy-seeded species, the former tending to emerge earlier and is common of FAC trees, such as American hornbeam (Streng *et al.*, 1989). As a shade-tolerant species (Burns and Honkala, 1990), numerous juvenile American hornbeam comprised a major component of the understory on the levees and mid-floodplain areas but was nearly absent in the sloughs. Likewise, most individuals of Chinese tallow, an invasive FAC tree, had germinated in only the past few years. Chinese tallow is a species of concern because it is notorious for reproducing quickly and outcompeting native species to create a monoculture (Barrilleaux and Grace, 2000; Butterfield *et al.*, 2004; Webster *et al.*, 2006; Zou *et al.*, 2009). In addition, Chinese tallow has a tolerance to flooding equal to, and a salinity tolerance greater than that of bald cypress (Conner, 1994), indicating the establishment of this species may be unrelated to flood patterns. Serious ecological consequences could result from the proliferation of Chinese tallow, particularly in regard to maintenance of native species in the floodplain forests of the Sabine River.

Insights about flooding tolerance can be gained by investigating how tree, shrub and herbaceous species were distributed among the three topographic zones: sloughs, mid-floodplain and levees. We found that floodplain vegetation was extremely sensitive to minor elevation changes that directly relate to flood characteristics. At all three sites, we observed OBL species were most common in the sloughs and least common on the levees, which may indicate that only the lowest topographic zones of the floodplain are suitable for wetland plants. It may also indicate that the lowest areas are the only places receiving sufficient flooding disturbance to limit non-wetland species because of stress but that higher elevation sites with less frequent disturbance can support non-wetland species and result in greater competition, especially for light (Streng *et al.*, 1989; Naiman and Decamps, 1997; Dewey *et al.*, 2006). Not only were OBL species more frequent in sloughs, they also were more dominant in sloughs than in the levees or mid-floodplains; the same held true for FACW species. We also found OBL species were more common farther downstream of the dam where dam impacts were minimal, and where geomorphology was different as characterized by lower relief and multiple distributary channels that allowed for extensive floodplain connectivity (Phillips, 2008).

Our evidence suggests that the hydroperiod that supports wetland species occurs within the narrow range of elevation between sloughs and levees, 74–284 cm, depending on the site. This suggests more frequent flooding or shallower groundwater tables could displace FAC and FACU trees with more OBL species, except in the case of Chinese tallow, which grows well even when flooded (Conner, 1994). Flooding stress also leads to reduced plant diversity. Lower species richness in the slough areas of floodplains has been documented by others because there are only a few tree species that are adapted to areas of more frequent inundation and soil anoxia (Hodges, 1997; Glaeser and Wulf, 2009; Kupfer *et al.*, 2010).

Toledo Bend lake levels are kept relatively high at all times to maximize hydropower production, so when major floods occur, large volumes of water must be released. As a result, we saw no effect on peak discharge at either the Bon Wier or Ruliff sites. However, in response to moderate flood events, evidence suggests that slower timed releases from the dam may have increased inundation times modestly in the very lowest floodplain elevations. This is in contrast to flood control dams that are operated primarily to reduce the hazards of floods by virtue of their large storage capacity behind them to reduce peak flows (Williams and Wolman, 1984; Brandt, 2000; Graf, 2006), resulting in floods of shorter duration and less total flood discharge (Williams and Wolman, 1984). If flood peaks had been lower after dam construction, we would expect less of the floodplain to be inundated by floods, thus reducing the total area of bottomland hardwood forests experiencing such flood pulses. We did, however, see significant post-dam decreases in total flood discharge and duration at Bon Wier, in comparison to several major flood events of greater magnitude prior to dam construction. Although Wellmeyer *et al.* (2005) proposed that pre-dam and post-dam flow changes on the nearby Trinity River were because of climatic factors, our analysis of rainfall trends indicated that climate was similar before and after dam construction, thereby not affecting any change in flow patterns. The geomorphology of the Sabine River has been mostly unaltered except for the first few miles just below Toledo Bend Dam (Phillips, 2003, 2008; Heitmuller and Greene, 2009; Heo *et al.*, 2009).

Significant increases in base flows were found at both gauges during the summer months as a result of water released from the reservoir to produce hydroelectric power. Groundwater may not be the dominant hydrologic factor in southern bottomland hardwood forests, but can be vitally important for sustaining vegetation and instream river flow to aquatic organisms throughout the year (Cole

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et al., 1997; Krause *et al*., 2007). In low-lying areas, groundwater can saturate the top layer of soil, creating anoxic conditions unsuitable for non-wetland species to survive. Elevated base flows can contribute to higher water tables in the hyporheic zone underlying a riparian area (Sawyer *et al*., 2009), but without monitoring wells, it is difficult to estimate how far into the floodplain the water table would be affected.

Relating flood stage heights to floodplain elevations allowed us to examine direct connections between flooding inundation time and elevation patterns. At both gauge sites, the lowest elevations remained inundated for longer periods after dam construction. This finding was surprising, especially at Bon Wier, where duration and total flood discharge were significantly reduced, although peak discharge and flooding frequency were unchanged so that stage heights reached the same elevations as before and as often. This may be attributed to the operation schedule of the dam that releases floodwaters over longer periods. In any case, the fact that flood duration did not decrease in these areas indicates that these areas are receiving floodwaters for the same amount of time, which may be one reason why we found very few established upland (FAC and FACU) species in the sloughs.

CONCLUSION

Wetlands are defined by greater than 50% of plant species in the OBL or FACW category, and yet these riparian areas were not dominated by wetland species. Instead, we found a similar finding to that by Dewey *et al*. (2006) that FAC species were more prevalent than OBL or FACW species combined. This study documented the composition and size structure of the vegetation community at the present time. Wetland species dominated the lower areas of the floodplain, whereas FAC and upland species dominated the mid-floodplains and levees. Without historical vegetation data, it is difficult to relate changes in vegetation composition to river hydrology patterns downstream from dams. After dam construction, total flood discharge and flood duration were reduced at Bon Wier, but peak discharge and frequency were unchanged, and there was no effect detected on any hydrologic variables studied at Ruliff. At both gauges, the lower elevations of the floodplain were inundated for longer periods of time, and we observed similar vegetation community composition among the different topographic zones at all sites; yet we did find very little regeneration among wetland species but whether that has changed since dam construction is unknown because there is no known historical vegetation data.

We believe our method is useful for those seeking to do similar *post hoc* research on other river systems. It is widely acknowledged that dams throughout America have altered the hydrology and sediment regimes of rivers downstream (Williams and Wolman, 1984; Brandt, 2000; Graf, 2006). Effects of altered regimes on riparian ecosystems vary and additional factors, such as channel planform, climate, and land use, influence the changes experienced by river systems (Scott *et al*., 1996; Friedman *et al*., 1998; Johnson, 1998; Steiger *et al*., 2005). The results from this study illustrate the need to conduct a comprehensive analysis of floodplain vegetation sensitivity to minor changes in flood characteristics when no predisturbance vegetation data exists.

Future research should focus on two objectives: inundation mapping and vegetation-flow response guilds (Merritt *et al*., 2010). Inundation mapping, such as that performed by Benke *et al*. (2000), would reveal which areas are flooded at certain river discharges, which could be linked back to elevation differences and riparian vegetation composition. Vegetation-flow response guilds have been proposed by Merritt *et al*. (2010) as a framework for predicting vegetation response to changing environmental conditions. Riparian species can be grouped by shared traits, such as life history, reproductive strategy, morphology, and adaptations to flooding and soil anoxia, which relate to the various components of the hydrologic regime. By placing these species into guilds, evaluations can be conducted at the community level, which respond to long-term flow regimes. Probabilistic models can be developed to predict changes in vegetation composition based on changes in flow, as well as aid in the establishment of instream flow recommendations.

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